GAS BALANCING AND LINE-PACK FLEXIBILITY

CONCEPTS AND METHODOLOGIES FOR ORGANIZING
AND REGULATING GAS BALANCING IN LIBERALIZED
AND INTEGRATED EU GAS MARKETS

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Voorwoord

Daar een engagement van twee zijden moet komen wou ik graag het volgende weten (vooraleer andere kandidaten af te zeggen): als u van mij de job aangeboden krijgt (en waarbij ik u mijn woord geef) mag ik dan aannemen dat u de job aanvaardt en dat er ook een engagement van uw zijde is?

-Indien ik de job zou aangeboden krijgen, zal ik deze aanvaarden en kunt u rekenen op mijn volledige engagement.

Nu dit boekje af is, kan ik wel zeggen dat ik mijn engagement ben nagekomen. Het is dan ook tijd om de vele mensen te bedanken die rechtstreeks en onrechtstreeks invloed hebben gehad op mijn doctoraatswerk.

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Abstract

The liberalization and unbundling of the gas industry in Europe creates new challenges for the operation of the gas system. In particular the short-term coordination of shippers and the gas-transmission-system operator becomes difficult as information and responsibilities are distributed between them. The balancing mechanism establishes the main interface between these two gas-market actors and thus its design is important. The industry has been reflecting on the proper organization of gas balancing, but no consensus design could be agreed on yet. At the same time, the interest in this topic by academia has been limited, even though independent research into the gas-balancing problem can further advance the debate. In this thesis, therefore, the organization of balancing is properly discussed by taking both the shipper's viewpoint and that of the TSO into account in a number of essays focusing on specific balancing problems and challenges. Moreover, this work presents quantitative methodologies on a conceptual level that can be applied to other, practical problems by other researchers and the industry.

The first part of this work provides a thorough, but concise overview of what balancing is and how it is organized and how it can be organized drawing lessons from other sectors like the US gas market and the EU electricity sector.

The second part presents essays on the challenges of balancing in a national context without cross-border interactions. First, current regulation of line-pack flexibility is found to be inefficient and actually gas-market distorting. Second, rising unpredictability of the gas demand, transferred from RES intermittency, creates challenges for gas-system balancing with respect to the balancing design. Both market-based and non-market-based designs are imperfect and policy makers have to be made aware of that problem.

In a third part of this work, methodologies are developed to study the effects of cross-border balancing in a multi-region gas market. Efficiency gains are shown to be possible for hypothetical gas systems if the settlement designs provide correct incentives. If wrong incentives are provided, on the other hand, the overall efficiency can reduce because imbalances are moved to regions that are less efficient in balancing. In a market-based balancing mechanism, TSOs can also cooperate with regard to the procurement of flexible gas or the exchange of line-pack flexibility. This kind of cooperation is shown to improve efficiency for hypothetical cases, but researchers who have access to real data can apply the conceptual methodology to calculate the efficiency gains of cooperating across a particular border.

Samenvatting

De vrijmaking en ontvlechting van de Europese gasindustrie introduceert nieuwe uitdagingen voor de uitbating van het gassysteem. In het bijzonder wordt de kortetermijncoördinatie tussen de bevrachters en de gastransmissienetbeheerder bemoeilijkt omdat informatie verspreid is over verschillende actoren met gedeelde verantwoordelijkheden in de hervormde gasmarkt. Het gasbalanceringsmechanisme vormt dan ook het belangrijkste interactieplatform tussen de actoren op de korte termijn en het ontwerp ervan is dus belangrijk. De gasindustrie is reeds lang aan het nadenken over de correcte organisatievorm voor gasbalancering, maar tot een consensusontwerp heeft men tot nu toe niet besloten. Tegelijkertijd bleef de aandacht van de academische wereld voor gasbalancering beperkt, hoewel onafhankelijk wetenschappelijk onderzoek nodig is om het debat verder te helpen. In dit onderzoekswerk wordt de organisatie van gasbalancering uitvoerig besproken in een aantal essays met oog voor de standpunten van de bevrachter en van de transmissienetbeheerder. Bovendien presenteert dit werk kwantitatieve methodologieën op conceptueel niveau die het debat objectiveren en funderen. Deze methodologieën kunnen dan ook toegepast worden op concrete problemen door andere onderzoekers of door de industrie.

In een eerste deel van dit werk worden de huidige benaderingen voor gasbalancering voorgesteld en worden lessen getrokken uit oplossingen die in andere sectoren zijn uitgeprobeerd, met name de gasmarkt in de Verenigde Staten van Amerika en de elektriciteitssector in de EU.

Een tweede deel presenteert essays over de uitdagingen van gasbalancering in een nationale niet-grensoverschrijdende context. Eerst wordt aangetoond dat de huidige regulering van gasnetwerkflexibiliteit inefficiënt is en marktverstorend werkt. Ten tweede wordt er gewezen op de uitdagingen van toenemende onvoorspelbaarheid van de gasvraag door haar interacties met intermitterende bronnen van elektriciteitsproductie. Zowel marktgebaseerde als niet-marktgebaseerde organisatievormen zijn niet volledig aangepast aan die wijzigende gasvraag, een probleem waar beleidsmakers zich vaak niet bewust van zijn.

In een derde deel worden methodologieën geïntroduceerd voor de studie van grensoverschrijdende balancering van gasnetwerken in een multiregionale gasmarkt. Grensoverschrijdende acties kunnen efficiëntieverhogend werken als onbalanstarieven de relatieve kosten weerspiegelen in de verschillende regio's. Wanneer verkeerde signalen worden uitgestuurd kan transnationaal gedrag van de bevrachter zelfs efficiëntieverlagend werken. Ook de transmissienetbeheerders kunnen grensoverschrijdend samenwerken met het oog op het efficiënt bekomen van flexibiliteit. De voorgestelde conceptuele methodologie kan door ander onderzoekers verder worden toegepast op reële cases wanneer hiervoor data beschikbaar is.

Abbreviations and symbols

Abbreviations:

ACER	Agency for the Cooperation of Energy Regulators
AUT	Autarky, no cross-border interactions
BARON	Commercial MINLP solver
BE	Belgium
BRP	Balancing responsible party
BSP	Balancing services provider
CCGT	Combined-cycle gas turbine
CEER	Council of European Energy Regulators
CEGH	Central European Gas Hub (Austria)
CHP	Combined heat and power
CONOPT	Commercial NLP solver
CPLEX	Commercial MILP solver
$D^{(*)}$	Domestic (* foreign) demand
DA	Day-ahead
DSO	Distribution-system operator
EC	European Commission
EFET	European Federation of Energy Traders
EIA	Energy Information Administration
Elia	Belgian TSO for electricity
ENTSOG	European Network of Transmission System Operators for Gas
ERGEG	European Regulators Group for Electricity and Gas
EU	European Union
EWEA	European Wind Energy Association
FE	Forecast error
FERC	Federal Energy Regulatory Commission
Fluxys	Belgian TSO
FS	Forum-shopping strategy (transnational TSO)
GCV	Gross caloric value (e.g., 11.5 kWh/m^3)
GFPP	Gas-fired power plant
GIE	Gas Infrastructure Europe
GLE	Gas LNG Europe
GRTgaz	French TSO
GSE	Gas Storage Europe

GTE	Gas Transmission Europe
GTS	Dutch TSO
HHI	Hirschmann-Herfindahl Index
ID	Intra-day
IEA	International Energy Agency
LDZ	Local Distribution Zone
LNG	Liquid natural gas
LP	Linear programming
MILP	Mixed-integer-linear programming
MINLP	Mixed-integer-non-linear programming
National Grid	UK TSO for electricity and for gas
NBP	National Balancing Point (UK)
NCG	Net Connect Germany
NLP	Non-linear programming
PD	Economic power dispatch
PEG	Point d'échange gaz (France)
PSV	Punto di scambio virtual (Italy)
RE	Relative efficiency of the expensive balancing region compared to the efficient balancing region
RES	Renewable energy sources
RMP	Reference market price
$S^{(*)}$	Domestic (* foreign) supply
SLP	Synthetic load profile
SMP	System Marginal Price
Tol	Tolerance
Tol-CD	Cumulative daily tolerance
Tol-CH	Cumulative hourly tolerance
Tol-D	Daily tolerance
Tol-H	Hourly tolerance
Tol-MR	Cumulative imbalance mid-range
TPA	Third-party access
TSO	Transmission-system operator
TTF	Title Transfer Facility (Netherlands)
UC	Unit commitment
UK	United Kingdom
ZIG	Dow Jones Zeebrugge Index Gas

Main symbols:

Sets

A	Set of pipelines, index *a(ij)*
$A^{in}(i)$	Subset of pipelines arriving in *i*
$A^{out}(i)$	Subset of pipelines departing from *i*
H	Set of periods, index *h*
I	Set of nodes, index *i*, *j*,...
R	Set of regions, index *r*

Parameters

buy_max	Maximum off-take allowed by contract [Mm^3/h]
buy_min	Minimum off-take allowed by contract [Mm^3/h]
CAP	Border capacity [Mm^3/h]
cflexdown	Unit cost of downward flexible gas [EUR/m^3]
cflexup	Unit cost of upward flexible gas [EUR/m^3]
cfuel	Unit cost of compressor fuel [EUR/m^3]
clpflex	Operational cost of line-pack flexibility [EUR/m^3]
cb	Shipper acquisition cost of gas [EUR/m^3]
cf	Unit cost of *ex-ante* flexibility [EUR/m^3]
demand	Exogenous demand for gas [Mm^3/h]
F	Imbalance-tariff fee [EUR/m^3]
flex_cap	Maximum storage level defined in *ex-ante* contract [Mm^3]
flex_max	Upper limit *ex-ante* upward flexibility [Mm^3/h]
flex_min	Lower limit *ex-ante* downward flexibility [Mm^3/h]
LP_max	Upper limit line-pack level [Mm^3]
LP_min	Lower limit line-pack level [Mm^3]
p_max	Upper pressure limit [bar]
p_min	Lower pressure limit [bar]
ps	Shipper sales price of gas [EUR/m^3]
Qdown	Maximum downward flexibility in bid [Mm^3/h]
Qup	Maximum upward flexibility in bid [Mm^3/h]
Vbase	Amount of base gas in a storage [Mm^3]

Variables

balancingcost	TSO objective [EUR]
Ecr	Primary energy for compression [Mm^3]
M	Trade between regions by shipper or TSO [Mm^3/h], positive if import
p	Nodal pressure [bar]

$\bar{p}$	Average pipeline pressure [bar]
profit	Shipper objective [EUR]
sign	Flow direction, +1: forward, –1: backward
$\dot{V}$buy	Shipper gas purchases [Mm^3/h]
$\dot{V}$en	Gas entry rate [Mm^3/h]
$\dot{V}$ex	Gas exit rate [Mm^3/h]
$\dot{V}$flex	Shipper *ex-ante* flexibility [Mm^3/h]
$\dot{V}$flexdown	TSO downward-flexibility rate [Mm^3/h]
$\dot{V}$flexup	TSO upward-flexibility rate [Mm^3/h]
$\dot{V}$i	Flow rate at node i for pipeline a(ij), [Mm^3/h]
$\dot{V}$imb	Shipper *ex-post* flexibility, [Mm^3/h]
Vimbacc	Shipper cumulative imbalance [Mm^3]
$\dot{V}$inj	Storage-injection rate [Mm^3/h]
$\dot{V}$j	Flow rate at node j for pipeline a(ij) [Mm^3/h]
Vlp	Line-pack level [Mm^3]
$\dot{V}$lpflex	Change of line-pack level [Mm^3/h]
$\dot{V}$sell	Shipper sales [Mm^3/h]
Vsto	Physical gas in storage [Mm^3]
Vstock	Shipper storage level [Mm^3]
$\dot{V}$wd	Storage-withdrawal rate [Mm^3/h]

Other

$\square_{\blacksquare}$	Indicator of location, e.g., a node or a region
$\square_{buy}$	Parameter related to purchase of gas
$\square_{in}$	Level at inlet of pipeline
$\square_{max}$	Maximum level
$\square_{min}$	Minimum level
$\square_{out}$	Level at outlet of pipeline
$\square_{sell}$	Parameter related to sale of gas
γ	Isentropic exponent [-]
δ	Relative density gas to air [-]
ε	Pipeline roughness [m]
η_{CCGT}	CCGT-plant dynamic efficiency [-]
η_{comp}	Efficiency of the adiabatic compression [-]
η_{mech}	Mechanical efficiency of the compressor [-]
μ	Statistical average
ρ	Gas density [kg/m^3]

σ	Statistical standard deviation
$\Delta S_{shipper,R1+R2}$	Efficiency surplus of the shipper(s) comparing cross-border interactions to autarky in the combined region R1+R2, positive if improving
$\Delta S_{TSO,R1+R2}$	Efficiency surplus of the TSOs comparing cross-border interactions to autarky in the combined region R1+R2, positive if improving
ΔW_{R1+R2}	Welfare change consisting of efficiency gains of shippers and TSOs in the combined region R1+R2, positive if improving
D	Pipeline diameter [m]
dp2	Difference of squared pressures [bar^2]
k_cr	Constant for adiabatic compression, dependent on chosen units
k_flow	Proportionality factor between flow rate and pressure drop, dependent on units
k_inj_1	First storage-dependent constant for injection rate
k_inj_2	Second storage-dependent constant for injection rate
k_lp	Proportionality factor between line-pack level and average pressure
k_wd	Storage-dependent constant for withdrawal rate
L	Pipeline distance [m]
m(r)	Import/Export quantity under restricted-trade conditions
m(t)	Import/Export quantity under free-trade conditions
$\dot{m}_{in}$	Mass flow at inlet of pipeline [kg/s]
$\dot{m}_{out}$	Mass flow at outlet pipeline [kg/s]
MP_{down}	Marginal price of downward flexibility procured by the TSO
MP_{up}	Marginal price of upward flexibility procured by the TSO
p(a)	Price in autarky
p(r)	Price under restricted-trade conditions
p(t)	Price under free-trade conditions
p_{dmin}	Minimum operating pressure [bar]
p_{emax}	Maximum operating pressure [bar]
$P_{el,CCGT}$	Electric-power output of CCGT [MW]
$P_{gas,CCGT}$	Gas power input of CCGT [MW]
q(a)	Production in autarky
q(r)	Production under restricted-trade conditions
q(t)	Production under free-trade conditions
T	Gas temperature
Z	Compressibility [-]

Units:

Bar	Unit of pressure [1 bar = 100 000 Pa]
BCM	Billion Cubic meters [10^9 m^3]
EUR	Euro
EUR/m^3	Euro per cubic meter
h	Hour
kWh	KiloWatt-hour
K	Kelvin, unit of temperature
m	Meter
M	Mega [10^6]
m^3	Cubic meter (st)
MCM	Million cubic meters [10^6 m^3]
MW	MegaWatt
MWh	MegaWatt-hour
Pa	Pascal [N/m^2]
st	Standard conditions: p_{st} = 101325 Pa and T_{st} = 288.15 K
TCM	Trillion cubic meters [10^{12} m^3]

General remarks:

- Greek symbols in Chapter 1 represent penalty parameters
- Flow rates in a period represent the average rate over the interval, thus, Mm^3/h integrated over one hour gives Mm^3

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CONCEPTS AND METHODOLOGIES FOR ORGANIZING AND REGULATING GAS BALANCING IN LIBERALIZED AND INTEGRATED EU GAS MARKETS

0. INTRODUCTION AND MOTIVATION

This chapter outlines the context in which the balancing of the gas network takes place and why gas-balancing design and regulation of network flexibility need to be studied to advance energy policy and gas-market regulation. The chapter ends with an overview of the research questions and the work that are the subject of this thesis.

0.1 General context

A combination of economic considerations, e.g., the investment costs and building time of a combined-cycle gas turbine (CCGT), environmental considerations, e.g., the reduction of CO_2-emissions, and government policy choices, e.g., the phase out of nuclear power, has turned natural gas, hereafter referred to as gas, from a "fuel of choice" into a "fuel of consequence". Therefore, gas is not an outdated fossil fuel, but a fuel that plays an important role in a sustainable and diversified energy mix in Europe for the next decades [1-5].[1] Therefore, the reliability of the day-to-day gas supply is key to the functioning of the gas market.

The gas-balancing mechanism establishes the interface between the users of the network, hereafter called "shippers", and the transmission-system operator (TSO). Its main function is to ensure the safe and reliable day-to-day operation of the gas system by maintaining the balance between gas entering and exiting the pipeline system accounting for the storability of gas and other flexibility instruments.

In the past, before the liberalization process had started, the gas-supply chain was controlled by a single vertically-integrated national utility company that had access to all information necessary to operate the supply chain in a reliable and cost minimizing way. Therefore, balancing the network was not really an issue. However, the introduction of legislation by the European Union (EU) to liberalize and integrate the national gas markets in an effort to bring energy in line with the rest of the internal market and increase efficiency and competitiveness in the gas sector, has dramatically changed the gas-market playing field [6-8].

To achieve market liberalization and integration, the European Commission (EC) opted to unbundle the competitive activities of production, import and supply from the non-competitive network-related activities of gas transport and distribution and ensure non-discriminatory third-party access (TPA) to the gas network, which is qualified as a natural monopoly in Europe. Furthermore, these networks of

[1] Key statistics about the global and European gas market can be found in Appendix A.

connected pipelines are organized in multiple **zones**, each governed by a particular set of rules organizing the market and balancing.

As a result of the chosen path by the EU, the gas-market architecture has become a complex of physical and contractual relationships with distributed responsibilities as illustrated in Figure 1.

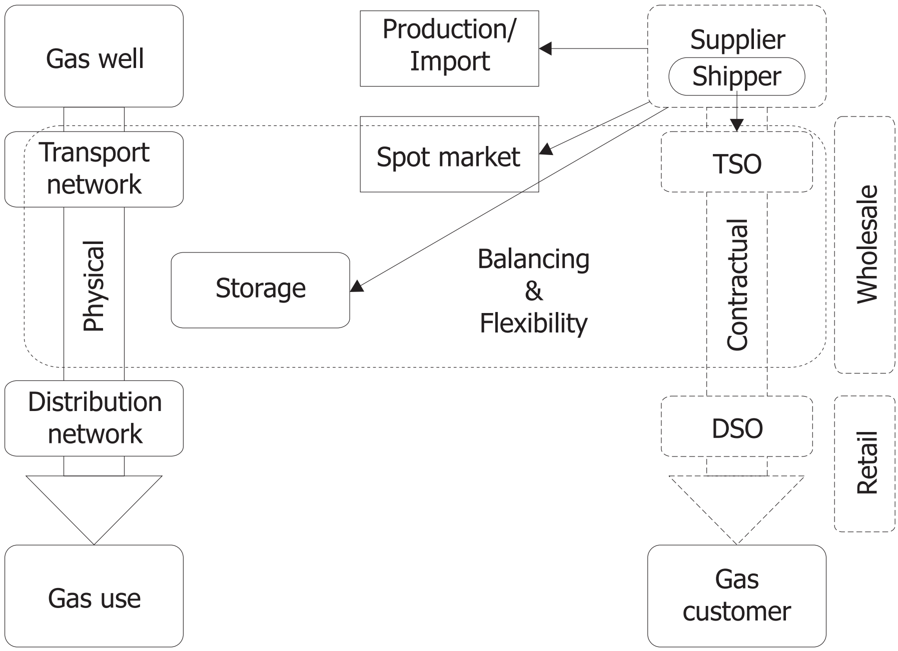

Figure 1. Gas-market architecture after liberalization (based on: [9]): the physical chain is distinct from the contractual chain, but both are linked through the shipper, the TSO and the balancing mechanism. The physical chain represents the flow of the commodity through the gas network, whereas the contractual chain represents the rights and obligations that govern interactions between the gas-market actors. The retail/distribution level is not always part of the physical and contractual supply chains and is not further discussed in this thesis.

The physical relationships concern the flow of gas molecules from the well to the place of use over the transport and distribution pipeline networks, possibly passing physical storage along the supply chain (left-hand arrow). The contractual relationships, on the other hand, concern the ownership rights and financial cash flows between the different market actors. Four types of market players can be distinguished in the typical institutional architecture of the EU gas market. The first group concerns the gas suppliers/shippers who are active in the wholesale part of the supply chain, acquiring gas by means of long-term contracts with domestic or foreign producers or from the spot market, and selling it to other wholesale players, retail suppliers or directly delivering it to big gas consumers like gas-fired electricity generation or industry. The concept of the "shipper" is further explained below. The gas consumers make up the second group of actors and include residential consumers that use gas for heating and cooking, the demand from the commercial-services sector and the demand from aforementioned electric-power and industrial sectors. Each customer type has specific characteristics regarding variability and uncertainty of the actual demand profile. Furthermore, large customers are typically connected to the transmission level, whereas residential demand and the commercial sector are served through the distribution network. The third group of market actors comprises the providers of network services: the transmission-system operator for the high-pressure national and international pipelines and the distribution-system operator (DSO) for the low-pressure local pipelines. Finally, the providers of flexibility services make up a fourth group. Beside these four actors, the regulatory authority, the competitive authority and policy makers perform important back-office functions to make the market function well. Note that the distribution level and the retail market are also part of the gas-market architecture, but they are not discussed in this work, which focuses on the transport level as marked with the dashed line.[2] On this transport level, the shipper and the TSO, the two protagonists of this thesis, are active. At the heart of their operational interactions lie the balancing rules and flexibility. The latter is crucial to align contractual and physical mismatches, whereas the former act as the coordination mechanism between both protagonists.

According to Codognet, the core role in the gas-market architecture is played by the shipper [10]. A strict definition of "shipper" refers to any gas player who has signed a contract for transport services with a TSO, and, thus, makes up a distinct role from the supply function that refers to contracts for gas molecules. In this thesis, however, a looser definition is applied, making no difference between the supply function and the shipper function. Therefore, the term "shipper" is used hereafter to refer to the two functions unless an explicit distinction is necessary. The shipper acts in a competitive and uncertain market and has to build a contract portfolio of gas-purchase and gas-sales contracts and transport contracts to move the commodity, all with the intent of maximizing profits [11]. Because of upstream rigidities and downstream variability and uncertainty, the matching of supply and demand is difficult even when flexibility contracts are available to the shipper. These mismatches cause physical imbalances in the network.

The TSO, on the other hand, controls the transport infrastructure and deals with the physical flow of gas and the physical reliability of the gas system. Hence, the TSO is ultimately responsible for handling the aggregate system imbalance. To transfer the balancing responsibility to the shippers, who actually cause imbalances, the TSO, in cooperation with the regulator, defines balancing rules in the network code, which encompasses the network services offered and the rules by which the network is operated.

[2] "Transport" and "transmission" are used as synonyms.

Therefore, two stages can be identified in the gas-balancing problem. The first stage, illustrated in Figure 2, encompasses the shipper balancing. The shipper has to match gas supply and gas demand, but these have different time patterns. To accommodate the resulting imbalance, the shipper can acquire and dispatch *ex-ante* flexibility, e.g., import-contract flexibility or storage flexibility, beforehand, or rely on the *ex-post* balancing and pay imbalance fees to the TSO.

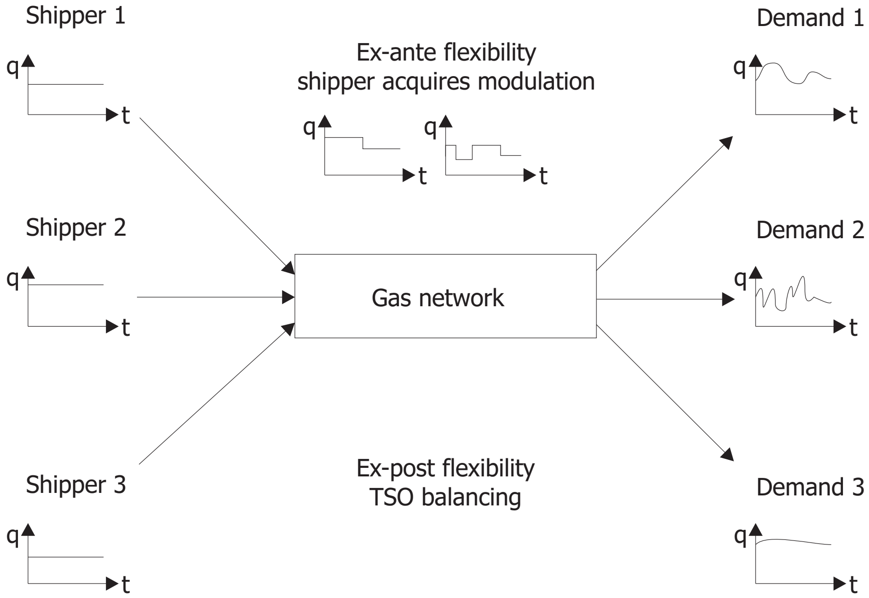

Figure 2. Shipper balancing: time patterns gas supply and gas demand mismatch, shipper has two options: acquire ex-ante flexibility or rely on ex-post balancing by the TSO and pay imbalance-settlement fees; in the graphical illustrations of demand and supply, "q" stands for an amount [Mm^3/h, to be integrated over the length of a period] and "t" stands for the hourly time periods [h].

The ex-post balancing by the TSO, then, makes up the second stage in the balancing problem and is illustrated in Figure 3. The TSO transports the injected gas at entry nodes (En.) over the gas network to the point of offtake at exit nodes (Ex.). Furthermore, the TSO has to accommodate the aggregated imbalance of the individual shippers. To this end, the TSO uses line-pack flexibility (pipeline storage) and dispatches other flexibility that is procured from flexibility providers, e.g., underground storage. The costs of these *ex-post*-balancing services are then transferred to the unbalanced shippers.

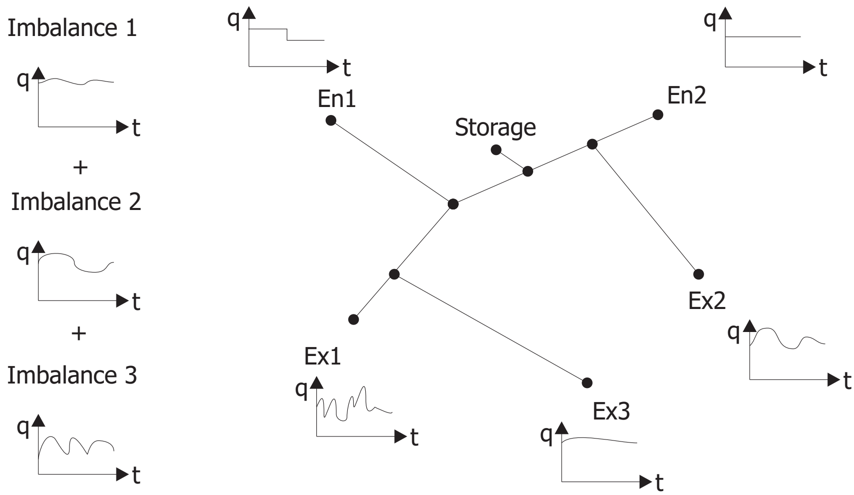

Figure 3. TSO balancing: TSO sees injections at entry points (En.), withdrawals at exit points (Ex.) and has to cover the aggregated (over all individual shippers) imbalance profile using network and other flexibility (e.g., storage); in the graphical illustrations of demand, supply and imbalance, ""q" stands for an amount [Mm^3/h, to be integrated over the length of a period] and "t" stands for the hourly time periods [h]

Summarizing, the shipper tries to maximize profits by buying gas in cheap locations and selling it in locations where gas has a higher economic value, but has difficulties to match supply and demand. The TSO has to move the gas physically, while ensuring economic and reliable operation of the gas network at minimal costs. Both actors are actually agents that affect the welfare of the great many European gas consumers. The increase of consumer welfare by means of increasing competitiveness and efficiency of the gas industry players is the ultimate objective of the gas-market reforms in Europe.

0.2 Motivation and relevance of gas balancing as PhD-thesis subject

Gas balancing is not only necessary from a safety point of view, but it is also essential to the functioning of the gas market. Understanding the effects of balancing-mechanism design and network-flexibility regulation on different stakeholders is relevant and necessary for policy makers and researchers studying gas-market integration in Europe. Moreover, balancing costs make up a substantial share of gas prices for consumers. Table 1 shows the shares of balancing related costs in the energy prices for a small consumer (roughly consuming 0.1 Mm^3 per year) and a large consumer (roughly consuming 25 Mm^3 per year) in a selection of EU countries.

Table 1. Estimated shares [%] of balancing costs in energy prices for small consumers and large consumers in 2004 [12]

Country	Share of balancing costs in energy price [%] paid by	
	small consumer (0.1 Mm^3/year)	large consumer (25 Mm^3/year)
Austria	9.1	5.1
Belgium	16.4	10.9
France	/	5.4
Germany	11.4	12.7
Netherlands	17	13.3
Spain	18.8	10.9
UK	12.8	6.4

0.2.1 The industry

Balancing has been a controversial topic since the start of the gas-market liberalization as demonstrated by the series of principles and guidelines developed by the regulators and TSOs, often consulting other stakeholders as well. The first reference to the gas-balancing issue in the liberalizing European gas market has been made by the Council of European Energy Regulators (CEER) in the early 2000s [13]. The European Regulators Group for Electricity and Gas (ERGEG) took over the role of CEER and started developing guidelines on how to design a balancing mechanism [14-17]. These guidelines, however, were just guidelines and thus non-binding. Moreover, the proposed principles suffered from a lack of clarity and a clear set of implementable best practices. The European gas-transmission-system operators set up a parallel process for publishing position papers with their viewpoint on the balancing issue [18-20]. A clear proposal for a common balancing-mechanism design was never laid down, though. Industrial consultants also contributed to the topic. KEMA advocated a daily balancing period and market-based balancing charges in an extensive report for the German energy regulator [21]. NERA and TPA Solutions conclude from an extensive review of different balancing-mechanism implementations that clear common balancing principles would move the liberalization forward without clearly specifying what an ideal balancing mechanism should look like [22]. Meanwhile, KEMA argued in a report for the EC that the lack of market-based balancing mechanisms potentially constitutes a barrier to cross-border trade and thus to market integration [23]. They further identified a number of design parameters such as balancing charges and the balancing period that can distort gas-market development. ERGEG proposed a target model for a common European balancing mechanism that has reopened the long-lasting discussion [24]. Although the views are not very different from those expressed in earlier position papers, the virtue of this draft framework consists in the firmer language it uses, e.g., by actually referring to a "target model". The result of that discussion has served as input for the EU Agency for the Cooperation of Energy Regulators (ACER), which essentially took over ERGEG's role in this debate. In 2011, ACER has published what appear to be final framework guidelines for gas balancing [25]. In response to ACER's work, the European network of transmission-system operators for gas (ENTSOG) has been working on the implementation of the guidelines in a network code, which is a work in progress at the time of writing this thesis.

0.2.2 The academic literature

The fairly limited academic literature on gas-balancing design and regulation of gas-network flexibility strongly contrasts with the extensive industrial interest in the topic. Codognet [26] has investigated the role of the institutions for European network-access contracts. The gas-balancing rules, according to his findings, establishes one of three dimensions of getting proper access to the gas market, the other two being the definition of capacity rights and the tariff structure. Furthermore, he highlighted the divergence in actual implementations of network-access rules in Europe and he pointed out the pivotal role of the shipper, who has to build a portfolio of standard service contracts tailored to his specific needs. The regulation of flexibility in the EU has been studied by Hallack [27] taking an institutional economics approach. In that work, it is argued that the changing gas demand is changing the operation of the network and thus challenging the existing regulation of the network. In Europe, the network is subject to open-access rules established by nationally regulated network codes, which limits the variety of services that can be offered by a TSO. As a result, homogeneous bundles of transmission services and network flexibility cannot capture the full range of preferences by the shippers resulting in market inefficiencies. Open-access rules, alternatively, can also be defined by heterogeneous direct contracts between shippers and pipeline companies detailing flexibility and transmission rights according to individual preferences. Evidently, flexibility makes up an important aspect of balancing as shippers and TSOs are competing for scarce flexibility services to help them fulfill their responsibilities. Finally, the financial settlement of shipper imbalances has received some attention as a mathematical optimization problem minimizing penalty costs in a bi-level framework with the shipper as the leader and the TSO as the follower, each with their specific objectives [28; 29]. The focus in that work, however, is not on the balancing-mechanism design or on the regulatory aspects of the gas network, but on the modeling of the problem and the profitability of a shipper strategy.

0.2.3 Filling the gap

Gas balancing is thus a relevant problem for the gas industry, but academic research has largely overlooked it due to its novelty, only having become a regulatory and operational problem after the liberalization. Furthermore, gas balancing is relevant from different viewpoints: TSO versus shipper, the regulation of network flexibility or the operational impact of the balancing mechanism. Therefore, gas balancing is a necessary subject to explore independently by academia, all the more so that the research basis to start from is limited. Hence, this thesis explores some fundamental aspects of gas balancing to fill the identified gap and to provide a further advanced starting point for other researchers dealing with the multitude of problems arising in the framework of gas balancing. It must be clear that, in a wider context beyond balancing, the gas market and the pipeline system have been studied in the academic literature: e.g., focusing on the mathematical modeling challenge or on longer-term topics like import dependency. The relevant works of this literature are further discussed in the respective chapters.

0.3 Research questions and overview of work

The work in this thesis encompasses a conceptual study of gas balancing in liberalized EU gas markets and the development of methodologies for studying gas balancing and operational flexibility while accounting for technical *and* economic considerations. The work features three main research questions concerning gas balancing and flexibility in liberalized EU gas markets:

- What is gas balancing, how is it organized and what are its challenges accounting for technical as well as economic aspects?
- What are the effects of balancing-mechanism design and network-flexibility regulation on the functioning of the gas market and on the gas-market players?
- What are the welfare/efficiency effects of cross-border balancing for the shippers and for the TSOs?

This thesis is structured along four parts, each divided in chapters that stand on their own, and can be read independently, but together the essays form a whole that is answering the overarching research questions. Furthermore, each chapter answers its own subquestion(s) using adequate methodologies.

Part 1 is titled "Fundamentals of gas balancing" and contains a single chapter in which, first, a proper framework and terminology are defined to discuss gas balancing and, second, different approaches are identified in the EU and US gas markets and gas balancing is compared with electricity balancing. This first part consisting of the first chapter will mainly serve as an introduction to the other parts of the thesis.

Part 2 deals with "national aspects of balancing and regulation of network flexibility". National is to be understood as independent of cross-border interactions in a multi-region gas market.

Chapter 2 applies concepts of regulatory economics and institutional economics and discusses the regulation of line-pack flexibility and the market-distorting effects of current balancing rules that are based on inefficient network-flexibility regulation.

Chapter 3 presents an operations-research model of the gas-transmission system to study economic effects of balancing and flexibility taking technical aspects into account. This model is then applied to the case of balancing wind-power intermittency with the gas system. In particular, market-based settlement and non-market-based settlement are compared with regard to their effectiveness in dealing with rising unpredictability.

Part 3 is introduced by Chapter 4 and looks at the cross-border aspects of gas-balancing design from a welfare and efficiency viewpoint, comparing autarky with cross-border trade. To this end, a self-developed efficiency-benchmarking methodology is applied in combination with the operations-research model introduced in Chapter 3.

Chapter 5 explores the opportunities for "forum-shopping" behavior by shippers responding to incompatible imbalance-settlement rules in geographically adjacent regions and the impact of this behavior on the efficiency surplus of the shipper and the TSO, respectively.

Chapter 6 presents a similar efficiency analysis of cross-border procurement of flexible gas and system-imbalance pooling.

Part 4 contains Chapter 7 and it presents a summary of the work, puts forward conclusions and makes suggestions for further research.

Overall, the conducted research focuses on short-term operational aspects of the gas-system balancing, taking the gas network as it is. It does neither cover long-term investments (changing the gas network), nor does it deal with capacity costs – apart from a conceptual argument in Chapter 2 – because studies of those topics establish PhD-research topics on their own.

0.4 Overview of papers incorporated

The work in this thesis builds upon research papers; either published as refereed journal papers, conference papers or working papers (publicly available through a weblink).

Chapter 0 contains elements from:

- Keyaerts, N., D'haeseleer, W., 2012. Increasing efficiency through market-based cross-border procurement of gas-balancing services in Europe.

Submitted for publication. Available in the TME Working-Paper Series. University of Leuven (KU Leuven) Energy Institute.

- Keyaerts, N., Meeus, L., D'haeseleer, W., 2009. First results of the integrated European gas market: one for all or far from one, World Gas Conference 24. IGU, Buenos Aires, Argentina.

Chapter 1 contains elements from:

- Keyaerts, N., Meeus, L., D'haeseleer, W., 2009. Entry in European natural gas retail markets: accessing the right contract portfolio, 6th International Conference on the European Energy Market (EEM), 2009, Leuven, Belgium.
- Keyaerts, N., Hallack, M., Glachant, J.-M., D'haeseleer, W., 2011. Gas market distorting effects of imbalanced gas balancing rules: Inefficient regulation of pipeline flexibility. Energy Policy 39, 865-876.
- Keyaerts, N., D'haeseleer, W., 2012. Forum shopping for *ex-post* gas-balancing services. Submitted for publication. Available in the TME Working-Paper Series. University of Leuven (KU Leuven) Energy Institute.
- Keyaerts, N., D'haeseleer, W., 2012. Increasing efficiency through market-based cross-border procurement of gas-balancing services in Europe. Submitted for publication. Available in the TME Working-Paper Series. University of Leuven (KU Leuven) Energy Institute.

Chapter 2 is based on:

- Keyaerts, N., Hallack, M., Glachant, J.-M., D'haeseleer, W., 2011. Gas market distorting effects of imbalanced gas balancing rules: Inefficient regulation of pipeline flexibility. Energy Policy 39, 865-876.

Chapter 3 is based on:

- Keyaerts, N., 2012. Using operations research to study optimal use of flexibility in liberalizing gas markets: GASFLEX. TME Working paper series. University of Leuven (KU Leuven) Energy Institute.
- Keyaerts, N., Rombauts, Y., Delarue, E., D'haeseleer, W., 2012. Impact of unpredictability on gas-balancing design in Europe. Submitted for publication. Available as Keyaerts, N., Rombauts, Y., Delarue, E., D'haeseleer, W., 2011. Impact assessment of increasing unpredictability in gas balancing caused by massive wind power integration. TME Working-Paper Series. University of Leuven (KU Leuven) Energy Institute.

Chapter 5 is based on:

Keyaerts, N., D'haeseleer, W., 2012. Forum shopping for *ex-post* gas-balancing services. Submitted for publication. Available in the TME Working-Paper Series. University of Leuven (KU Leuven) Energy Institute.

Chapter 6 is based on:

- Keyaerts, N., D'haeseleer, W., 2012. Increasing efficiency through market-based cross-border procurement of gas-balancing services in Europe. Submitted for publication. Available in the TME Working-Paper Series. University of Leuven (KU Leuven) Energy Institute.

http://www.mech.kuleuven.be/en/tme/research/energy_environment/PublicationsEnergyandenvironment/Journalpapers

PART 1

Fundamentals of gas balancing

1. FRAMEWORK, TERMINOLOGY AND APPROACHES TO GAS BALANCING

This chapter outlines the fundamentals of gas balancing and, therefore, sets up a framework for the deeper study of the positive and negative effects of balancing-mechanism design on market-operation and efficiency. First, the operational security of the pipeline system is discussed, introducing a definition for physical imbalance and defining the roles and responsibilities of the TSO and the shipper. These roles correspond to the two stages of the balancing problem represented by Figure 2 for shipper balancing and Figure 3 for TSO balancing in the introductory Chapter 0. Next, the balancing mechanism is decomposed in its elementary parts: procurement of flexible gas and settlement of imbalances. After the introduction of the proper framework and terminology, national approaches within the EU are presented to illustrate the practical implementation of gas balancing. The final sections discuss to what extent lessons from the US gas-market and the EU electricity-balancing experiences can be applied to gas balancing in the EU.

1.1 Operational security of a gas-pipeline system

1.1.1 The role of the TSO

In a network-based gas industry, the pipelines serve as the backbone of all other activities. Monitoring network reliability, therefore, is of utmost importance to the functioning of the gas market and is ultimately the responsibility of the TSO.

The responsibility for reliability can be decomposed in a long-term responsibility concerning "network adequacy" and a short-term guarding of "system integrity", using an adapted version of Eurelectric's framework for security of supply of electricity (Figure 4).

In the long term, the TSO maintains the adequacy of the network by investing in the pipeline system in order to meet the current and future demand for gas-transmission services.

System integrity, on the other hand, deals with the safe and continuous operation of the pipeline system and comes down to keeping the pipeline-pressure levels or the **line-pack** levels within the safe operational limits of the pipeline system.[3] **Physical imbalances** affect the pressure level in the pipeline, raising it when more gas is

[3] Line pack is the total amount of gas in the pipelines and is directly related to the average pipeline pressure. To enable gas transport, a minimum amount of gas is to be kept in the lines.

entered than withdrawn ($\dot{m}_{in} > \dot{m}_{out}$) or dropping it when less gas is entered than withdrawn ($\dot{m}_{in} < \dot{m}_{out}$). For this reason, the gas system has to be balanced.

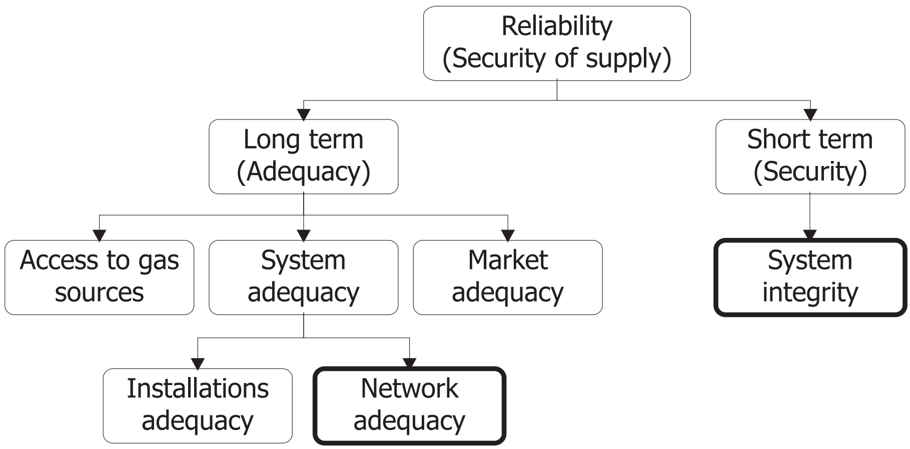

Figure 4. Eurelectric's security-of-supply framework – adapted to gas, TSO responsibilities framed in bold (source: [30])

However, gas is a compressible and thus storable product and gas dynamics allows small diurnal imbalances to be covered by the **line-pack flexibility**. Indeed, the line-pack level can be varied while maintaining the same gas-flow rate. Therefore, the correct system imbalance equation reads:

$$\dot{m}_{in} - \dot{m}_{out} = \frac{\partial(\rho V_{geo})_{storage}}{\partial t} . \tag{1.1}$$

The right-hand side term in Eq. (1.1) reflects the change over time (t, expressed in s) of the gas mass stored inside the pipeline by means of line-pack flexibility. The imbalance, then, is reflected in that storage term, in which V_{geo} represents the geometrical volume (m^3) of the pipeline section and ρ the gas density (kg/m^3). Therefore, line-pack flexibility makes balancing gas networks an intertemporal problem. Indeed, the short-term storage in pipelines allows matching demand and supply over a time interval, rather than instantaneously. In other words, only when the line-pack level, or, alternatively, the pipeline pressure rises too high or drops too low, physical intervention is required by the TSO. The role of the TSO, thus, is to control the pressure in the pipeline system and to physically intervene when the inherent network flexibility has been exhausted. In this last case, the TSO has to procure **flexible gas** from flexibility providers. Flexible gas stands for the buying and selling of gas by the TSO to correct an excessive system deficit (line-pack level too low) or a system surplus (line-pack level too high), respectively. Note that, in view of pipeline reliability, the TSO remains responsible for the balancing, but that the shippers, who are further discussed in the next subsection, actually cause imbalances.

1.1.2 The role of the shipper

In the liberalized gas market, the shipper has become a competitive actor who has to build a portfolio of contracts spanning the whole supply chain. Upstream, access to gas sources needs to be ensured with *gas-purchasing contracts*. Downstream, the shipper needs to sign *gas-sales contracts* with customers to take off the gas. Next, *gas-transport services* are needed to move the gas between different locations. Finally, the shipper can buy insurance against gas-business risk under the form of *flexibility contracts*.

1.1.2.1 Gas-purchase contracts: accessing the commodity

The European gas industry has a long tradition of bilateral long-term contracts, typically 20 years or longer, and often specifying take-or-pay clauses, between gas producers and shippers.[4] These contracts are an effort to reduce transaction costs of renegotiation and to mitigate the hold-up risk, effectively tying both parties to each other [32; 33]. In continental Europe, long-term contracts are estimated by the International Energy Agency (IEA) to still account for 75 percent of consumption [3]. However, relatively shorter-term contracts are observed to have increased in importance and the length of new long-term contracts has reduced compared to the length of pre-liberalization long-term contracts [34; 35].

Alternatively, a shipper could also rely on the shorter-term wholesale market (encompassing the spot market, forward market and futures market) to purchase the necessary gas quantity.[5] This purchasing strategy requires deep liquid markets, defined as markets where always the desired amount of gas is available at a price based on demand-supply dynamics and where no single player can set the price. An indicator of the market liquidity of a hub is the churn factor, which expresses the ratio of traded quantities over physical quantities consumed in the area served by the hub [36; 37].[6] The UK based National Balancing Point (NBP), the Belgium based Zeebrugge Hub and the Dutch Title Transfer Facility (TTF) are currently the main

[4] Take-or-pay clauses stipulate that the buyer must pay for a certain quantity of gas whether the gas is taken or not, on the one hand, and that the seller must make available a certain quantity of gas independent of the price [31, p. 48].

[5] The spot market deals with very-short-term trade (e.g., day-ahead and intra-day trade). The forward and futures markets deal with trade of gas that is delivered in the future, e.g., the next month, at a price that today represents the expected future value of the gas. Forwards and futures differ in their institutional aspects: e.g., a future is a standardized contract and exchange based, whereas a forward contract can be bilateral and tailor-made.

[6] The churn-rate definition presented here, is the one used by EU DG Energy, e.g., in its Quarterly Report on European Gas Markets; further details on the interpretation of the definition are not available.

European hubs. Their respective churn factors range from 8 to 15, 3 to 6 and 3 to 6. Other hubs are starting to emerge in Germany (Gaspool and Net Connect Germany, NCG), France (Point d'échange gaz, PEG), Italy (Punto di scambio virtual, PSV) and Austria (Central European Gas Hub, CEGH): their respective churn factors are still well below the TTF and Zeebrugge levels. According to the churn-factor measure, European gas-hub liquidity is still poor as liquidity is generally associated with churn factors above 15 [38; 39]. Moreover, with the exception of the UK, the traded volumes and the number of active traders in most markets are at best moderate [40].[7] Therefore, the wholesale market seems better suited for fine-tuning of the supply portfolio, rather than as the single supply basis.

In general, gas supply is rather rigid because the high investment costs benefit from high capacity utilization and thus more constant flows from the well. Swing production can follow a seasonal pattern, but shorter-term flexibility from production is expensive and limited to production that is close to consumption, like the Groningen gas field in the Netherlands for the case of Belgium and the Netherlands.[8] The inclusion of production flexibility is, evidently, reflected in a higher contract price. In the short term, which is the relevant horizon in this thesis, gas is typically bought with a flat profile throughout the day and diurnal flexibility is added in separate contracts.

1.1.2.2 Gas-sales contracts: accessing the customer

To complement the gas-purchase contracts, a shipper needs to sign contracts to sell gas to customers. In the scope of this thesis, three distinct customer types are considered: first, the residential supplier who serves as a proxy for residential and commercial-sector customers, second, demand from the electricity sector for gas-fired electric power plants (GFPP), and third, industrial demand. Below, the specificities of these three groups are further discussed.

Residential and commercial-sector customers primarily use gas for heating purposes, both space heating and sanitary hot water. Hence, a strong seasonal pattern is present. Figure 5.a presents a generic hourly demand profile, expressed in Mm^3/h, for one calendar year in Belgium.[9] Taking a closer look, residential demand displays a typical intra-day variation with peaks in the morning before working hours and in the early evening after working hours (Figure 5.b).[10] So, supply modulation will be

---

[7] Ecorys [38] has estimated the ratio of total gas traded (782 TCM) over total gas consumed (513 TCM) in Europe to be about 1.5, whereas the same ratio for electricity was estimated at 2.3. Note that the area here is Europe, whereas the churn factors relate to smaller areas.

[8] Swing is defined as "*the maximum monthly delivery divided by the average monthly delivery in a given year*" [31, p. 58].

[9] Note that all gas volumes are expressed in million cubic meters (Mm^3) at standard conditions (st): pressure p_{st} = 101325 Pa and temperature T_{st} = 288 K, unless specified otherwise.

[10] A gas day starts at 6.00 am and ends at 6.00 am the following calendar day.

necessary to match hourly demand variability. As these customers use gas for basic needs and have limited fuel-switching capabilities, they have a relatively low sensitivity to price. Therefore, they are less able to quickly respond to price signals. Forecasts suggest that the share of this type of customers in the overall gas demand will decrease in Europe from 40 percent to approximately 30 percent over the next decades [41; 42].

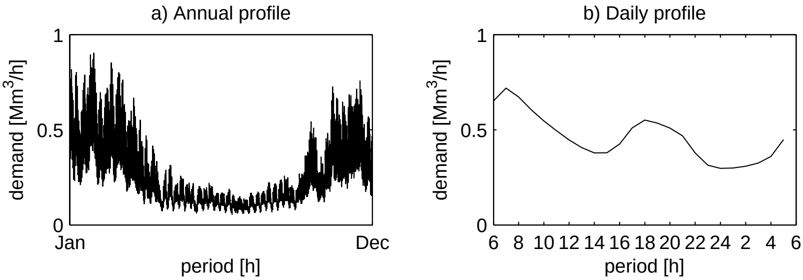

Figure 5. Residential gas demand: a) hourly demand profile with seasonal pattern for one year in Belgium, b) hourly profile for two gas days (adding up to 48 hours) [43]

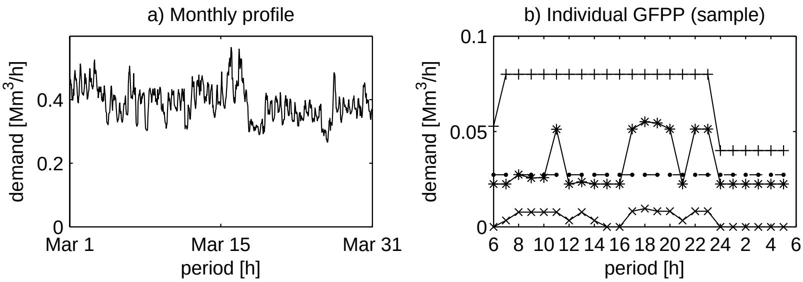

Figure 6. Electricity-sector demand: a) hourly profile of aggregated GFPP in the Belgian electricity-generation system for one month, b) hourly demand profile for a selection of GFPP for one gas day [43]

The gas-demand profile of the *electricity-generation sector* depends on the cost-based ranking and the use of the specific GFPP as base load, mid load or peak load. Gas consumption by a selection of Belgian GFPPs shows a volatile pattern depending on actual electricity demand and the relative coal-to-gas price and possible costs for CO_2-emissions (Figure 6.a).[11] Intra-day variations differ between individual GFPP as shown in Figure 6.b for a single gas day. Base-load and mid-load plants consume gas

[11] Coal-fired electric power plants in Belgium are becoming less important.

throughout the day at a flat level. Other plants, on the other hand, have a variable and unpredictable demand profile, e.g., as peak units or back-up for non-dispatchable electricity-generation plants. The main growth of gas demand in Europe is believed to come from GFPPs [2; 3; 41; 44].

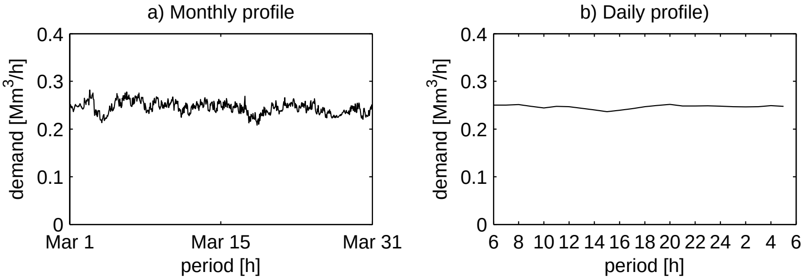

Figure 7. Industrial-sector demand: a) hourly demand profile of aggregated industrial demand in Belgium in March, b) hourly demand profile for industrial demand for one gas day [43]

Compared to residential demand and electricity-sector demand, *industrial gas consumption* is much flatter throughout the year because the heating component is relatively less important. Figure 7.a illustrates this for the month of March in Belgium. Intra-day industrial demand is almost completely flat (Figure 7.b). Yet, demand profiles can differ substantially between industrial consumers depending on the size of the customer and the use of the gas. The price sensitivity of industrial customers is higher than that of residential. Indeed, larger industrial consumers have back-up installations and fuel-switching or shipper-switching options available to cover a planned or unplanned interruption of gas supply.

1.1.2.3 Transmission-services contracts: moving the gas

As gas purchasing and selling are usually located apart, the gas has to be moved over the pipeline network. Therefore, the shipper has to acquire transmission services from the TSO.

First, capacity has to be booked to enter gas into the pipeline system and to withdraw it at another location. Second, the shipper has to nominate, day-ahead (DA), an hourly transport program with the forecasted gas quantities that will be entered and withdrawn at booked entry and exit points, respectively. Further re-nominations are possible, even intra-day (ID). But, in principle, the shipper cannot deviate from the inserted transport program and gas entry should match gas exit.

1.1.2.4 Flexibility and balancing

Shipper nominations are subject to matching problems. On the one hand, gas consumption is unpredictable, leading to forecast errors that impact the "unit commitment" at the gas-supply side.[12] On the other hand, the predictable variability of consumption (see Figure 5-Figure 7) and rigidity of production/import requires flexibility for modulating supply to meet gas consumption. The main ***ex-ante* flexibility** instruments, meaning flexibility contracted upfront as opposed to the ***ex-post* flexibility** provided by the TSO through the balancing mechanism, are fast-cycling storage, interruptible customers and supply-side flexibility.[13] Deep and liquid intra-day spot markets could provide flexibility as well. Gas markets have **no clear gate closure** to distinguish between the *ex-ante* market and the *ex-post* market, in which only the TSO can act. Indeed, shippers can re-nominate entry and exit throughout the gas day to correct individual or system imbalance positions. This is further explained in section 1.5 in which gas and electricity balancing are compared.

1.2 Market coordination through the balancing mechanism

In the previous section, it has been demonstrated that the TSO is responsible for the safe operation of the pipeline system, but that the shippers cause imbalances because of imperfections in their contract portfolios. To redistribute the balancing responsibilities and to adjust the actions of the TSO and the shippers, a coordination mechanism is required: the **balancing mechanism**.

A balancing mechanism deals with **procurement** of balancing services, on the one hand, and **settlement** of shipper imbalances, on the other hand.[14] Both concepts are further discussed in the next subsections, but first the institutional organization of the gas network is discussed as this affects the organization of balancing and flexibility.

1.2.1 Institutional organization of networks in the EU gas market

To properly discuss balancing and time flexibility, it is necessary to understand the institutional organization of the network services because network-capacity rights can be defined in different ways. Lapuerta and Moselle [45] make a distinction between point-to-point rights, entry-exit rights and postal rights. **Point-to-point rights** specify the contract path as gas should be injected in one defined point and withdrawn in one other specified point. Hence, this capacity definition corresponds best to gas markets organized according to individual pipelines. **Entry-exit rights**

[12] This "unit commitment" is defined as the *ex-ante* calls on supply and flexibility contracts to meet the expected gas consumption. After this commitment, the shipper has much less or even no options left to further modulate his profile.

[13] Fast-cycling means that multiple cycles of (physical) injection and withdrawal occur within a year.

[14] Note that the "balancing-services" concept encompasses "line-pack flexibility" and "flexible gas".

allow a shipper to inject gas at any entry point for which capacity has been booked, and to withdraw it at any point for which exit capacity has been booked. This definition of capacity rights effectively organizes the network as a zone covering a set of connected pipelines without specifying paths between the contracted points. The organization of the networks in Europe reflect these zonal principles. **Postal rights** are a special case of entry-exit rights that make no distinction between using a point for injection or withdrawal of gas.

The choice for either a pipeline-oriented point-to-point organization of the network or a zone-oriented entry-exit model has implications for the geographical and time flexibility that is offered by the network. Indeed, the zonal entry-exit approach removes competition between contractual flow paths and includes geographical flexibility because contracted access and offtake points can be changed freely. This geographical flexibility should make the trading of capacity rights easy, but Ruff [46] argues that the oversimplification of the network effects – which should be taken into account as demonstrated by Midthun [47] – results in too much transport capacity kept off the market for guaranteeing the bundled geographical flexibility. Furthermore, time flexibility, e.g., pipeline storage, is typically also covering the network zone as a whole.

This institutionalized bundling of geographical and time flexibility with the transport service in a zonal context results in a reduction of capacity that can be made available for gas transport as has been demonstrated by Lapuerta and Moselle [45] for geographical flexibility, and by Keyaerts et al. [48] for time flexibility.[15] The organization of the network flexibility, then, affects how gas balancing can or should be organized as a shared responsibility between the TSO and the shippers.

A network organization relying on competing pipelines and point-to-point services avoids this capacity trade-off for the TSO, but instead lays the responsibility for acquiring flexibility on the shipper. Indeed, the shipper negotiates and combines individual pipeline contracts specifying time flexibility and geographical flexibility [49]. As a result, the TSO can market more transport capacity that is now better reflecting the physical state of the gas network [46]. Moreover, the competitive nature of the network operation implies a strong reliance on trading of capacity rights to achieve the allocation of capacity rights that generates the highest value. Thus, balancing becomes a clear pipeline-bound shipper responsibility and is much less complex than balancing a zone of interconnected pipelines.

The organization of gas balancing with regard to its spatial dimension, then, cannot be separated from the organizational context of the network services.

[15] See Chapter 2 for a discussion of the trade-off between transport and flexibility.

1.2.2 Procurement of balancing services

Unbundling implies the separation of commodity and transport activities, meaning that a TSO cannot be active in gas production or import. As a consequence, additional balancing services, beyond the TSO-controlled line pack, have to be procured from balancing-services providers (BSP).

The sources of flexible gas for the TSO are the same as the *ex-ante* flexibility sources for the shipper. Therefore, both actors are competing for scarce flexibility. Fast-cycling storages can provide both upward (TSO buys gas) and downward (TSO sells gas) flexibility, whereas interruption of demand only offers upwards flexibility. Ramping production up or down could provide two-way flexibility. But, given the high investment costs, producers prefer high and constant production rates over variable production. Table 2 provides an overview of the presence of different flexibility sources in the gas markets of EU-15 [23].

Table 2. Indicative role of different sources of flexibility for gas-system balancing in EU-15 countries (source: [23])

Country	Line pack	Production	Storage	LNG	Import
Austria	X		X		X
Belgium	X		X	X	X
Denmark	X	X	X		
France	X		X	X	
Finland	X		X		
Germany	X	X	X		X
Greece	X			X	
Ireland	X		X		
Italy	X		X		
Luxembourg	X				
Netherlands	X	X	X	X	
Portugal	X		X	X	
Spain	X		X	X	
Sweden	X		X		X
UK	X	X	X	X	

According to KEMA [23], procurement of balancing services (not including pipeline-owned line pack) is predominantly based on medium-term and long-term agreements that are most frequently non-market based (Table 3). Examples of these are a regulated or direct contract with a storage operator or an LNG-terminal (liquid natural gas) operator, or the transmission-system operator can have ownership of a source of flexibility: the TSO in Denmark, e.g., controls his own storage. Even market-based procurement is often on a medium-term horizon, e.g., using an annual tender for flexibility. Only a few countries rely on short-term procurement mechanisms, meaning day-ahead (DA) or intra-day (ID).[16] Indeed, they use the wholesale market or a separate balancing market as their main, and sometimes only, source for procurement of balancing services. These non-market-based procurement mechanisms or longer-term market-based procurement mechanisms, still according to KEMA, can inhibit competition on the side of flexibility provision in the gas market.

Table 3. Procurement mechanisms according to contract horizon and reliance on market-based and non-market-based mechanisms (source: [23])

Procurement horizon	Non-market based	Market-based
Short term (DA/ID)		-wholesale market (5)[a]
		-balancing market (4)[a]
Medium/Long term	-ownership / regulated (7)	-tender (7)[b]
	-direct contract (3)[a]	

(x) number of countries using the mechanism (total sample 22 countries)

[a] update on KEMA report: the Netherlands moved to using a balancing market in 2011 and France moved from a separate balancing market to using the wholesale market since late 2009

[b] tenders can also be short term (e.g., daily) like in Spain and Germany

Although not much is publicly known about gas-procurement costs, the remuneration of balancing services can be subdivided in two components: an energy cost for actually dispatched balancing energy, on the one hand, and a capacity cost for reservation of an amount of flexibility regardless of its use, on the other hand (Table 4). These reservation fees are more likely in medium-term and long-term contracts. When balancing services are procured on the market, or by means of a merit-order mechanism, the offers are usually remunerated at a pay-as-bid rate as opposed to a marginal-bid rate.[17] KEMA advocates short-term market-based procurement at just the energy cost, excluding capacity-reservation fees. Indeed, that mechanism allows for the broadest participation of gas-market players, including new entrants, and has lower transaction costs for moving towards cross-border procurement in a TSO-BSP or a TSO-TSO framework (see further in Part 3).

[16] Austria, France, the Netherlands and the UK rely in full or partly on short-term procurement of flexible gas on the market. Day-ahead means that the gas is delivered on the next day, whereas intra-day trade deals with gas that is to be delivered on the same day.

[17] Pay-as-bid means that the provider of flexibility is paid his bid price, whereas a marginal-bid rate remunerates all providers of balancing services at the rate of the final accepted bid, which is the lowest price when the TSO sells excess gas, or the highest price when the TSO has to make up a deficit. Pay-as-bid auctioning can lead BSPs to hiding their true costs.

Table 4. Procurement costs of flexible gas: function of cost and cost-recovery mechanism

Capacity fee [EUR/m^3/h]	Energy cost [EUR/m^3]
to ensure availability of a rate of flexibility (MW or Mm^3/h) throughout the contract period	related to actually dispatched flexible gas (MWh or Mm^3) at a certain time
typically socialized in network charges or covered through mark-ups or mark-downs (penalties)	covered by balancing charges that often refer to a market price

Although the same flexibility sources make up the supply of flexibility in the DA and ID markets, the actually dispatchable balancing services become more constrained closer to real time. Indeed, gas travels at a limited speed and as a consequence some flexibility sources are too distant to be considered. This changing of the flexibility supply closer to the real time is illustrated in Figure 8, which shows cost data derived from published data by the Dutch TSO [50].

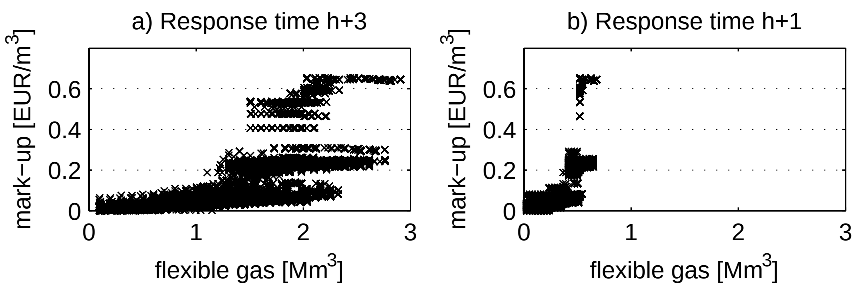

Figure 8. Supply of upward flexible gas excluding line-pack flexibility for a) delivery within 3 hours (h+3), and b) delivery within one hour (h+1) with mark-up costs [EUR/m^3] representing the mark-up above the DA price of gas. Closer to the real time (h+1), less flexible gas is available and the costs rise sharply for small amounts of flexibility; whereas further away from the real time (h+3), more and cheaper sources can provide flexibility (sources: [50; 51]).

Figure 8.a shows the mark-up cost (EUR/m^3) above the DA price of gas for dispatching of upward flexible gas (Mm^3) with delivery within 3 hours from the time of activation. Mark-up costs remain rather low and flat before rising sharply at about half the total amount of offered flexibility. Closer to the real time, however, less flexible gas is available and the costs rise sharply for a small amount of flexible gas as illustrated in Figure 8.b. Note that these offer curves do not include TSO-controlled line-pack flexibility, which will be dispatched by the TSO before activating any other source of flexibility.

Because gas-system balancing should be a cost-neutral business for the TSO, procurement costs have to be recovered from unbalanced shippers through an imbalance-settlement mechanism [13; 24; 25; 52].[18] Any unintended profit or loss should, then, be passed on to the network users through the general network tariffs [see, e.g., 25; 53]. Thus, procurement should be carried out as efficient as possible, meaning at the lowest costs because, in the end, the gas consumers pay these costs and their welfare is the ultimate objective of the EU gas-market reforms. Chapter 6 discusses the potential efficiency gains of procuring balancing services across borders in a multi-region gas market.

1.2.3 Settlement of imbalances

The imbalance-settlement mechanism serves two main purposes. The primary objective is to transfer the financial responsibility for *ex-post*-balancing services to unbalanced shippers by means of balancing charges. These charges should, in principle, reflect the actual balancing costs, i.e. energy costs and, when applicable, capacity fees, for the TSO. Chapter 2 will demonstrate that cost reflection is rarely attained in current settlement mechanisms, at least not in a transparent manner. The second objective consists in incentivizing shippers to balance *ex ante*, often by means of a non-cost-reflective penalty for unbalanced positions.

According to Eq. (1.1), inherent line-pack flexibility adds a storage term to the physical balancing equation. Physical disequilibrium of the gas system only becomes a problem when it persists over longer time intervals. Hence, settlement mechanisms define imbalances economically as differences between the amount that has been injected and the amount that has been taken off by the shipper, disregarding whether the physical system is affected or not.

Basically, a settlement mechanism is a three-dimensional construct (Figure 9). The main dimension, evidently, accounts for the balancing charges, represented by "settlement" in Figure 9. These charges relate to imbalances that are to be defined first by demarcating a two-dimensional balancing-playing field.

[18] Cost neutrality or "budget balance" is the customary principle for *ex-post* balancing according to the many position papers by TSOs and regulators [13; 24; 25; 52]. It is meant to ensure that cost signals are passed on to the shippers and the TSO does neither make a profit nor a loss from settlement [13]. The main argument for that approach is the inevitability of shipper imbalances and the fear of penalizing price setting by the TSO. However, the TSO is subject to regulation that should control the imbalance tariffs. Nevertheless, TSOs can be allowed by national regulation to make some profit to incentivize them to efficiently procure balancing services [25]. Therefore, both cost-neutral imbalance pricing and marginal-cost pricing are investigated throughout this work.

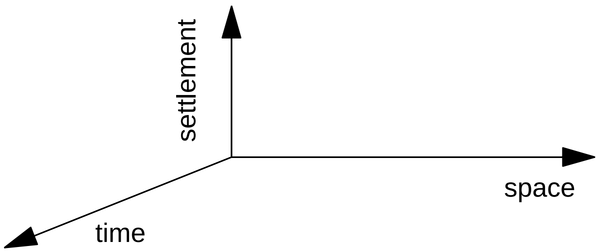

Figure 9. Settlement mechanism as a 3D-construct of time (balancing period), space (balancing zone) and settlement (balancing price)

The first dimension covers the demarcation of a geographical **balancing zone** ("space" in Figure 9). One balancing zone corresponds to one balancing-mechanism design. Ultimately, complete gas-market integration would be reflected in the removal of all spatial limitations with regard to balancing, meaning that the European gas system becomes a single balancing area. Currently, according to the gas-industry literature [13; 16; 19], technical grounds preclude a balancing zone of such size as the pressure management would become uncontrollable without massive investments. Therefore, smaller territories are delimited and often these territories coincide with countries. Some national gas systems have been consisting, or still consist, of multiple balancing zones: this is the case in Belgium, France and Germany. Consequently, shipper imbalances are calculated by balancing zone, meaning that gas entering an area should match gas leaving that area. Note that this balancing zone is a reflection of the organization of the gas network as discussed in subsection 1.2.1.

The second dimension of the balancing-playing field deals with time. Because of the previously explained line-pack flexibility, instant balancing of the gas system is not required and imbalances are defined over an arbitrarily chosen time interval. ERGEG [24] advocates a daily **balancing period**, meaning that aggregate gas injection and withdrawal should only match at the end of each gas day. Hourly (e.g., Austria) and even monthly balancing exist too [23; 54]. Unmatched injections and withdrawals within the formal balancing period are not considered imbalances in the framework of the settlement mechanism. However, these mechanisms often include other balancing frequencies or cumulative definitions of an imbalance. These additions provide extra balancing incentives to shippers on an intra-balancing-period basis.

In summary, the balancing period and balancing zone demarcate the balancing-playing field. Subsequently, they confine the definition of imbalances within the settlement mechanism.[19] An imbalance, thus, is defined as the difference between aggregated gas injection and withdrawal in a balancing zone at the end of the balancing period compared to the beginning of the period. The balancing-playing field also determines adequacy and availability of different flexibility instruments for *ex-ante* and *ex-post* balancing. Storage, for instance, is a major source of flexibility, but only fast-cycling storages with high injection and withdrawal rates seem plausible flexibility providers.

Any settlement mechanism defines balancing charges to settle unbalanced shippers. The complexity of the balancing-tariff structure, though, strongly varies between balancing zones. Balancing charges should, preferably, be market based and reflect actual system-balancing costs [23; 24].

Balancing-charge structures encompass three elements: cash outs, penalties and tolerances. Below, a distinction is made between, first, basic imbalance settlement that comprises single-price methods in which the same price is used for either shipper imbalance position and dual-price methods that include a penalty term (see below in subsection 1.2.3.1) to be added to the cash-out fee, and, second, more complex incentive schemes that include multi-level penalties and tolerances (subsection 1.2.3.2). Finally, a market-based tariff structure is discussed (subsection 1.2.3.3). The tariff structures discussed in the following subsections are conceptual representations of actual settlement mechanisms and do not necessarily reflect optimal tariffs.

1.2.3.1 Basic imbalance settlement: cash out (single price vs. dual price)

End-of-balancing-period imbalances are financially settled through cash out: short shippers pay a fee to the TSO for the gas withdrawn from the system without having made a matching injection (withdrawal exceeds injection), whereas long shippers (injection exceeds withdrawal) receive a fee from the TSO for injected gas surpassing offtakes over the period.

Table 5 summarizes the most simple tariff structure for imbalance settlement. Long and short imbalances are cashed out at the same reference market price (RMP) independent of whether the shipper instigated the system imbalance or helped mitigate it.

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[19] Balancing charges are based on energy (MWh), but throughout this thesis Mm^3 is used, which is the typical unit for gas flow analysis. Conversion between both units is straightforward by assuming a single gross caloric value (GCV), e.g., 0.0115 MWh/m^3.

Table 5. Tariff structure 1: Basic settlement through cash-out fees (single price) for short and long shipper positions

Tariff structure 1 [EUR/m^3]		System imbalance	
		Short	Long
Shipper imbalance	Short[a]	RMP	RMP
	Long[b]	RMP	RMP

[a] shipper pays reference market price (RMP) per unit of imbalance to system operator

[b] shipper receives RMP from system operator

Tariff structure 1 succeeds in transferring financial responsibility for *ex-post*-balancing services to shippers; although, actual balancing-cost reflection might be doubtful. But this simple cash-out structure entirely fails at providing additional incentives to balance *ex ante* because a shipper cannot do worse than by trading on the spot market. These tariffs just settle energy costs. Possible capacity costs are typically socialized by means of the general transport tariffs.

Penalties make up the straightforward way of providing *ex-ante*-balancing incentives to shippers. Penalties are non-cost reflective by their very nature, but as mark-ups on the RMP they can help to recover costs like capacity costs. However, this opens the door for excessive revenue-generating penalties for the TSO as had happened in the US gas market before the gas-balancing mechanism in the US had been reformed [54] (see further in section 1.4).

Table 6. Tariff structure 2: cash out with added penalty (dual price) for short and long shipper positions

Tariff structure 2 [EUR/m^3]		System imbalance	
		Short	Long
Shipper imbalance	Short[a]	RMP * (1+α)	RMP * (1+β)
	Long[b]	RMP * (1–γ)	RMP * (1–δ)

[a] shipper pays imbalance fee per unit of imbalance to system operator

[b] shipper receives fee from system operator

Table 6 presents a cash-out system with added incentivizing penalties. Long shippers receive less than full RMP and short shippers pay more than just RMP. Penalties can be symmetrical (α, β, γ and δ equal), or asymmetrical (α, β, γ and δ different). In the latter case, it is possible to differentiate the cash out according to the relative positions of the aggregated gas system and the individual shippers. That way, the tariff structure allows punishment of system-imbalance-instigating shippers and rewarding shippers with opposite mitigating imbalances. This distinction is not customary in current settlement-mechanism design, though. Differences in the sets of parameters α-δ between different balancing areas tempt shippers to arbitrate between different balancing mechanisms to minimize imbalance costs. This cross-border settlement is the subject of Chapter 5.

If mark-ups are used to attribute capacity costs of flexibility to unbalanced network users while aiming for cost neutrality, the economic literature recommends Ramsey pricing as it generates an efficient outcome with regard to allocating costs under a profit constraint [55; 56].[20] Ramsey pricing has often been used for regulating public utilities. Hogan [57; 58], for instance, has applied Ramsey pricing to the transmission-system operator in the electricity sector. Ramey pricing has also been applied to the gas sector, e.g., for transmission services in a spatial context by Cremer et al. [59] and Cremer and Laffont [60], but not for gas balancing.[21] The basic principle of Ramsey pricing is to have a mark-up above marginal costs to recover costs that are not otherwise covered by the marginal prices, e.g., capacity costs. Mark-ups for different customers of the services, then, are inversely proportional to the respective customers' elasticity. Hence, inelastic customers pay a higher mark-up than customers who respond more flexibly to prices.

1.2.3.2 Complex incentive schemes: intra-period penalties and imbalance tolerances

Settlement mechanisms with more complex incentive schemes go beyond just imbalance settlement. They impose penalties for unmatched positions inside the formal balancing interval, effectively reducing the actual balancing interval. Examples of such charges are penalties for hourly imbalances when the formal balancing period is a day or charges for the peak cumulative imbalance within the formal balancing interval. Some mechanisms, e.g., France, even impose supra-period penalties.

Table 7. Tariff structure 3: intra-interval penalties and tolerances on top of basic settlement for short and long positions

Tariff structure 3 [EUR/m^3]		System imbalance	
		Short	Long
Shipper intra-period imbalance	Short	ε * RMP * (Imb-Tol)	ζ * RMP * (Imb-Tol)
	Long	η * RMP * (Imb-Tol)	θ * RMP * (Imb-Tol)

[20] Ramsey pricing is also often referred to as Ramsey-Boiteux pricing as Boiteux [56] applied this pricing of services under a budget constraint to natural monopolies.
[21] The full development of Ramsey pricing for recovering flexibility costs is not part of this thesis, but is recommended for further research.

Tariff structure 3 (Table 7) shows penalties (with parameters ε, ζ, η and θ) for intra-period imbalances (Imb) based on the RMP. These penalties are meant as additional balancing incentives and always involve payments to the system operator by the shipper, complementing the settlement charges illustrated in tariff structure 2. Note that even shippers who help the system by having an imbalance with the sign opposite to the system have to pay these penalties.

Still more complexity can be added to the tariff structure by means of granting penalty exemptions for some amount of tolerated imbalance (Tol). These tolerances actually reduce *ex-ante* balancing incentives as the penalties are now only imposed on the part of the imbalance beyond the tolerance level.

1.2.3.3 Market-based settlement

In the previous tariff structures, the RMP refers to a spot-market price that is not necessarily reflecting actual balancing costs. If the TSO uses market-based procurement of balancing services and settlement of shipper imbalances, the imbalance tariff can be linked directly to the marginal price of dispatched flexibility by the TSO. The TSO, then, procures upward flexibility at marginal price MP_{up} if the system is short, and MP_{down} is the price of the marginal unit of dispatched downward flexibility if the system is long. This market-based settlement system succeeds in passing on the energy costs of flexibility to the users of that flexibility and provides signals to the market with regard to flexibility services.

Table 8. Tariff structure 4: Market-based settlement through cash-out fees for short and long shipper positions

Tariff structure 4 [EUR/m^3]		System imbalance	
		Short	Long
Shipper imbalance	Short[a]	MP_{up}	MP_{down}
	Long[b]	MP_{up}	MP_{down}

[a] shipper pays marginal cost of upward (MP_{up}) or downward flexibility (MP_{down})

[b] shipper receives marginal price of upward (MP_{up}) or downward flexibility (MP_{down})

The marginal cost in tariff structure 4 can be replaced with the average cost of procurement. In that case, however, the signaling function of the marginal price is lost.

1.3 EU country approaches to balancing

This section presents the practical implementation of balancing mechanisms for a selection of EU countries, based on a review of national network codes. Note that the focus lies on the settlement, rather than on procurement as little information concerning the latter is publicly available.

1.3.1 Belgium

Belgium is divided in four balancing zones – three for high-quality gas and one for low-quality gas – and applies a formal daily balancing period.[22] The reference prices are determined as either the lowest, for long shippers, or the highest, for short shippers, from a basket containing the DJ ZIG day-ahead price, the APX-OCM intra-day System Marginal Price (SMP) and the actual price seen by the Belgian TSO. Note that the applicable RMP depends on the shipper-imbalance position and, thus, distinct RMPs exist for short (RMP_{buy}) and long (RMP_{sell}) shippers. The RMPs do not depend on the state of the gas system.

Table 9 and Table 10 present the Belgian tariff structure and granted tolerances, respectively.[23] The Belgian cash-out design implies that the full end-of-day imbalance is settled at the Belgian RMP: either the TSO sells gas to a short shipper, or the TSO buys surplus gas from the long shipper. Note that hourly surpluses are not penalized; whereas hourly short positions give rise to a penalty based on the hourly capacity cost of transport. Penalties for daily imbalances or intra-day peak cumulative positions follow a piecewise-linear cost curve according to the bracket the imbalance is in. A daily imbalance exceeding twice the daily tolerance, but less than three times the tolerance, for instance, gives rise to a penalty of 0 for the part below the tolerance, 40 percent of the RMP for the part between one time the tolerance and twice the tolerance, and, finally 60 percent of the RMP for the part beyond twice the tolerance.

Tolerances are granted based on subscribed exit capacity for hourly (Tol-H), cumulative hourly (Tol-CH) and daily (Tol-D) imbalances. Booked capacity of 6 Mm^3/h, for instance, corresponds then to an hourly tolerance of 1 Mm^3, a cumulative tolerance of 3 Mm^3 and a daily tolerance of 1 Mm^3, symmetrical for short and long positions. Beyond the bundling of base flexibility with transport services, the Belgian TSO sells additional tolerances as unbundled flexibility.

[22] Belgium is in the process of installing a new market-based balancing mechanism, the details of which are not decided on at the time of writing of this thesis [61]. Gas quality is dependent on the specific energy content of the gas, but is not further considered in this thesis.

[23] Belgian granted tolerances depend on the specific type of booked exit capacity, e.g., firm SLP (synthetic load profile) capacity for serving customers that follow a "synthetic load profile" (residential demand). Synthetic refers to the fact that these (individual) customers are not actually measured on the transmission level, but rather a standardized profile is used to distribute the annual load over the year-hours.

Table 9. Tariff structure for imbalance settlement – Belgium [62; 63]

Tariff structure Belgium [EUR/m^3]		System imbalance	
		Short	Long
End-of-day cash out[a]	Short	RMP_{buy}	
	Long	$-RMP_{sell}$	
Hourly penalty[b]	Short	0 / Cost of an hour of exit capacity	
	Long	0	
Daily penalty[b,c]	Short	0 / 0.4 RMP / 0.6 RMP / 0.8 RMP	
	Long		
Cumulative intra-day penalty[b,c]	Short	0 / 0.4 RMP / 0.6 RMP / 0.8 RMP	
	Long		

[a] negative sign indicates a cash flow from the TSO to the shipper

[b] applicable penalty dependent on imbalance bracket: 0→Tol / Tol→2Tol / 2Tol→3Tol / 3Tol→…

[c] RMP means RMP_{buy} for a negative imbalance and RMP_{sell} for a positive imbalance

Table 10. Tolerances granted (firm SLP capacity) for different balancing intervals – Belgium [63; 64]

Share of subscribed capacity [m^3/h]	Short	Long
Tol-H	–1/6	1/6
Tol-CH	–1/2	1/2
Tol-D	–1/6	1/6

1.3.2 France

France is divided in four balancing zones – three for high-quality gas and one for low-quality gas – managed by two TSOs. The formal balancing period is daily, but settlement is also based on an imbalance account that allows carrying forward part of the end-of-day imbalance [65; 66]. As a result of this imbalance-account mechanism, settlement in kind is possible throughout the month and beyond.

The French RMP is determined as the trade-volume weighted composition of the average price the TSO traded on the day-ahead market, on the one hand, and the average price the TSO traded on the intra-day market, on the other hand, in the framework of the TSO's balancing responsibilities [65].[24]

[24] The details of the RMP calculation for France can be found in [65].

Table 11. Tolerances granted (Zone N) for different intervals – France [67]

% of subscribed daily capacity [Mm^3/d]	Tolerance granted (symmetrical for short and long positions)
Tol-D	30% (0→0.043 Mm^3/d) 20% (0.043→0.174 Mm^3/d) 5% (0.174→4.35 Mm^3/d) 4.5% (4.35→… Mm^3/d)
Tol-MR	40% Tol-D
Tol-CD	5x Tol-MR

Furthermore, the French settlement mechanism defines three tolerance levels (Table 11).[25] The daily tolerance (Tol-D) is granted based on the booked capacity according to capacity brackets. Indeed, different percentages apply for these brackets. Beyond the tolerated-imbalance level, a penalty term of 0.3 times the RMP is added to, or subtracted from, the RMP. Next, the cumulative-imbalance mid-range (Tol-MR), equal to 40 percent of the daily tolerance, represents the limit of daily imbalance that can be carried forward by means of the aforementioned imbalance account. This part of the imbalance, thus, is not settled in cash at the end of the gas day. Finally, the cumulative daily tolerance (Tol-CD) is equal to five times the mid-range and poses a limit to the imbalance account as a penalty is lifted for the amount of accumulated imbalance on the account that is beyond this tolerance. Note that this penalty does not involve settlement of the imbalance account. So, the end-of-day imbalance is partially carried forward and partially settled at the RMP, or the RMP and a penalty term. The complete tariff structure for imbalance settlement is summarized in Table 12, which details the end-of-day cash-out and a penalty for imbalances accumulated over multiple days for different tolerance brackets.

[25] The tolerances granted depend on the relevant balancing zone.

Table 12. Tariff structure for imbalance settlement – France [67]

Tariff structure France [EUR/m^3]		System imbalance	
		Short	Long
End-of-day cash out	Short[a]	Carry-forward / RMP / 1.3 RMP	
	Long[b]	Carry-forward / RMP / 0.7 RMP	
Cumulative daily penalty	Short[c]	0 / 0.2 RMP	
	Long[c]		

[a] shipper pays fee according to following brackets: 0→Tol-MR / Tol-MR→Tol-D / Tol-D→…

[b] shipper receives fee according to following brackets: 0→Tol-MR / Tol-MR→Tol-D / Tol-D→…

[c] penalty due for brackets 0→Tol-CD / Tol-CD→…

1.3.3 Netherlands

The Netherlands turned around their balancing mechanism from a design similar to the Belgian one towards market-based procurement and settlement. Indeed, an hourly bid ladder for upward and downward flexibility is used by the Dutch TSO to physically intervene when the line-pack level is too low or too high [50; 68; 69]. Although the balancing mechanism no longer defines a formal balancing period, the settlement practice implies balancing on an hourly basis. In fact, shippers are settled whenever the TSO dispatches flexible gas from the bid ladder according to the following principles: a shipper aggravating the system imbalance (same sign) pays the unit price of the marginally accepted bid, whereas helpers of the system (opposite sign) are settled at this marginal-bid price. Therefore, the Dutch balancing mechanism can be qualified as a single-price cash-out mechanism, with the price determined by the state of the system and with an incentive in the form of using the marginal cost as opposed to the average cost of the dispatched flexible gas (Table 13).[26] Moreover, the balancing mechanism uses, what could be called, an implicit "rolling gate closure" with every hour a decision by the TSO to take over – i.e. starting *ex-post* settlement mechanism – or not. Note that in the hours that no call is made, the TSO still uses line-pack flexibility to balance the system. As a result, line-pack costs are not allocated to the users of this service, but are socialized in the transport tariffs.

[26] Indeed, the use of the marginal price instead of the average price results in a profit for the TSO that can be used to lower the general tariffs or to invest in flexibility. At the same time, the unbalanced shippers are properly incentivized to balance themselves (an instigator is implicitly penalized) or to keep helping the system (mitigation is implicitly rewarded).

Table 13. Tariff structure for imbalance settlement – Netherlands [50; 68; 69]

Tariff structure Netherlands [EUR/m³]		System imbalance	
		Short	Long
Shipper imbalance	Short[a]	marginal price upward flexible gas	marginal price downward flexible gas
	Long[b]		

[a] shipper pays fee

[b] shipper receives fee

1.3.4 The UK

The UK applies straightforward daily balancing without tolerances or explicit penalties. Balancing charges (Table 14) refer to the buying and selling of gas by the TSO on the intra-day market.[27] The SMP_{buy} is then the highest price paid by the TSO for balancing during that day, whereas the SMP_{sell} represents the lowest price seen by the TSO for a balancing action [53].[28] The spread between the SMP_{buy} and the SMP_{sell}, on the one hand, and the intra-day market price, on the other hand, serves as an implicit penalty to incentivize shippers to balance *ex ante*.

Table 14. Tariff structure for imbalance settlement – UK [62; 63]

Tariff structure UK [EUR/m³]		System imbalance	
		Short	Long
End-of-day cash out[a]	Short	SMP_{buy}	
	Long	$-SMP_{sell}$	

[a] negative sign indicates a cash flow from the TSO to the shipper

1.3.5 Austria

Austria is a unique case in Europe as it applies a formal hourly balancing period in its "Regelzone Ost" [70-72]. Furthermore, an hourly merit order is used to procure flexible gas beyond line-pack flexibility with the offers remunerated at pay-as-bid. To ensure sufficient availability of flexible gas "market makers" can be appointed. These market makers are providers of flexibility who are paid a capacity fee to be available.

[27] APX On-the-day Commodity Market (OCM) [51].

[28] The network code specifies a default marginal cost to be added or subtracted from the System Average Price (SAP), which is the average price for the balancing actions. If the spread between the SMP and the SAP is smaller than the default marginal cost, then that default should be used.

But this instrument has not been used in practice as the merit order has been sufficient.

The hourly RMP, then, is calculated based on the volume-weighted costs of the accepted bids, both for upward and downward flexibility, in the specific hour.

Table 15. Tariff structure for imbalance settlement – Austria [70; 73]

Tariff structure Austria [EUR/m^3]		System imbalance	
		Short	Long
Hourly cash out	Short[a]	RMP	RMP
	Long[b]		

[a] shipper pays fee

[b] shipper receives fee

1.3.6 Italy

The Italian balancing-mechanism design is special because of its explicit referral to storage as flexibility provider [74]. In particular, a difference is made between shippers who have contracted storage services and those who do not have storage. Only the latter pay a balancing charge for their daily imbalance, whereas the former pay a capacity charge if they overrun their storage rights.

The RMP is actually a fixed price that varies with the imbalance bracket, which is dynamically determined as a percentage of the daily offtake. Long and short positions are cashed out at the same price.

Table 16. Tariff structure for imbalance settlement – Italy [74]

Tariff structure Italy [EUR/m^3]		System imbalance	
		Short	Long
End-of-day cash out[c]	Short[a]	0 / 0.0041 EUR/m^3 / 0.0124 EUR/m^3	
	Long[b]		

[a] shipper pays fee

[b] shipper receives fee

[c] brackets: 0→8% daily offtake / 8%→15% daily offtake / 15%→...

1.4 Experience in the US

The US has a mature and liberalized gas market that is made up of five interconnected regions, each containing a number of liquid physical trading points, like Henry Hub in Louisiana [75].[29] These regions have no major institutional differences and, e.g., forward contracts all refer to the dominant reference price provided by the Henry Hub. The well-functioning US gas market could thus serve as a guide for Europe, in particular for designing balancing mechanisms. Indeed, imbalance management has not been an issue in the US since the introduction of a regulation for imbalance services by the Federal Energy Regulatory Commission (FERC) in 2000 [49; 54]. Makholm, however, argues that copying the US solutions for market design to the EU gas market is difficult or even impossible because the institutional setting is completely different [49; 76]. In the second subsection, Makholm's defined institutional differences are reviewed in the framework of balancing-mechanism design in the US and the EU. First, the current imbalance-management policy in the US is discussed.

1.4.1 FERC Order No. 637

Before the introduction of FERC Order No. 637, US pipeline companies applied penalties in a monthly balancing framework, to deter shippers from gambling the system by short-selling when gas prices were high and going long when gas prices were low. According to FERC, these penalties led to inefficiencies and distorted the market for transport services. Therefore, Order No. 637 imposed a new policy regarding short-term flexibility and imbalances. It requires pipeline companies to offer tailored imbalance-management services and to allow other flexibility providers to offer such services in their pipeline system. At the same time, adequate and non-penalizing incentives had to be provided to shippers to stay in balance. Note that the Order does not regulate the flexibility to be offered by pipeline companies, but just imposes that flexibility has to be made available in the form of "innovative services".

The obligation to offer flexibility *ex ante* results in a transport-services market in which shippers who need flexibility pay directly for it, instead of paying via the *ex-post* balancing and the general transport charges. Penalties still exist in the new balancing mechanism, but they should be limited to those situations that effectively threaten system integrity.

This particular organization of the network in the US makes up the main difference with the EU organization of the pipelines. Indeed, the US is relying on individual pipelines with point-to-point capacity rights. Consequently, competitive markets have been developed with regard to transport services and flexibility services. Thus, the focus lies on the *ex-ante* flexibility market with the obligation for the pipeline company to offer time flexibility, which can be network based, e.g., marketing of line-pack flexibility, or to have others offer it. Moreover, the flexibility providers are free in how to organize this flexibility offer. Hence, tailored contracts between the

[29] These regions are Gulf, Midwest, Northeast, Southeast and Western.

pipeline company and the shipper, and pipe-to-pipe competition are possible in the US. In Europe, on the other hand, the zonal approach implies that flexibility is bundled in homogeneous standard services specified in network codes covering a (balancing) zone operated by a TSO who is a regulated monopolist. Additional institutional differences exist and are the subject of the next subsection.

1.4.2 Institutional differences

If the US balancing mechanism is effective and well accepted by the industry, Europe could perhaps draw lessons from the US experience and install a similar mechanism in the EU gas markets. This copying has not yet happened and is unlikely to happen because the institutional setting in Europe is different from the US [76]. Makholm refers to the regulatory authority, the third-party-access rules, the unbundling of activities, information dissemination and property rights.[30] These institutional aspects are discussed below in the framework of balancing-mechanism design.

First, FERC is a federal regulatory authority that could impose a regulation for the whole US territory, as opposed to the many strong national regulators in Europe. Each national regulator, then, is responsible for a small territory without a powerful supranational regulator. As a result, all regulators have equal saying in how the balancing mechanism should look like, and each regulator only knows the national peculiarities.

Next, gas networks in the EU are subject to non-discriminatory third-party access (TPA), meaning that all governing rules have to be included in the network code. In the US, on the other hand, there is no TPA as the investment framework for gas pipelines depends on long-term relationships between the pipeline company and the users of the pipeline who value the transport service most. These long-term contracts allow the tailoring of transport and flexibility services, whereas in a TPA framework, all network users have a right to the same service as any other user, making homogenous services necessary.

Furthermore, the separation of pipeline companies and supply companies has never been doubted in the US, limiting the links between the two activities. In the EU, unbundling has been a slow process, demonstrating strong links between the TSO and the incumbent supply company. In such a market, the TSO might be tempted to design the balancing mechanisms in such a manner that it favors the linked shipper. However, the latest regulation concerning unbundling calls for truly independent TSOs, removing this institutional difference [6; 7].

The FERC considers all information regarding a regulated pipeline service as public information that is necessary to have good market functioning as market players can

[30] Makholm actually uses the concept of "common carriage" instead of "third-party access", but the two concepts reflect the same idea.

base their decisions on maximum available information. Information about shippers in the EU gas market is considered confidential as it is commercial information that could threaten competitiveness if disclosed. If no information dissemination can occur, the only way to ensure non-discriminatory access is to offer only a single non-tailored service.

Finally, the US has a true market for network services, where shippers can trade their capacity rights to other users that value these rights more. In the EU, secondary markets for network services exist, but are rarely used. So, because of these institutional differences, the US balancing mechanism cannot just be copied: either the institutional setting has to change in Europe, or other solutions have to be developed taking into account the existing institutional framework in the EU gas market.

1.5 Comparison with electricity balancing

Gas-balancing design in Europe could also learn from the liberalization and unbundling of the electricity market, which has been on-going in parallel with the gas-market reforms. A recent overview of what has been happening in the economic and engineering literature regarding electricity balancing has been made by Vandezande, and can be found in [77] of which the main findings are presented below. Furthermore, this section focuses on the main differences between gas balancing and electricity balancing that impede the copying of solutions, or at least require adaptations to the peculiarities of the industry in question.

Like gas balancing, and despite regional coordination efforts, electricity balancing has remained predominantly national in scope. Nevertheless, there is a cross-border solidarity principle to deal with the requirement of instant electric-load balancing. This need for instant balancing is not present to the same extent in the gas sector due to the line-pack flexibility that allows a longer time constant.

Regarding the procurement of real-time electric-balancing energy, a design based on procurement at energy costs is proposed, preferably excluding capacity reservation costs. All procurement costs, then, should be allocated to unbalanced shippers through a settlement mechanism that uses cost-reflective imbalance prices. This imbalance price should include a component representing capacity payments if these could not be avoided during procurement.

The principles for electricity balancing and gas balancing are thus similar, yet the industries are different. A first institutional difference between electricity and gas in the framework of load balancing lies in the control of flexibility. In the European electricity market, the transmission-system operator, in principle, has to procure all flexibility from the market as the TSO cannot have direct ownership of electric-power generation plants due to the unbundling of generation and transmission.

Furthermore, electric energy cannot be stored in the grid infrastructure. Nevertheless, long-term strategic reserves contracts allow an electricity TSO to have a great amount of control over his balancing tools. However, the tools for real-time electricity balancing become much more expensive closer to the real time. In the gas market, on the other hand, the gas-transmission-system operator controls the pipeline pressure and thus the line-pack flexibility that is inherent to the dynamics of gas transmission and allows the storage of gas in the pipelines as a first line of defense against unbalanced shippers.

The absence of an explicit gate closure (GC) in the gas market makes up a second institutional difference with electricity. The gate closure marks the end of the wholesale market (forward and spot markets), which the network users can use to balance *ex ante*, and the start of the TSO-controlled operations for *ex-post* balancing. Because of the non-existing gate closure in the gas market, shippers can re-nominate within the formal balancing period before settlement, e.g., by trading on the ID market, as is illustrated in Figure 10. This re-nomination is possible even if a DA GC exists.

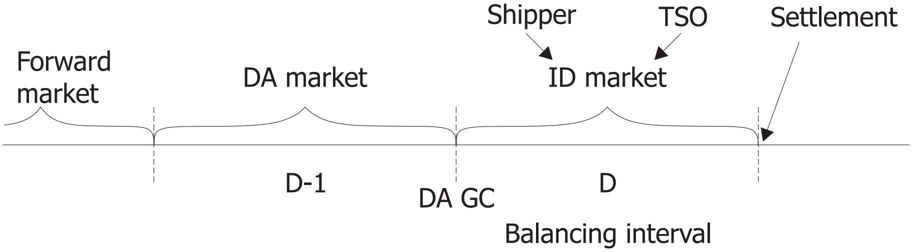

Figure 10. Relation between balancing interval and gas markets (forward, day-ahead and intra-day markets) without true gate closure (GC): typically a DA GC is defined, but both the shippers and the TSO are trading in the intra-day wholesale market to procure flexibility; the nominations of the shipper can thus change within the balancing interval to correct (expected) imbalance positions before settlement at the end of the interval; based on [77]

Consequently, a clear distinction between shipper activities in the regular wholesale market – that can be intra-day – and the actions of the gas-transmission-system operator is missing [78]. Moreover, electricity-transmission-system operators are usually not allowed to trade in the wholesale market because they have access to information that other market participants have not. Hence, they can distort the functioning of the wholesale market due to the unequal access to information [77]. In the gas market, on the other hand, wholesale trading by the TSO is advocated, even though the same information imbalance exists. Electricity-balancing services should be acquired in the upfront reserves market or in the real-time market after the gate closure. This contradicts with the general view on gas-balancing markets, which advocates the active participation of TSOs in the wholesale market to procure flexible gas [25; 79; 80]. As a result of this design, unbalanced shippers and the TSO are competing for the same flexible gas. However, pipeline flexibility, which is often not offered on the *ex-ante* market, is the most responsive instrument close to the real time and at the same time it has the cheapest operational costs compared to other sources of flexible gas offered on the DA and ID markets. The distorting effects of this are investigated in Chapter 2.

Technically, electricity is the textbook example of a just-in-time product with any imbalance between injection of electric power and the offtake thereof to be covered instantly by adding flexibility (up or down) anywhere in the grid.[31] Gas transmission and, thus, gas balancing is a different problem because gas travels at a limited speed [81; 82]. Therefore, it matters where flexibility is added to the system, turning physical gas balancing into a spatial problem as well as a temporal problem: flexibility added 150 km away can only contribute some two hours later to the system balance as gas typically travels at a speed of roughly 75 km/h. Hence, the effectively available flexible gas is location and time dependent.

Finally, gas is easier and more efficient to store than electricity, providing a major source of flexible gas that is only available to a limited extent in the electricity market, e.g., by means of hydro-pump stations.

The whole of differences makes that the regulation of the gas market cannot be copied directly from the electricity-market regulation. At the same time, electricity and gas markets become more and more linked through the (expected) rise in GFPPs. This interdependence creates spill-over effects from one market to the other. For instance, the gas-balancing period is commonly a day, whereas in electricity balance has to achieved over much shorter intervals, e.g., 15 minutes in Belgium. These spill-over effects are beyond the scope of this thesis, though.

1.6 Summary and Conclusions

This chapter has presented a framework to discuss balancing-mechanism design, introducing proper terminology and concepts that are necessary to build a nuanced view of gas balancing.

This balancing of the gas network is required because a physical disequilibrium between gas entering the pipeline system and gas leaving it results in a change of the pipeline pressure and thus the line-pack level. If the pressure drops too low or rises too high, the security of the pipeline system is threatened, and this pipeline network is the backbone of a reliable gas supply. Because gas dynamics enables the storage of gas in the pipeline by playing with the pressure levels, the balancing of the gas system becomes an intertemporal problem.

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[31] Note that the location of electricity-balancing services can become more relevant when grid congestion is involved. Also the balance of reactive power for voltage support is location sensitive as reactive power is not easily transported.

In the liberalized gas market, the TSO is the ultimate responsible for gas-system reliability. But the shippers cause imbalances because the supply and demand contracts in their portfolios have different time patterns and are subject to prediction errors. Therefore, a coordination mechanism is required: the balancing mechanism. This mechanism deals with the procurement and dispatching of line-pack flexibility and flexible gas by the TSO for physical balancing of the system, on the one hand, and the settlement of shipper imbalances to recover the balancing costs borne by the TSO from the responsible shippers, on the other hand. The main design options have been introduced throughout the chapter: e.g., different formal and informal balancing intervals, or the market-based or non-market-based determination of imbalance fees.

Furthermore, this chapter has demonstrated that national network codes take different approaches towards balancing, resulting in a patchwork of balancing-mechanism designs in the multi-region EU gas market. The establishment of a daily balancing period can be considered as common to almost all balancing mechanisms. National implementations, though, still apply their own adaptations by adding intra-day or supra-day constraints. Thus, a common design has not yet been established. The opportunities and threats of these different approaches will be investigated in Part 3 of this thesis, which deals with cross-border aspects.

Finally, this chapter has argued why lessons from established balancing-mechanism design in other sectors, namely, the mature US gas market and the EU electricity market – that has been leading the gas market with regard to market regulation – are not directly applicable. To copy solutions from the US gas market, the institutions in Europe would have to change, focusing more on heterogeneous services directly agreed between the TSO and the network users, and the development of an actual market for transport and flexibility services. The electricity-market solutions, on the other hand, need to be adapted to the technical and institutional peculiarities of the gas system, which allow imbalances to be stored in the network that is controlled by the TSO, as opposed to electric-load balancing that is relying on procured balancing services that become more expensive closer to the real time. Hence, line-pack regulation is specific to the gas industry and it needs appropriate regulation to prevent market distortions due to the cheapest balancing tool being part of the *ex-post* market. Suggestions to look into solutions for balancing-mechanism design provided by other markets or sectors, therefore, have to be met with caution.

PART 2

National aspects of gas balancing and regulation of network flexibility

2. REGULATION OF LINE-PACK FLEXIBILITY[32]

This chapter investigates the value and costs of line-pack flexibility, which is the property of the gas network to function as a short-term storage. Furthermore, the impact of its regulation on the competitive and non-competitive gas-market activities is assessed and the trade-offs are identified between the transmission function and the storage function.

The chapter starts with an introduction that sets up the regulatory framework, after which the technical trade-offs are explained. This leads to a discussion of the economic trade-offs in the third section. The market-distorting effects of existing line-pack regulation and balancing rules are reviewed in section 2.4.

2.1 Introduction

Gas pipelines and compressors are the physical backbone of a gas market, and they can be used to make gas flow and to store it. There are, however, important trade-offs between both possibilities to engage the gas infrastructure. If this dual functionality, which is embodied by line-pack flexibility, is neglected, negative effects are carried into the gas-commodity and gas-transport market. Yet, almost no reference to the problems with line-pack flexibility can be found in the literature. The problem is further complicated because aspects of investments, network operations and balancing markets have to be dealt with simultaneously. Therefore, this chapter aims to shed some light on the problem setting through analysis of the economic consequences of the trade-offs between the transport function and the flexibility function of the pipelines in the context of the European liberalizing gas markets. The pipeline flexibility can be seen as a positive externality of the transport-network design. The right to use this flexibility, on the other hand, decreases the available transport capacity. So, the benefit of flexibility in the timing of injections and withdrawals that is possible because of line-pack flexibility should be weighed against the harm of reducing available transport capacity in order to assure the flexibility [83]. In section 2.2, the technical relationship between the two functions of the infrastructure is explained in detail. It is evident that the line-pack flexibility has an economic value (for different actors), and that this value can be bigger than the harm provoked by its use. Still according to Coase [83, p. 7]: *"It is necessary to know whether the damaging business is liable or not for damage caused since*

[32] This chapter has been published as: Keyaerts, N., Hallack, M., Glachant, J.M., D'haeseleer, W., 2011. Gas market distorting effects of imbalanced gas balancing rules: Inefficient regulation of pipeline flexibility. Energy Policy 39, 865-876 [48].

without the establishment of this initial delimitation of rights there can be no marked transactions to transfer and recombine them." In Europe, the right to use the pipeline flexibility is defined by the balancing rules and the network code, as underlined by ERGEG [84].[33]

The Coase theorem further specifies that the allocation of rights has no welfare implications if there is a workable market and price signals.[34] However, in the European gas-transport case, the transport function and the network flexibility are considered the monopoly of the network operators. Thus, the related services are considered regulated services with regulated tariffs. Nevertheless, the problem of the dual function has been raised many times by institutions such as the European Commission's DG Transport and Energy [86], ERGEG [14; 84], and Gas Transport Europe (GTE) [20]. A clear proposition on how to take it into account in the balancing tariffs has not been formulated, though. Some national network operators, e.g., GRTgaz in France, have also been concerned about the issue [87; 88]. GRTgaz particularly called attention to the problem of whether investments caused by unbalanced shippers should affect the gas-transport tariff of all shippers. As will be shown in sections 2.2 and 2.3**,** line-pack flexibility and balancing are closely related. The possible negative impact of balancing tariffs on the gas-market competition, and how these balancing mechanisms potentially increase entry barriers for small shippers have been shown before [89; 90]. Moreover, many policymakers have advocated that the balancing tariffs should reflect costs and that the offering of a regulated monopoly service should not be a profitable business for a network operator [91]. Hence, the TSO should achieve cost neutrality, or, in other words, all balancing costs have to be passed on to unbalanced shippers.

The tariffs and balancing rules, thus, should reflect the actual costs of line-pack flexibility, which is currently the main tool for *ex-post* gas-network balancing. *Ex-post* balancing means that balancing is done by the TSO within the framework of the balancing rules, whereas *ex-ante* balancing means that the shipper contracts flexibility instruments beforehand to balance himself. The line-pack costs include variable costs of pipelines and compressors as well as sunk costs of this infrastructure. The cost decomposition of pipelines between its two different functions of transport and flexibility is complex. In fact, the supply function of two services produced by a common network infrastructure can be classified by the classic microeconomics theory as a multi-product monopoly. Moreover, the transport

[33] In gas markets where transport capacity is sold based on bilateral contracts (e.g., Australia, Brazil and US) the issues addressed in this chapter are of less interest. The bilateral coordination mechanism allows the rights and obligations of the players as well as the time and geographical flexibility to be defined in a heterogeneous manner [49; 54; 85]. This is very different from Europe where the gas network offers services with pre-defined and regulated characteristics for all users.

[34] A less-stringent supposition states: if property rights are clear and contracts are possible.

and storage services offered by this multi-product monopoly are part of different markets – as both have different substitutes – even if the production costs of the two services are dependent [92]. Because the transport market and the flexibility market have different substitutes, they may have a different elasticity. Therefore, it is not possible to solve the problem as a single product monopoly with a sequential solution. The traditional approach to regulating a multi-product monopoly is to charge Ramsey-prices for each of the products according to each product's demand elasticity [93]. Although the gas-network service can be considered a natural monopoly, the pipeline flexibility is competing with other real or potential sources of flexibility such as contract flexibility and other storage mechanisms [31]. Thus, the network flexibility is actually not a monopoly, but rather an oligopoly.

So, it is not sure whether pipeline flexibility should be regulated at all. The market for flexibility services is principally a competitive market. Nevertheless, many flexibility services remain (partly) regulated in Europe. The case for regulation of line-pack flexibility is strong, though, because the underlying infrastructure belongs to the regulated part of the gas market. An inefficient tariff for pipeline flexibility can result in a misallocation of resources in the flexibility market, which subsequently raises a need for regulation to develop other flexibility like storage. Therefore, inefficient regulation of pipeline flexibility impedes the development of a truly competitive flexibility market.

Because of this complexity, the understanding of the trade-offs between the transport function and the storage function of the pipeline infrastructure is a key issue to improve network regulation. The proper understanding of this allows the opportunity costs of time flexibility to be determined in a similar way as has been done by Lapuerta and Moselle [45] for an analogous problem regarding geographical flexibility. These authors use opportunity costs to compare different capacity systems with regard to flexibility rights (e.g., entry-exit versus point-to-point) and tariffs, and to evaluate the market consequences.[35] Opportunity costs have also been applied to evaluate externalities of energy markets [94-97]. The definition of such costs is essential to determining an efficient tariff because in the absence of a clear market price, it is the tariff rules that define the allocation of rights to use the monopoly infrastructure, addressing the Coase problem as a feasible second best [98; 99].

Hence, this chapter explores the economic consequences of the trade-offs between pipeline transport and pipeline storage. Furthermore, an important consideration is raised concerning the role of cumulative intra-day imbalances in solving the non-trivial problem of pricing line-pack flexibility. Indeed, in an unbundled market, the bundling of the two very different services of the pipelines is challengeable, and a separate price for line-pack flexibility can increase transparency and efficiency in the market.

2.2 Line-pack flexibility: origin and uses

The ability of gas networks to store gas inside pipelines is a consequence of the physical properties of the transport network where the volumetric gas flow can vary according to the pressure difference as explained in the technical literature [81; 82; 100]. The TSO can decide how much gas to transport and how much gas to store taking into account some technical limits. These technical limits determine the line-pack flexibility. A distinction is necessary between the concept "line pack", which is the total amount of gas present in a pipeline section, and the concept "line-pack flexibility", which is the amount of gas that can be managed flexibly by controlling the operation-pressure levels between a minimum and a maximum level (Figure 11). The following subsections explain how this network-based flexibility is produced as a consequence of the gas-transport dynamics, and how it is useful for managing a gas-network system.

2.2.1 Production of line-pack flexibility

The general flow equation for compressible-gas transport is described by Eq. (2.1) in which $\dot{V}$ stands for the volumetric flow rate (m^3/s), D represents the diameter (m) of the pipeline section of length L (m), and p_{in} and p_{out} are the pressure (Pa) at the inlet of the pipeline and at the outlet of the pipeline, respectively [81].[36] The constant c represents material and gas characteristics such as pipeline roughness and gas density, and is also dependent on the units chosen for the other parameters.[37]

$$\dot{V} = cD^{2.5}\sqrt{\frac{p_{in}^2 - p_{out}^2}{L}} \tag{2.1}$$

Basically, the gas-flow rate is related to the difference of the quadratic pressures at both ends of the pipeline section, and not the difference in pressures themselves. Pipelines, then, can be operated at a range of pressures. The upper bound is formed

[35] Entry-exit defines capacity rights as the right to enter gas at one or more entry nodes and withdraw at one or more exit nodes without any specification of the physical path. This provides geographical flexibility to shippers. Indeed, they can change nominations at entry and exit without having to worry about the transport of the gas. Point-to-point, on the other hand, defines capacity rights as the right to use a path between two defined points. Hence, geographical flexibility is absent (see Chapter 1).

[36] Volumetric flow rate ($\dot{V}$) under reference standard conditions is equivalent with mass flow rate ($\dot{m}$), differing only by a constant reference density.

[37] Values for c in Eq. (2.1) and w in Eq. (2.2) can be found in, e.g., [81; 82; 100; 101].

by a maximum operating pressure (p_{emax}), which is determined by the material characteristics. The minimum operating pressure (p_{dmin}) is a lower bound that ensures flow by compensating friction or it can be determined by contractual arrangements for a certain delivery pressure.

So, the TSO can ensure the safe operation of the pipeline network by operating within the pressure band. This operational flexibility in gas-transport networks results in the ability to store gas in the pipelines. Moreover, normal gas transport is still ensured while using line-pack flexibility. The pressure drop (p_a to p_b or p_c to p_d) required for the transportation service and the available storage potential (area p_a p_b p_d p_c) are both illustrated in Figure 11.

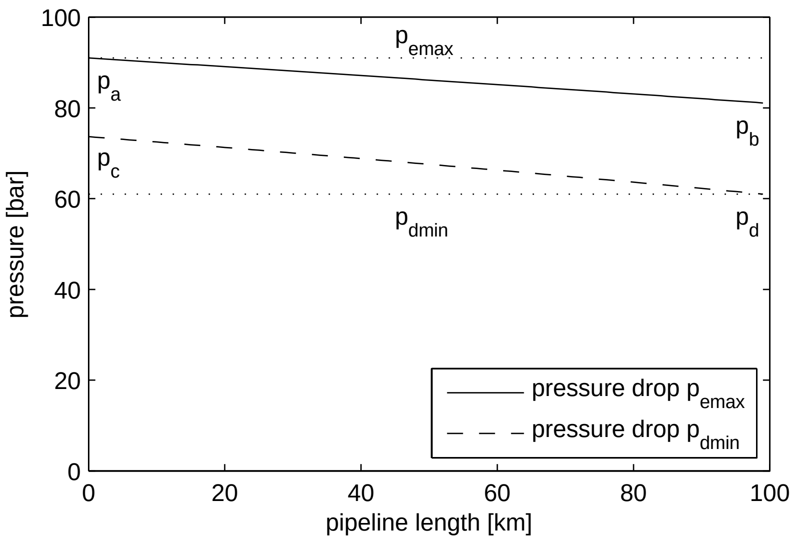

Figure 11. Line-pack flexibility and pressure development along the pipeline: the area defined by p_a p_b p_d p_c visualizes the storage potential in the pipeline while simultaneously ensuring the flow rate corresponding to the squared-pressure difference $p_c^2 - p_d^2$ at the lower boundary or $p_a^2 - p_b^2$ at the upper boundary; p_{emax} and p_{dmin} represent the upper and lower operational-pressure limits of the pipeline [48; 81]

The available line-pack flexibility, expressed in standard cubic meters, is determined by Eq. (2.2) in which *w* is a constant that is dependent on the geometric volume of the pipeline and the chosen reference conditions [81].

$$V_{LPflex} = w\left(\frac{\overline{p}_{ab}}{Z_{ab}} - \frac{\overline{p}_{cd}}{Z_{cd}}\right) \tag{2.2}$$

Basically, the storage potential depends on the difference between the higher average pressure $\bar{p}_{ab}$ (Pa) and the lower average pressure $\bar{p}_{cd}$ (Pa) that enable the same flow rate. Both average pressures are calculated according to Eq. (2.3) (for $\bar{p}_{cd}$ index *a* is replaced by *c*, and index *b* by *d*) [81].

$$\bar{p}_{ab} = \frac{2}{3}\left(\frac{p_a^3 - p_b^3}{p_a^2 - p_b^2}\right) \tag{2.3}$$

Z_{ab} and Z_{cd} are compressibility numbers (dimensionless) corresponding to $\bar{p}_{ab}$ and $\bar{p}_{cd}$, respectively.[38] The higher average pressure, $\bar{p}_{ab}$, corresponds to the pressure drop that has an entry pressure p_a (p_{in} in Eq. (2.1)) equal to p_{emax} and an exit pressure p_b (p_{out} in Eq. (2.1)) that depends on the desired flow rate. The lower average pressure, $\bar{p}_{cd}$, on the other hand, depends on the entry (p_c) and delivery (p_d) pressures that correspond to the same desired flow rate, but with p_d equal to p_{dmin}. So, multiple pressure pairs enable the same flow rate, but result in a different line-pack level. If the full pressure difference (p_{in} = p_{emax} and p_{out} = p_{dmin}) is required to make the gas flow, there remains no storage potential, whereas if there is no flow the full geometric volume of the pipe can be used to store compressed gas.

Figure 12 illustrates the trade-off between flow rate and line-pack level for a certain pipeline with operational limits. In the upper panel (Figure 12.a), the line-pack level is plotted as a function of the flow rate. The solid line keeps the entry pressure fixed at the upper limit and the dashed line has the exit pressure fixed at the lower limit. So, if the entry pressure is fixed, the exit pressure has to drop to allow a higher flow rate, but then the average pressure, and thus the line pack decreases. If the delivery pressure is fixed at the minimum level, flow can only increase by raising the entry pressure, which increases the average pipeline pressure and line-pack level. Note that the dashed line also indicates the minimum level of line pack that has to remain in the pipeline to enable safe transport of gas. Furthermore, note that the crossing of the two lines indicates the operational maximum of the flow rate with the corresponding entry and exit pressures equal to the maximum and minimum operating pressures, respectively. Indeed, a flow rate of, e.g., 2.4 Mm^3/h requires the entry pressure to rise beyond the operational maximum, or the exit pressure has to drop below the minimum level, thus, violating the safe limits. The maximum flow rate is marked in both panels by the dotted line. The lower panel (Figure 12.b), then, shows the substitution curve of line-pack flexibility and flow rate. This substitution curve is obtained by subtracting the line-pack levels corresponding to p_{dmin} (dashed line) from the line-pack levels corresponding to p_{emax} (solid line) in the upper panel. If the flow rate is maximal, there is no flexibility in the pipeline, and maximal pipeline storage is attained when there is no flow. The curve, then, represents the substitution rate of flexibility into flow. Or, in other words, how much flow rate has to be sacrificed for an additional unit of line-pack flexibility.

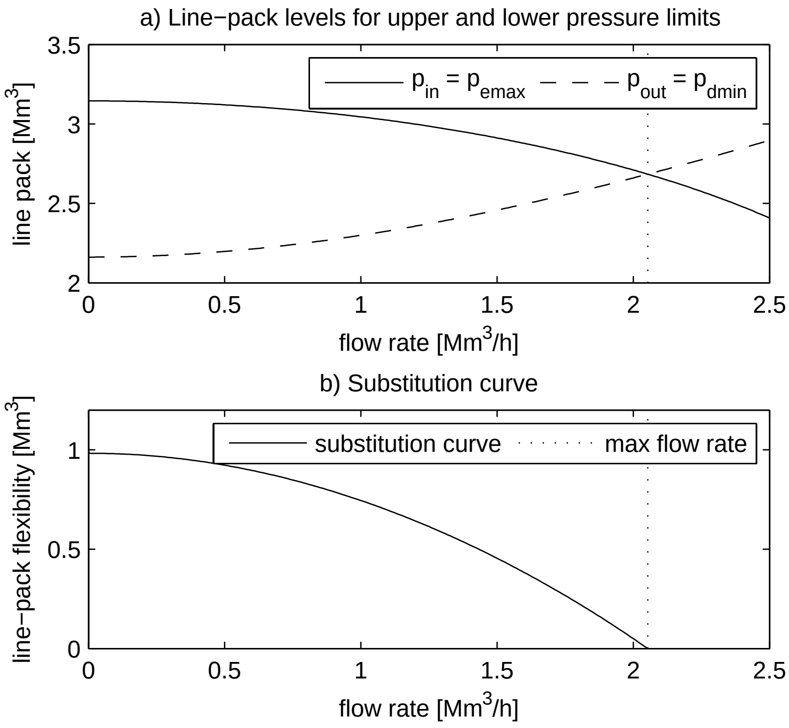

Figure 12. Trade-off between flow rate [Mm^3/h] and line pack [Mm^3]: a) line-pack level for varying flow rates with entry pressure equal to upper pressure limit (solid line) and exit pressure equal to lower pressure limit (dashed line), b) substitution curve of line-pack flexibility and flow rate representing the amount of flow that has to be reduced to have an additional unit of flexibility; the curve is obtained as the difference of the full and the dashed line in the upper panel; the dotted line marks the maximum flow rate – e.g., if p_{in} is constant, flow can only increase by lowering p_{out}, resulting in a lower average pressure, thus decreasing the line-pack level (actual numbers are case dependent)

[38] The compressibility number is a measure to correct for real-gas behavior (as opposed to ideal-gas behavior) and is below, but close to, 1 for natural gas. For pressures ranging between 50 and 100 bar, the compressibility number is around 0.8. Fittings can be found in [81; 102].

2.2.2 Use of line-pack flexibility: pipeline storage

Line-pack flexibility is then produced by making use of the still available pressure difference which results in the storage of gas inside the pipeline. The basic principle of storage is that one can only withdraw what has been injected before. Therefore, line-pack flexibility operates like a buffer that is filled first, and emptied at a later time. This *buffer* concept has been defined by Lapuerta as the part of the line pack that can be used without any safety problem [90, p. 66]: "*at any point in time, the available buffer is the difference between line-pack at that time and the minimum safe level of line-pack*". In other words, "*the available buffer is the maximum amount that line-pack can fall within-day from its current level without introducing a positive probability of supply failure*". In this thesis, the line-pack buffer at any time is equivalent to the used line-pack flexibility.

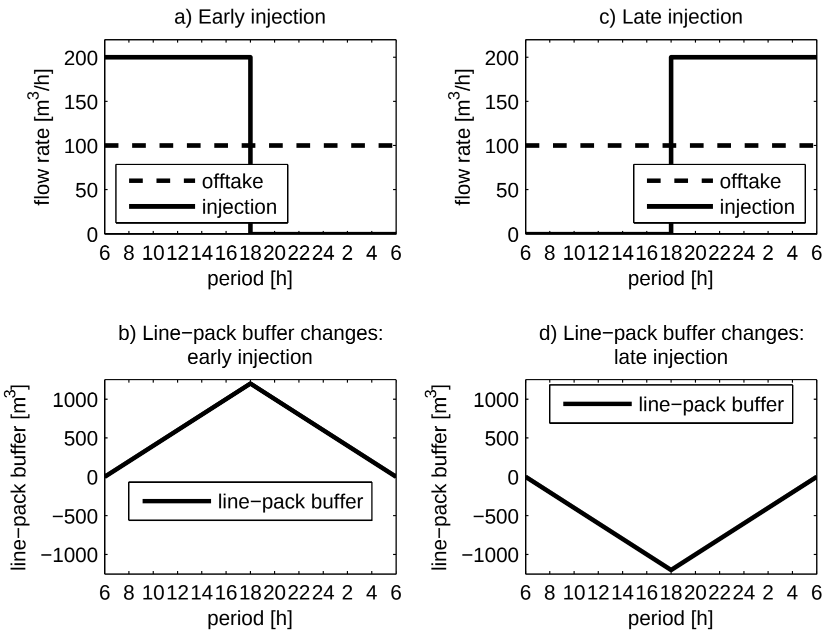

Figure 13. Accommodation of different time patterns for gas injection and gas offtake: a) early injection [m^3/h], b) line-pack buffer creation [m^3], c) late injection [m^3/h], d) line-pack buffer extraction [m^3]

Figure 13 shows the interdependent nature of line-pack flexibility and the gas-transport service. Indeed, short-term gas flow is often non-steady-state flow. This means that the time patterns of injections in the pipeline and withdrawals from it do not match. The pipeline flexibility, then, absorbs this difference by acting as a buffer.

Hence, the line-pack buffer is the time integral of the difference between injection and withdrawal flow-rate (cf. Eq. (1.1) in Chapter 1).

The examples in Figure 13 assume constant demand over the course of a day. In Figure 13.a the shipper injects all gas during the first half of the day, building up a buffer for withdrawal during the second half of the day (Figure 13.b). If the shipper injects late (meaning in the second half of the day) gas is withdrawn from the line-pack buffer during the first 12 hours (Figure 13.c and Figure 13.d). In both examples the shipper needs entry capacity of 200 (m^3/h) and exit capacity of 100 (m^3/h). So, the shipper counts on the pipeline storage to balance the actual loads.

To allow the withdrawal of gas before the injected gas has reached the withdrawal point (Figure 13.c and Figure 13.d) the line-pack buffer has to be used to satisfy demand. This buffer needs to be created and kept in storage within the physical boundaries of the pipeline. Therefore, part of the capacity (equivalent to a flow rate of 100 m^3/h) cannot be allocated to transport services. The same logic can be applied the other way around: if the gas is injected in the pipeline by a shipper before a withdrawal demand arises (Figure 13.a and Figure 13.b), and the flexibility is guaranteed, it is necessary to keep gas inside the pipeline until there is a demand for withdrawal by that shipper. It cannot be used by a second shipper, unless there is a guarantee that gas will be available for delivery to the first shipper when he demands it. The part of the pipeline committed to gas buffering is determined by the cumulative-imbalance swing (difference between highest intra-day cumulative peak and lowest intra-day cumulative dip), and is equal to 1200 m^3 in both hypothetical illustrations in Figure 13. These technical relations confirm the occurrence of trade-offs between offering line-pack flexibility and selling transport capacity.

So, the line-pack flexibility enables the network operator to store gas inside the pipelines to facilitate the matching of gas supply and demand over time. The line-pack flexibility is thus particularly suited to immediately accommodate short-lived imbalances between demand and supply.

2.3 Economic value and costs of line-pack flexibility: trade-offs

Joskow [103] argues that the creation of well-functioning liberalized gas markets is technically not much of a challenge because of the ability to store gas along the supply chain. However, the presence of flexibility makes the economics of the gas-market liberalization very challenging. Line-pack flexibility in particular is a service with special characteristics that cannot be discussed without taking notice of the whole gas-transport system.

In the absence of an efficient market, regulated tariffs reflecting long-term marginal costs are a second-best solution for the gas-transport system as described by Kahn

[104] and Spulber [105]. In Europe, this has resulted in line-pack flexibility being regulated by the balancing rules. Indeed, EU rules demand provision of appropriate balancing incentives to shippers in the balancing rules [6; 7]. Furthermore, these rules advocate that balancing charges shall be cost reflective. However, balancing rules allocating line-pack flexibility for free and balancing charges based purely on gas prices can be observed throughout Europe, even if the spot market has not been the main tool to physically balance the system.[39] Hence, cost reflection is imperfect. Therefore, the ensuing subsections present approaches to derive the costs and value of line-pack flexibility, both of which contain necessary information to adequately regulate the line-pack flexibility.

2.3.1 The economic value of line-pack flexibility

The fundamental value of line-pack flexibility can be attributed to its buffer function to quickly cover temporal imbalances between supply and demand. Technically, pipeline storage reflects physical "imbalances" between gas entering and gas leaving the system. The economic definition of a gas imbalance, on the other hand, depends on the balancing period. Indeed, real gas injections and withdrawals should only match over a specified time interval and this interval can theoretically last from a second to an hour or even a day or a month. Taking into account that the value of gas demand varies in time, and that the production or import of gas is often less costly when it is flat, there is a value to facilitate the matching of gas demand and gas supply over time. This value is even increasing due to the development of short-term gas demand for electricity generation with GFPPs [90; 106; 107].

Moreover, the economic value created by the flexibility to store gas inside the pipeline and to transport gas through a full or empty pipeline can be appropriated by different players: the TSO can use this property to minimize its pipeline investments, whereas shippers can use it for price arbitrage and load management.

2.3.1.1 Line-pack value for a TSO: network investment

The transmission-system operator is responsible for network investment and thus for the sizing of the network. Therefore, an efficient TSO maximizes the sale of transport capacity while minimizing the capacity that is built. Line-pack flexibility, then, helps the TSO to avoid over-investment. Over-investment is defined as an investment in capacity that will not be used during the pipeline deprecation horizon.[40]

In a network based on entry-exit capacity rights, transport capacity is marketed through the separate selling of entry capacity and exit capacity, as detailed by

[39] This means that line-pack costs or costs of intra-day imbalances are socialized by means of the general transport tariffs and are not allocated to the users of this flexibility.

[40] Capacity is planned on the long term and thus typically accounts for expected demand growth.

Lapuerta and Moselle [45] and KEMA [23]. Table 17 provides a fictional example of entry flow (supply) and exit flow (demand) for two periods, t_A and t_B, each lasting one hour. The demand varies between 400 (m^3/h) in the first period and 600 in the second period. For the supply there are two options. Option 1 exists in supplying exactly the demanded flows in period t_A and period t_B. Option 2, on the other hand, takes into account the available line-pack flexibility and supplies 500 in every period.

Table 17. Example of demand and supply flows for two hourly periods (t_A and t_B) under different capacity offers, injection before withdrawal [all units m^3/h]

Period [1 h]	Demand A Exit cap 600 [m^3/h]	Supply option 1 Entry cap 600 [m^3/h]	Supply option 2 Entry cap 500 [m^3/h]
t_A	400	400	500 (store 100)
t_B	600	600	500 (withdraw 100)

The exit capacity offered by the system operator should allow the delivery of gas during the peak period (t_B in Table 17). Therefore the exit capacity needs to amount to 600. The TSO can now choose the amount of entry capacity he offers to the gas suppliers. The straightforward solution (option 1 in Table 17) is to allow the suppliers to follow the demand with the supply flows and offer an entry capacity of 600. According to option 1, the upstream pipeline infrastructure needs to be designed to deliver 600 at the entry point in period t_B (either by pipeline flow or local storage).

If the TSO takes into account the presence of line-pack flexibility (option 2 in Table 17), on the other hand, the investment in entry capacity can be limited to 500. This entry capacity, then, is fully used in both periods. Moreover, option 2 allows optimizing the investment in the upstream infrastructure to deliver a stable flow of 500 in the two periods instead of building a transport capacity to handle the import peak of 600 in period t_B.

The TSO confronted with demand A observes an economic value of storing 100 m^3 that is equivalent to the investment difference to make available an entry capacity of 600 or 500 to face the same demand. The marginally saved investment constitutes a negative opportunity cost for the TSO. This benefit should be transferred to all network users through reduced gas-transport tariffs.

2.3.1.2 Line-pack value for a shipper: load management and price arbitrage

In a liberalizing gas market, shippers, who can be any gas buyer or seller, are profit-maximizing market players. They buy their gas as cheaply as possible and sell it as expensively as possible (or use it when it has a larger economic value). This means that in a market context shippers prefer to buy gas on a flat-rate basis if irregular offtake is more costly for them. If prices are fluctuating, they prefer to buy gas in off-peak periods when prices are lower, and to sell it in peak periods, which are characterized by higher prices [31].[41]

So, if an opportunity turns up for a shipper to buy cheap gas in t_A, inject it in the pipeline and sell it at a premium in t_B, the shipper will be interested in using the line-pack flexibility to arbitrate between prices. Evidently, a shipper could also sell gas from the line-pack buffer in t_A, if gas prices are high, and inject in t_B, when gas has a lower price to match his purchase and sales portfolio.

In the example of Table 18, the peak demand is in the first period and the off-peak demand in the second period. There are again two options for supply. Option 1 exists in supplying exactly the demanded flow in each period, whereas option 2 uses the line-pack flexibility to cover the different time patterns.

Table 18. Example of demand and supply flows for two hourly periods (t_A and t_B) under different capacity offers, injection after withdrawal [all units m^3/h]

Period [h]	Demand B Exit cap 600 [m^3/h]	Supply option 1 Entry cap 600 [m^3/h]	Supply option 2 Entry cap 500 [m^3/h]
t_A	600	600	500 (borrow 100)
t_B	400	400	500 (inject 100)

Again, the exit capacity offered by the TSO should allow the delivery of gas during the peak period, which is t_A in Table 18. Therefore, the exit capacity needs to amount to 600. If the shipper is not obliged to balance over t_A (e.g., the formal balancing period is t_A+t_B), the TSO becomes responsible and assumes the costs for the safe operation of the network. In other words, the transmission-system operator cannot be sure that the gas will be completely injected in t_A because the shipper has the flexibility to inject only 400 or 500 and still take off 600, "borrowing" the difference. Similar to the observations made in Figure 13, the TSO needs to buffer gas in the pipeline before period t_A. Indeed, the shipper is allowed to withdraw 600 in t_A before he makes the matching injections in t_B.

So, the economic value of pipeline flexibility for the shipper consists of the possibility to arbitrate between injecting (buying) gas when it has a lower price and withdrawing gas from the pipeline (selling) when it has a higher economic value. The TSO, as the safeguard of gas-system integrity, anticipates this withdrawal and keeps gas in pipeline storage before the shipper acts [90]. Evidently, this valuable flexibility has economic costs too.

[41] On an annual basis, e.g., shippers buy additional gas in summer to sell it in winter. Similar opportunities are sought out on a shorter-term horizon as well.

2.3.2 The costs of line-pack flexibility for the TSO

The fixed cost of line-pack flexibility for the TSO can be evaluated by the part of the pipeline cost used to store gas in order to address unbalanced situations, or by the opportunity cost of this line-pack flexibility. Indeed, the market value of the available transport capacity differs with and without bundled line-pack flexibility. The examples from Table 17 and Table 18 (and also Figure 13 for different numbers) clearly illustrate this argument: to sell the firm-withdrawal capacity of 600 m^3/h, the TSO needs to ensure that the pressure level in the pipeline will not drop below the pressure level required for the load buffer. So, the TSO needs to keep gas in storage that might be withdrawn before a matching injection is made.

The opportunity cost of pipeline flexibility, therefore, depends on the amount of capacity that is unavailable for transport services due to its commitment to buffering. This amount is related to the largest cumulative swing that the network has to sustain, as explained in section 2.2. With reference to the numbers in Figure 13.b and Figure 13.d, 100 m^3/h of pipeline flow capacity is committed to pipeline flexibility and cannot be sold as entry capacity if flexibility is bundled with transport capacity. The market value of this amount of unavailable transport capacity defines a trade-off cost for the infrastructure.

In the vertically-integrated industry all flexibility costs were inserted in the integrated gas company's pool of costs to supply gas to consumers. In the unbundled European gas industry the picture has changed. Nowadays, the transport network is managed by a separate TSO who is responsible for the execution of the transport service and the system balancing. And both services physically depend on the pressure management.

Because of its obvious relationship with the pressure management of the pipeline system, line-pack flexibility in Europe is controlled by the TSO. The principal short-term trade-off for the TSO, then, exists in the mutually exclusiveness of offering a unit of pipeline storage versus offering a unit of pipeline transport, within the framework of a physically limited pipeline capacity. Furthermore, actual pipeline use depends on pre-defined (national) regulation that provides a framework for all services offered by a TSO. These network codes explicitly or implicitly determine the amount of line-pack flexibility that is kept out of the market by the TSO to guarantee bundled flexibility for each unit of transport made available.

The shippers, on the other hand, hand over gas to the TSO at entry points and take back control over (less or more) gas at exit points. *"In a liberalised market, system balancing is achieved through the interaction of network users and the TSO. Whilst network users should aim to minimise and be obliged to take the financial responsibility for any deviation between the inputs and off-takes, the TSO remains the only instance that is able to ensure the physical balance of the overall network"* [23, p. 34]. So, national balancing rules establish balancing charges in order to transfer the costs of *ex-post* balancing to the shippers. Indeed, the shippers cause imbalances and should thus be incentivized to balance their flows *ex ante* by means of storage and other flexibility contracts on the market.

2.3.3 The cost allocation of line-pack flexibility: the settlement mechanism

In Europe, the line-pack costs are in part socialized by means of transport tariffs and in part allocated to shippers through balancing rules, charges and tariffs. Line-pack flexibility is often the main balancing tool applied by all TSOs. Therefore, the balancing charges should at least reflect the costs of line-pack flexibility.

In section 2.2, the cost impact of *ex-post*-balancing services offered by the TSO has been demonstrated to technically depend on peak cumulative imbalances within the formal balancing period. A shipper, though, only has to balance his position over the defined balancing period and the balancing payments depend on the charges asked for this end-of-period imbalance. So, the actual balancing costs for the TSO relate to the swing of line pack throughout the day, but the intra-period imbalances that cause this swing are not allocated to the shippers. The longer the balancing period, the higher the balancing cost for the TSO can become due to the accumulation of imbalances within the interval for which the TSO is responsible. These costs, then, are socialized through network tariffs.

Thus, the better the balancing charges reflect the actual system-balancing costs, the more efficiently these charges incentivize shippers to choose the most economic balancing tool, *ex ante* or *ex post*. Given the demonstrated role of the maximum swing of cumulative imbalances, any cost-reflective price for *ex-post*-balancing charges should explicitly or implicitly refer to peak cumulative imbalances over the formal balancing period, or the balancing interval has to become shorter to better allocate costs.

A typical settlement mechanism specifies time and space boundaries in which the shipper has to balance his position. Some balancing rules add tolerances, offering the shipper some margin to have imbalanced positions without any penalization. Furthermore, the settlement mechanism specifies balancing charges that should reflect the costs incurred by the TSO to balance the transport system and sometimes it specifies extra charges just to penalize and incentivize unbalanced shippers.

In actual EU settlement mechanisms, however, line-pack costs are rarely included in the balancing charges even if line-pack flexibility is the first tool applied by the TSO to balance the system [23; 108].[42]

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[42] The Spanish balancing rules is a rare exception that explicitly refers to the line-pack capacity that is bought bundled with transport capacity by the shipper. This line-pack capacity demarcates the tolerated amount of imbalance [109].

2.3.3.1 Settlement-mechanism-design options

First, the definition of the balancing period is a key definition because it establishes the division of balancing responsibilities between TSO and shippers. Inside the balancing period the TSO carries out balancing at no cost for the shipper, but at the end of the period the shipper should balance himself by means of *ex-ante flexibility* or *ex-post*-balancing. If the balancing period is an hour, injection and withdrawal should be balanced every hour; whereas in a daily balancing mechanism the shipper should only balance every 24 hours. Therefore, and referring to the examples in Figure 13, the TSO needs to provide gas from (pipeline) storage in case a shipper withdraws gas before he injects, and needs to keep gas in storage that was injected for withdrawal at a later time.

Second, the definition of the imbalances that are subject to balancing charges and the size of these charges is not homogeneous in Europe. Imbalances within the balancing period have, in principle, no financial consequences for the unbalanced shipper. In other words, flexibility costs within the balancing period are socialized. Some countries (e.g., Belgium and the Netherlands before 2011), however, have added rules to limit the free flexibility inside the balancing period (Section 1.3). These rules are meant to discourage huge differences between injections and withdrawals over smaller intervals within the formal balancing period. At the same time they implicitly try to limit the peak intra-day cumulative imbalance. Furthermore, balancing rules have very different approaches to dealing with tolerance levels and penalty charges. A small imbalance that is less expensive or free is defined by the tolerance levels, which reflect the availability of line-pack flexibility. By offering tolerances, the TSO commits himself to keeping a certain level of line-pack flexibility for storage services at the cost of selling this capacity for the purpose of transport. In balancing mechanisms that define a smaller balancing interval, or that do not include tolerances, the TSO can sell more capacity for transport services. Thus, the cost of different balancing rules relates to the opportunity cost of unavailable pipeline-transport capacity.

Third, there exist different options to set up balancing charges. Most European balancing mechanisms base balancing charges solely on gas-market prices, as is recommended by the regulators and the European Federation of Energy Traders (EFET) [25; 79; 84]. In other words, by the end of the balancing period a shipper should not have any remaining imbalances. If the shipper has imbalances, he will be subject to pay the cost for the equivalent amount of gas as if that gas had been bought or sold on the market.[43]

[43] The availability of an adequate market price for gas is an issue that has been discussed by ERGEG [14; 84]. In the argumentation in this thesis, a proper gas price is assumed to be present to show that even in that case line-pack flexibility is treated inadequately.

Figure 14 shows a daily balancing mechanism with additional intra-day rules and tolerances, illustrating the balancing-mechanism definitions. A basic daily balancing mechanism only cashes out the end-of-day imbalance, which is marked by the last dot of the dash-dotted line. The bars, then, represent the free intra-day flexibility for the shipper. More complex balancing mechanisms add tolerances (dotted lines) and intra-day penalties. These intra-day penalties are due by the shipper for hourly imbalances and peak cumulative imbalances beyond the tolerated level.

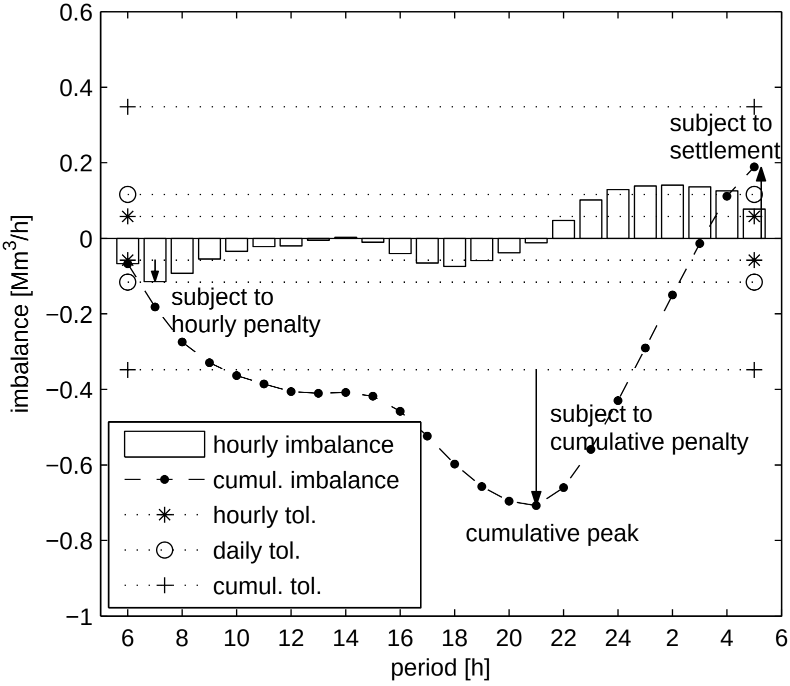

Figure 14. Illustration of a daily balancing mechanism with additional intra-day charges and tolerances (based on: [64])

As a result, intra-day flexibility is no longer completely costless for the shipper. Also, the cumulative peak in the figure illustrates well that this peak intra-day cumulative imbalance can be substantially larger than the end-of-day imbalance that gives cause to balancing charges.

If the balancing period would be an hour, on the other hand, every single bar would represent an imbalance that causes a balancing charge. Within-hour imbalances, not shown in the figure, could still occur, but are expected to be much smaller on a cumulative basis than the cumulative within-day peak.

Taking into account the above definitions, balancing mechanisms can be further divided in regulated and market-based mechanisms. Although regulated charges should reflect the actual balancing costs of the system, these charges do not include, at least not in a public and transparent manner, the costs of the network that have been discussed above. On the contrary, the charges are mostly based on gas prices and often appear to be solely designed to steer shipper behavior with penalties. Moreover, balancing charges that are entirely based on gas-market prices actually imply the impossibility to use line-pack flexibility as a tool to store gas for price arbitrage. Indeed, such balancing charges come down to an obligation for the shipper to have bought or sold all the gas in the pipeline at the gas price of the period, whereas price arbitrage has the objective of trading gas at different prices in different periods.

2.3.3.2 Inadequate cost allocation leads to cross subsidies

The European practice of providing a longer balancing interval and offering free tolerances actually means giving free short-term storage. "Free" in this context means that the costs are socialized in the general transport-network tariff. So, shippers who need more flexibility, especially intra-day, pay less than the costs they cause to the network. Shippers who require less flexibility pay more than the costs caused by their actual use of the flexibility. Consequently, this free line-pack flexibility may inhibit the development of other less-costly short-term flexibility, as will be discussed in section 2.4.

Intra-day flexibility becomes more and more important because of the increasing participation of GFPPs in the gas market. This trend has been observed in recent years and is expected to continue in the next decade [2; 3; 41; 106]. The interdependence of gas and electricity demand profiles [110] through these GFPPs increases the short-term volatility of gas demand. Thus, in a daily balancing model, the flexibility that needs to be provided to accommodate the intra-day demand variability of GFPPs is paid for by all gas shippers, and thus all gas consumers [87; 111]. This cross-subsidization decreases the overall gas-system efficiency and should, therefore, be addressed.

In Figure 15, the changes of hourly gas demand of CCGTs, a particular type of GFPP, are compared with the demand changes of the Local Distribution Zones (LDZ) of the UK.

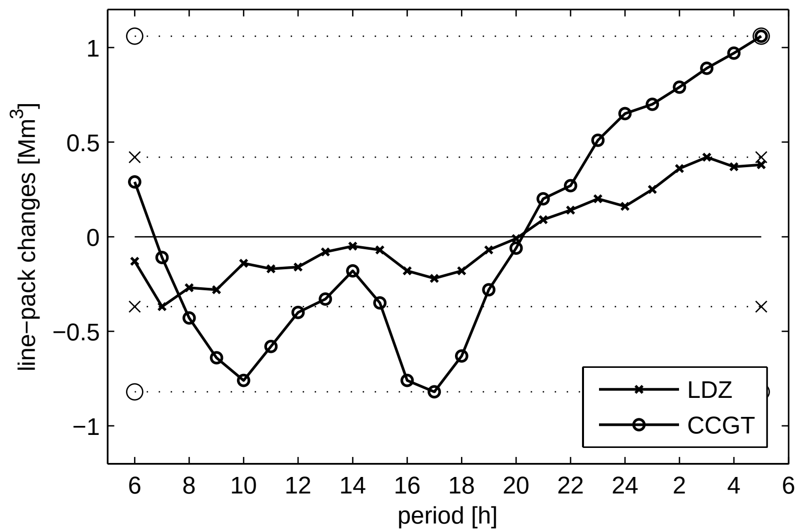

Figure 15. Description of the maximum hourly line-pack depletion for local distribution zones (LDZ) and combined-cycle gas turbines (CCGT, a particular type of GFPP) in UK (2001-2002) (sources: [90; 91])

Note that the changes are much larger for the CCGT demand, with the highest negative disequilibrium (withdrawal exceeds injection) amounting to -0.82 Mm^3, and the highest positive disequilibrium (injection exceeding withdrawal) amounting to 1.06 Mm^3. The respective peaks for LDZ demand are -0.37 Mm^3 and 0.42 Mm^3. The daily swing, then, amounts to 1.88 Mm^3 for CCGTs and 0.79 Mm^3 for LDZ. As the UK balancing charges are based on gas-market prices with a daily reference period, it is clear that the LDZ consumers will pay more for their balancing services due to the flexibility needs of the CCGTs, despite the LDZ not having contributed (as much) to the greater costs for the system.

2.3.4 Conclusion on the value and costs of line-pack flexibility: *ex-ante* balancing vs. *ex-post* balancing

Line-pack flexibility, as argued above, is a pivotal element in balancing gas networks. In many countries, it is the network operator's main tool to perform physical balancing. Implicitly, an imbalance becomes a storage-service contract based on line-pack flexibility between the shipper and the TSO. So, with the current balancing framework in mind, the shipper makes a trade-off between *ex-ante* balancing (contracting flexibility upfront) and *ex-post* balancing (relying on the TSO-balancing mechanism). If contracting flexibility is more expensive for the shipper than paying the balancing charges, the shipper will prefer the implicit pipeline-storage contract. Consequently, the deployment costs and the capacity cost of line-pack flexibility should be properly reflected in the balancing charges in order to target the costs to the actual users of the storage services. As the true balancing cost for the TSO is related to the peak cumulative imbalance within the balancing period, balancing charges should preferably refer back to this intra-day cumulative imbalance. Alternatively, a shorter balancing period allows better targeting of costs to those who cause these balancing costs.

In other words, the balancing rules, tariffs and charges in the European network should take into account the real costs of TSOs to provide network flexibility. This cost-reflection issue becomes even more urgent with the changing gas-demand profile. Indeed, the interaction between the gas and the electricity industry increases intra-day volatility. Nevertheless, in practice, the balancing charges and balancing rules have not been reflecting the long-term network costs, at least not in a transparent way. This is illustrated by the example of the French regulator, who states in its deliberation of March 2009 [112, p. 2] that "*the first conclusions of the study on the gas infrastructures' capacity to satisfy the electricity power stations' requirements for intra-daily flexibility show that GRTgaz ought to find new internal and external sources of flexibility. GRTgaz has indicated to the CRE that these new requests are likely to mean extra operational costs, [which are] not planned in the current tariff trajectory. The CRE is going to consider how to design a regulated offer of intra-daily flexibility for the users in question. Depending on the progress of this work and if the extra costs presented by the TSOs are confirmed, the CRE may make a new tariff proposal, after consulting with all of the players, in the course of 2010.*"[44]

So, the French TSO is concerned that the changing gas demand requires more flexibility. However, the costs of this additional flexibility have not been included in the tariff plan. Hence, flexibility costs cannot be recovered by means of the existing tariffs as these no longer reflect the changed costs.

2.4 The market distorting effects of inefficient regulation of pipeline flexibility

The choice between balancing *ex ante* or balancing *ex post* implies that line-pack flexibility not only affects the availability of transport capacity through the trade-off mechanism explained in the previous sections, but it also affects the market for other flexibility tools and even the spot market.

[44] In April 2011, GRTgaz started his "Intraday Flexibility Contract", specifically for high modulation sites like combined-cycle gas turbines (CCGT) [113; 114].

Cost allocation and cost reflection are both cornerstones for dealing with line-pack flexibility. A discrepancy in the tariff for the pipeline-flexibility service, bundled or unbundled with the transport service, in relation to its true costs, can negatively affect two parts of the gas industry: the regulated part by allocating costs regardless of the consumer preferences, and the potentially competitive part by building an uncompetitive product regardless of its real cost.[45]

ERGEG [108, p. 19] has stated: "*Economically, the cost for balancing the transmission network should be made where balancing can be done the cheapest. In other words, the penalties should reflect the actual and efficient cost of balancing the system.*" Economic efficiency is only achieved if the balancing service is provided by whoever can produce the service at the lowest costs. However, in a liberalized market the players' decisions are not centralized. So, only if the prices/tariffs reflect the real costs, the players will make the right decisions, and the least expensive balancing tools will be developed.

If cash-out charges and penalties are high enough, e.g., GFPPs may rely less on *ex-post* balancing. Indeed, they may prefer to contract more *ex-ante* flexibility or buy more *ex-ante* network services to allow the revision of their nominations (e.g., hourly) in order to meet their obligations as well as to minimize their costs associated with balancing charges.

2.4.1 Distorting effect on the regulated infrastructures

Nowadays in the EU gas market, the pipeline flexibility is either unbundled or bundled with other transport services according to the balancing rules. Furthermore, it is subject to regulated prices according to the balancing tariffs, which are usually linked to a commodity price. As was demonstrated earlier in this chapter, these rules and tariffs need to take into account not only the commodity price, but the actual balancing cost of the TSO. This cost is thus dependent on the infrastructure that has to be committed to flexibility in order to cover the peak cumulative imbalance within the balancing period. Otherwise, perverse incentives can be spread to the transport market and flexibility market. Summarizing, the TSO has to make a trade-off between offering time flexibility and selling transport capacity, and the shipper makes a trade-off between *ex-ante* and *ex-post* balancing. And both trade-offs are interdependent.

The often applied pricing solution of a single regulated tariff for the bundled service is not cost reflective as the pipeline-capacity commitment to the buffer function is not taken into account. Hence, all network users end up paying for the network-flexibility needs caused by a specific group of users. The bundled-service tariff is not

[45] Because the capacity costs are not attributed to the flexibility function of the pipeline, line-pack flexibility might be built, even if other flexibility products might have lower costs.

only inefficient, but it prevents the provision of clear market signals for investment in transport services.

2.4.2 Distortion of the competitive markets

According to the IEA [31], liberalized gas markets rely on both new market mechanisms and traditional flexibility tools, meaning supply and demand adjustments and storage mechanisms, to match demand and supply over different time horizons. In the same report, the IEA stresses that flexibility is an absolute requirement for the efficient functioning of the gas market. Table 2 in Chapter 1 provides an overview of flexibility tools that can be used for balancing in different EU countries: line-pack flexibility and storage are available in almost all countries. However, the availability of a tool does not imply its actual application for balancing.

The choice for the most efficient tool, then, should be based on the tool's economic costs and benefits and not on the balancing rules without any economic justification. This unjustified obligation to balance with a particular tool is happening in Italy with storage [74], in Spain with LNG [109], and in most (if not all) EU countries with line-pack flexibility. The misallocation of network flexibility does not only provide wrong incentives in the transport service as discussed above, but also in the other segments of the gas industry that are able to deliver short-term flexibility: the spot market and the flexibility market.

2.4.2.1 The spot market

According to the IEA [31], market mechanisms are still the common flexibility providers in most product markets. In the European gas sector, however, complete reliance on only the commodity-market mechanism for the balancing of demand and supply has not yet been applied; presumably because it has high social costs. These social costs have been explained in the literature by the analysis of the transaction costs along the industry value chain or by looking at the small price elasticity of demand and supply [26; 33; 115-122].

Furthermore, in that same literature, it has been underlined many times that various parts of the gas industry chain are subject to high asset specificities [26; 33; 115-120].[46] Economically, this asset specificity implies that the transaction costs of market coordination are increasing and that the market players are driven to other mechanisms to coordinate the supply of services.

[46] Asset specificity refers to the value that an asset has for a specific purpose, but a much lower value in any other context: e.g., a gas pipeline between Russia and Germany is only useful to transport gas between these countries. It cannot be used differently and generate the same value. Other coordination mechanism than the market are, e.g., long-term take-or-pay contracts (see footnote 4).

The small price elasticity of supply and demand impedes the market price to achieve the equilibrium where the cost of production would be equal to the value of demand, at least in the short term. The EC [121] has reported that the demand elasticity is dependent on the consumer category and the availability of multi-fuel installations. Furthermore, Stern [122] has demonstrated that even the demand of the consumer category with the highest elasticity has not been able to respond according to expectations, to the recent price increase in Europe.[47]

Therefore, it can be assumed that the *ex-ante* gas market is not a sufficient tool to balance supply and demand in the short term. However, the inadequate pricing of *ex-post* balancing possibly even contributes to the low liquidity in the spot market if the shipper is better off at trading within the balancing-mechanism framework than on the spot market. On the supply side, domestic production (e.g., in Norway, the UK and the Netherlands) is the main source of flexibility as has been shown by Lapuerta [90] and Creti [116]. Most of the EU countries have no or very little domestic gas. Hence, production cannot be considered a fundamental tool for gas-system balancing.

The gas imported from distant sources through very long pipelines can bring some flexibility [123]. However, the cost of this flexibility is subject to the same trade-off between pipeline transport and pipeline storage that has been described earlier in this chapter. Moreover, reduced transport capacity in long-distance pipelines may have even higher opportunity costs due to the high investment costs that are involved.

LNG is claimed to be another major source of flexibility allowing a decrease of contract rigidity as demonstrated by Neuhoff and von Hirschhausen [124] and allowing more arbitrage as explained by Zhuravleva [125]. However, LNG is still small business in comparison to pipeline gas and it remains a costly tool. And these costs will be taken into consideration at the time of a flexibility-investment decision.

The current regulation of line-pack flexibility, thus, distorts the gas spot market and makes it less attractive to rely on, providing a further argument for other coordination mechanisms like long-term contracts. However, a better regulation of the network flexibility can enhance spot-market trade, and, thus, reduces the need for other mechanisms.

2.4.2.2 The flexibility market: fast-cycling storage

Pipeline storage differs from traditional underground storage, which usually has a business model with a longer-term profile and is dedicated mainly to seasonal needs. These underground storages, e.g., depleted gas fields or aquifers, typically have

[47] Stern refers to customers that can invest in fuel-switching capabilities in the short term and concludes that those users that have not invested yet in this flexibility are unlikely to do this in

lower injection and withdrawal rates and large storage capacities. Consequently, they allow only one or a few cycles (meaning a switch between loading and unloading of the facility) per year. Pipeline storage, on the other hand, has a daily cycle and very high deliverability, but is limited in working volume [126].

Pipeline storage answers the need for higher-frequency balancing, as explained by the EC's DG Transport and Energy [123, p. 69]: "*High-frequency optimisation, i.e. optimisation on a daily basis can be regarded as fine-tuning of the stock level. Short term optimisation allows gas market agents to utilise the price differences that exist on a day-to-day basis.*" Still according to the same report, the salt caverns and LNG-peak-shaving facilities are the most flexible types of storage because they have higher withdrawal and injection rates compared to aquifers and abandoned fields, but also higher costs. The real cost of a specific storage facility is strongly case dependent.

So, pipeline storage is in competition with these fast-cycling storage facilities. The offer of pipeline flexibility is basically a regulated decision, whereas the demand for it depends on the "tariff" to use this flexibility service and on the costs of the other flexibility sources. In order to have an efficient mechanism of storage selection, especially concerning the short-term storage, the tariffs should reflect the costs of line-pack flexibility. If the line-pack storage is free to shippers in the short term, they will not have any interest to contract other kinds of storage that can be used with the relevant frequency. In other words, the potentially competitive storage market can be distorted because the actual line-pack flexibility costs are carried by the transport network and are socialized by means of transport tariffs, meaning that shippers with a flatter profile subsidize shippers with more volatile consumers in their portfolio [111].

2.4.3 Policy recommendations

Line-pack flexibility, thus, is valuable for balancing the gas system, but its current regulation through the network code and balancing rules distorts the liberalized gas market. Ideally, the regulation of network-flexibility services should be separated from the regulation of transmission services. Indeed, transport is a regulated monopoly in Europe, but flexibility is part of (potentially) competitive market.

The network flexibility, therefore, should be marketed as *ex-ante* flexibility at a price determined through a market mechanism. However, to correctly distribute the pipeline costs between its transport and its flexibility functions, further research is necessary on the cost decomposition of the gas infrastructure, both regarding its short-term and its long-term costs.

the face of short-term price peaks.

2.5 Summary, conclusions and recommendations on regulation of network flexibility

This chapter states that line-pack flexibility is an important balancing tool with an economic value and cost for different actors. This cost has been demonstrated to relate to the amount of capacity that has to be committed to flexibility. And this amount is dependent on the swing between peak cumulative imbalances throughout the balancing period. However, current gas regulation does not properly take into account these actual costs of line-pack flexibility. The subsequent inadequate regulation results in market distortions in the regulated transport market, the competitive spot market and the market for *ex-ante* flexibility, which is at least potentially competitive. By not considering the actual costs of line-pack flexibility, policy makers neglect the market-impeding role of an imperfectly regulated pipeline-flexibility service in the choice of the shipper between *ex-ante* and *ex-post* balancing.

In other words, the balancing service offered by the line-pack flexibility is a valued service. If its cost is socialized, especially by means of the transport tariffs, there is a tendency to have an "over-demand" of line-pack flexibility and an "under-demand" of transport because the regulated price passes on the costs to all consumers and not to the actual users of the flexibility. If the flexibility demand by the shippers is heterogeneous, this situation becomes even worse because the flat consumers (requiring no investment in pipeline flexibility) will subsidize the gas-transport network required by unbalanced shippers (actual users of pipeline flexibility).

The competitive market-based solution consists in taking away line-pack flexibility from the regulated TSO and including it in the *ex-ante*-flexibility market. The price for line-pack flexibility would be set by the marginal unit of flexibility contracted by the market players in a way comparable to the merit curve that is used for unit commitment and economic dispatch in electricity generation systems.

This chapter further demonstrates that gas dynamics behind line-pack flexibility makes the complete separation from pipeline transport and pipeline flexibility unlikely. The work in this chapter takes the first steps to a different way of calculating a regulated tariff. Because several gas-system and gas-market aspects have to be taken into account, the correct pricing of line-pack flexibility, which is a second product offered by the monopoly gas network, is non-trivial. The traditional methodologies to set tariffs for monopoly infrastructures, like Ramsey pricing, cannot be applied, due to the flexibility product being actually part of an oligopoly market. In this context, the trade-offs and related opportunity costs constitute a framework for policy makers to take into account the costs of line-pack flexibility in the overall network system. Moreover, the price of line-pack flexibility in a settlement mechanism with a formal balancing period should refer to the maximal swing within the formal period. Alternatively, a shorter balancing period leads to a better link between the actual balancing costs and those instigating that cost.

Furthermore, the regulated decision to offer more or less line-pack flexibility should be based on the real network costs and benefits. As there is a trade-off for the TSO between offering transport capacity and offering time flexibility, an additional unit of flexibility comes at the cost of decreased available transport capacity. This cost can be measured by comparing the costs of transport-capacity availability with more or less bundled flexibility.

As the evidence in this chapter illustrates, further research is required to develop a deeper understanding of the complex interactions between the network flexibility, the flexibility market, the short-term contracts and the flexibility clauses of the long-term contracts and the spot market. The calculation of the identified inefficiencies in practice would give a better insight into the money on the table, but is left for further research.

3. THE IMPACT OF IMPERFECT WIND PREDICTABILITY ON GAS BALANCING[48]

This chapter explores the impact of the increasingly unpredictable electricity-generation system on the balancing of the gas system. It starts by describing the challenges introduced in the electricity system through intermittent – a concept that combines variability and unpredictability [128] – and non-dispatchable renewable energy sources (RES), and the transfer of flexibility needs to the gas system through the dispatching of GFPPs. Second, an operations-research model of the operational gas system is introduced. This model allows studying balancing-mechanism design in a short-term operational context. Third, the model is then used to study the effects of wind-power prediction errors on gas balancing. Conclusions, then, are derived regarding the design of gas-balancing mechanisms at the end of this chapter.

Figure 16 and Figure 17 schematically represent the balancing problem that is discussed in this chapter. Wind power is thus unpredictable and variable and is often balanced by GFPPs. So, the transfer of flexibility needs from the electricity-generation system to the gas system introduces a "new" unpredictable gas demand to the "historic" more-predictable or better-understood gas demand. This is represented in Figure 16 by the two possible demand profiles that result from different forecast errors, whereas only one supply can be committed by the wind shipper. The "wind shipper" is defined as a shipper who only has GFPPs in his portfolio and who balances wind in the electricity-generation system. The "historic shipper" serves industrial customers. Disregarding *ex-ante* flexibility, the system imbalances become larger and possibly more volatile because of this new demand. And the *ex-post* balancing will have to reflect this.

[48] Much of this material has been submitted for publication: Keyaerts, N., Rombauts, Y., Delarue, E., D'haeseleer, W., 2012. Impact of unpredictability on gas-balancing design in Europe [127]. The electricity part was modeled by Rombauts and served as input for the main discussion on gas balancing by Keyaerts.

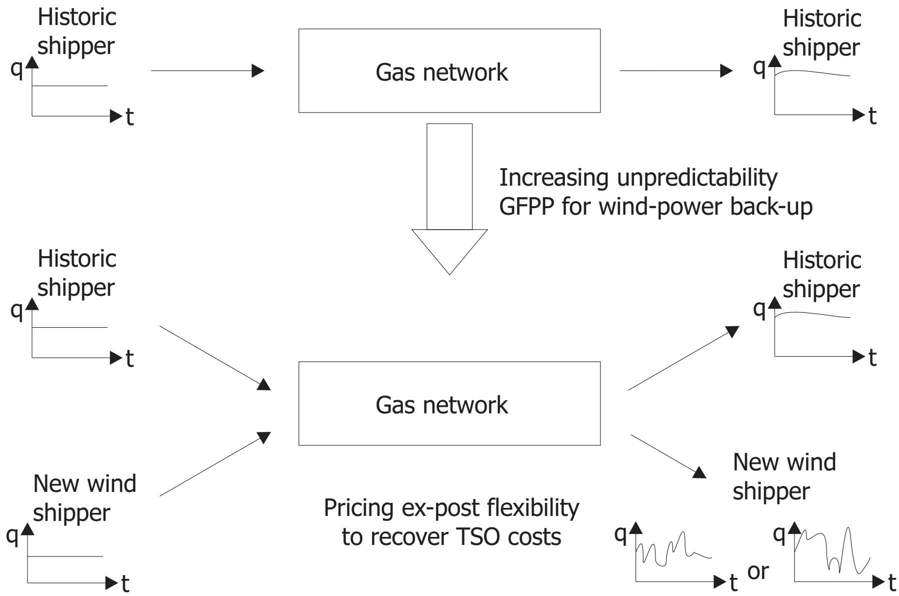

Figure 16. Schematic overview of shipper balancing: the increasing share of unpredictable gas demand changes the balancing costs and, thus, the settlement of ex-post balancing for the historic shipper (serving industrial demand) and the new wind shipper (serving CCGTs that balance wind in the electricity-generation system); in the graphical illustrations of demand and supply, "q" stands for an amount [Mm^3/h, to be integrated over the period's length] and "t" stands for the hourly time periods [h]

First, the TSO-balancing problem is examined (Figure 17). The dispatching of network and storage flexibility by the TSO is optimized for several deterministic system-imbalance profiles. These imbalances are a function of assumed wind-forecast errors that transfer into the wind-related gas demand. The TSO's balancing costs, then, are derived from the system-flexibility dispatching. The second part of the problem focuses on the recovery of these costs through the settlement mechanism for *ex-post* balancing (Figure 16). The TSO can use different pricing mechanisms to recover balancing costs and these design options have different effects on the shippers and on the sustainability of the settlement mechanism.

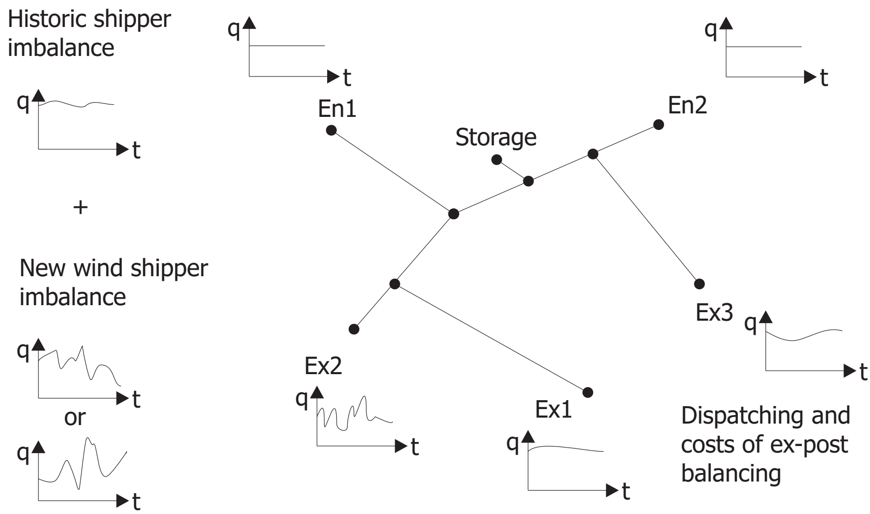

Figure 17. Schematic overview of TSO balancing: the TSO faces possibly larger and more volatile system-imbalance profiles as new shippers with unpredictable demand enter the system; system-flexibility dispatching and resulting balancing costs are determined for different scenarios regarding the shipper's demand-forecast error; En. and Ex. represent entry and exit points, respectively; in the graphical illustrations of demand, supply and imbalance, "q" stands for an amount [Mm^3/h, to be integrated over the length of a period] and "t" stands for the hourly time periods [h]

3.1 Interactions between electricity and gas systems

Wind power has zero marginal costs and as such replaces other electric power plants in the dispatching order [129; 130]. Nuclear, conventional coal and combined-heat-and-power (CHP) plants typically make up the main part of base-load generation. GFPPs mostly run as mid load and peak load, although efficient CCGTs can enter base load depending on the relative gas-to-coal price and a possible CO_2 price [129]. Hydro can be base load according to its marginal costs, but its operational flexibility makes it a useful technology to act, e.g., as storage (if a dam is present) to cover peak electricity demand. Climate and safety concerns deteriorate the image of coal and nuclear, respectively, whereas the abundance of recoverable shale gas and the surge of LNG facilities improve the outlook of natural gas as a lasting and increasing part of the energy mix [3; 41].[49]

[49] The outlook of gas improves in two ways: first, additional gas molecules can be delivered anywhere around the world; second, more gas lowers future gas prices, moving gas into a more comfortable competitive position relative to other depletable and non-depletable resources.

Moreover, gas-fired electric power generation suits the requirements imposed by massive integration of wind power that is dependent on variable and unpredictable wind speeds. This increasing electric-power-generation volatility needs flexible reserves as back up for which gas-fired technology is the prime candidate. Indeed, lower investment cost, favorable CO_2-emission characteristics, flexible operability and a relatively short lead time between final investment decision and actual operation of a plant make CCGT an attractive technology [3; 41; 131; 132].[50] Current high fuel prices in Europe represent a downside of CCGT technology, but the worldwide development of shale gas and the LNG market may change this. Furthermore, the inclusion of CO_2 prices improves the relative fuel cost compared to, e.g., coal-fired electric power plants.

Wind power, then, replaces (part of the) base load with CCGTs serving as its back-up power like communicating vessels: ramping up when wind speeds are low, ramping down when much wind is present and again ramping up when the wind speeds exceed the cut-off level beyond which the wind-power unit is shut down as is illustrated by the wind-to-power curve in Figure 18. Note that other electricity-balancing tools exist: e.g., demand-side response and hydro-pump storage. They are not further considered in this work, though.

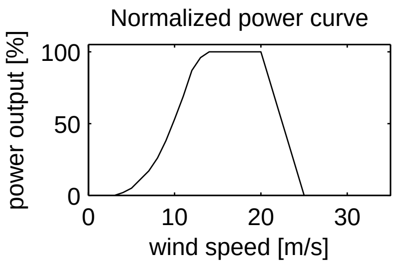

Figure 18. Normalized power curve: wind-turbine power output [% power capacity] is 3rd power function of the wind speed [m/s] between the cut-in speed (3.5 m/s) and the speed of maximum output (about 14 m/s), at higher speeds the output remains flat until the cut-off speed (20-25 m/s) beyond which the output drops from the maximum to 0 [133]

Consequently, the flexibility needs of the electricity-generation system are (partly) transferred to the gas system, imposing a need to allocate system-flexibility costs to the users thereof. Balancing-responsible shippers can rely on the *ex-post* balancing services provided by the gas TSO or they can take measures to contract *ex-ante* flexibility services [48]. Pivotal to this choice are the gas-balancing rules that have to

[50] Open-cycle gas turbines (OCGT) are actually providing more dispatching flexibility as that technology allows even higher ramping rates than CCGTs. However, for the conceptual analysis in this chapter, CCGTs have been chosen arbitrarily as the considered GFPP technology.

allocate the system costs to the unbalanced party, on the one hand; and incentivize shippers to balance beforehand, on the other hand. The addition of wind power and its interaction with mainly GFPPs changes the gas-demand characteristics. It will be demonstrated that some current balancing-mechanism designs become impractical (and on the long term maybe unsustainable) to deal with this changing gas demand.

The role of gas and wind in the power-generation mix has been underlined many times in the literature. Delarue et al. [134] have demonstrated that for electricity systems with a diverse generation mix, wind power mainly interacts with GFPPs. The Spanish electricity system with its massive amount of wind power has been shown to strongly rely on CCGT-related flexibility to deal with rising electricity-generation volatility [135]. The expected impact of massive wind-power integration on the UK gas network has been found to come down to more CCGTs operated in a flexible way and results in big line-pack swings, more gas-compression-power consumption and more overall gas use for electric power generation [136]. Furthermore, concerns are raised in that study by Qadrdan et al. [136] regarding very rapid depletion of the line-pack buffer if the "wrong" circumstances occur: a combination of low wind-power output, peak electrical gas demand and peak non-electrical gas demand. In a way, massive wind power is crowding out other electricity-generation technologies in favor of more flexible gas in terms of new capacity added (MW). Moreover, long stretches of cold weather, and thus high heating demand, often coincide with periods of low wind speeds. The effective number of operating hours of CCGTs, and thus the number of MWh produced per year , on the other hand, is said to rise by some studies, e.g., [131], whereas other studies argue the effective running hours of flexible CCGTs, or GFPPs in general, will go down, e.g., [132]. Nevertheless, gas' qualification as "fuel of consequence" is justified.

The argumentation above makes clear that the gas demand related to electric power generation is changing, even though this impact should not be overestimated either [132]. The fuel needs become intermittent, introducing additional variability and unpredictability in the gas demand. Hallack [27] extensively discusses the changing needs of the gas network imposed by these new demand characteristics of increasing gas-fired electric power. In the new gas market, short-term flexibility, exchangeability and storability (for short periods) are the keywords and the regulatory framework for gas-infrastructure development has to respond to these needs. The French regulator also has raised concerns about the surge of GFPPs, especially in the field of daily balancing of the gas loads [87; 112]. Indeed, the balancing of gas supply and demand on an hourly and daily basis becomes more challenging because the flexible dispatching of GFPPs coincides with strongly varying gas needs: when ramping up a CCGT, gas withdrawal soars instantly, whereas the ramping down requires gas flows to drop almost instantly. Evidently, the management of pressure in the pipelines can deliver the needed flexibility. Yet, pipeline-based flexibility is limited in volume and can only be used for short-term storage [48].

The deployment of line-pack flexibility is not limited to a specific kind of gas demand, but evidence from the UK suggests that flexible CCGTs cause higher swings in the line pack, defined as the amplitude between the maximal and minimal line-pack level over a gas day, than the residential sector [48; 90; 91]. This was not perceived as very troublesome because the share of electric power generation in the European gas demand has been relatively low. Germany, Italy and Spain, however, show a remarkable growth of gas consumption in the electric power sector over the last decade [137; 138]. Although smaller in absolute numbers, a similar trend can be observed in the other European countries as well, the exception being the UK, which remained more or less stable because its "dash for gas" already started in the late 80s and early 90s [139]. Moreover, power generation is projected to remain the main driver of growth in future (European) gas demand [3; 41]. Consequently, the short-term gas-flexibility needs of the electric power sector will become a big issue.

The effect of wind-power variability and unpredictability on the electricity system has also been studied extensively, e.g., [140-143], but the impact of massive integration of these intermittent RES on the load balancing of the gas system is less studied, e.g., [136]. The flexible dispatching of GFPPs to compensate for wind power causes physical changes in the line pack, on the one hand; whereas the gas-settlement mechanism deals with the economic implications of load balancing, on the other hand. To the extent that variability is predictable, gas shippers can commit flexibility beforehand reducing the physical system imbalance that actually causes balancing costs for the gas-transmission-system operator. Wind-power output, nevertheless, is subject to forecast errors, which have a big impact on the electricity-system planning [131]. Therefore, gas-system flexibility is still required to handle unforeseen CCGT dispatching. Imbalance settlement, then, can be done either according to a market-based mechanism or a non-market-based mechanism. Both options will be examined below for increasing unpredictability of gas demand, applying the electricity-generation concepts "unit commitment" and "power dispatching" to the gas system. First, an operations-research model of the gas system is introduced.

3.2 GASFLEX: a model to study operational balancing and flexibility from different viewpoints[51]

Operations-research models are useful tools to support decision making as they rely on the optimization of a cost function, which can take many forms, while accounting for constraints that are defined by the problem under investigation. In this thesis, a multi-period shipper-portfolio-optimization model and gas-network-optimization model are presented, together referred to as "GASFLEX". The shipper problem (Figure 2) and the TSO problem (Figure 3) are solved sequentially. Constraints represent the physical and contractual relationships of the gas industry in the short term, whereas the objective functions go from maximizing shipper profits, to minimizing system-balancing costs. Other objective functions could be defined to study other effects, e.g., minimizing imbalance volumes.

3.2.1 Overview of existing gas models and their applications

The gas industry is often used as the subject of optimization models because the non-linear relationship between pressure and flow constitutes a mathematical challenge. The literature on gas modeling, thus, is extensive and a complete overview of it is beyond the scope of this chapter. Nevertheless, this section presents a brief overview of existing models; for a more elaborate overview, see, e.g., [145-148]. Midthun [147] classifies gas models according to their main object as *investment models*, *value-chain models*, *equilibrium models* and *transport models*.

Investment models take a long-term perspective and look at, e.g., sizing and designing the gas-pipeline network [149-151]. *Value-chain models* typically simultaneously optimize production, storage, transport and sales along the gas-supply chain taking a long-term or short-term perspective [145]. An example of an operational value-chain model that integrates a fairly detailed transport model is Selot et al. [152], and Bopp et al. [153] integrates stochastic optimization along the value chain. *Equilibrium models* focus on strategic interactions between multiple market actors, usually on the long term [146; 154-157]. *Transportation models* focus on the optimal use of the gas network, minimizing compressor costs while taking the non-linear flow equation into account. These transportation models can be further divided in *steady-state models* [158; 159] and *transient models* [160; 161]. The former have time steps of days or longer, whereas transient optimization focuses on short time steps, e.g., hourly optimization. Gas-transportation models have also been integrated with electricity models by Unsihuay et al. [162] or Chaudry et al. [163]. The gas part of the model in Chaudry et al. [163] shows similarities to the model

[51] The material discussing the GASFLEX model has been published as a Working Paper: Keyaerts, N., 2012. Using operations research to study optimal use of flexibility in liberalizing

presented in the next subsections, but has been used with a different finality. Indeed, in that work, network adequacy is studied for high levels of wind penetration [136]. Finally, imbalance settlement has been modeled by Kalashnikov et al. [28] and Kalashnikov and Ríos-Mercado [29] as a strategic bi-level game between a shipper and a TSO focusing on contracts and taking the settlement design as given.

Midthun et al. [47] have demonstrated that even in models with an economic baseline, technical aspects, and in particular network effects, cannot be disregarded. On the other hand, the detailed modeling of the non-linear and non-convex transportation problem can cause computational difficulties and numerical instabilities.

The model used in this thesis combines short-term shipper-portfolio optimization (value chain) and transport-system optimization with a focus on settlement costs and balancing costs, respectively. As the ultimate objective of the models comes down to studying the effects of different balancing designs, economic applicability of the model has to be balanced with technical accuracy. The role of line-pack flexibility in balancing the system, for instance, requires a transient model, but such detailed flow development would make the model too rigid for its purpose in this thesis.

3.2.2 Shipper-portfolio optimization: contractual

The shipper-portfolio optimization is modeled as a mixed-integer-linear-programming (MILP) problem. In it, the shipper maximizes his profits by calling gas ($\dot{V}buy$, Mm^3/h) through his upstream contracts and selling it to his customers ($\dot{V}sell$, Mm^3/h).[52] Gas demand is assumed to be exogenous. This assumption can be relaxed by the introduction of flexibility, e.g., from interruptible-delivery contracts. The gas-supply contract is built as a contract that enables the shipper to call gas within specified contract limits for minimum and maximum offtakes. Moreover, the supply rate is assumed to be flat throughout the gas day. Therefore, intra-day flexibility has to come from separate flexibility contracts ($\dot{V}flex$, Mm^3/h) like fast-cycling storage or spot-market transactions.[53] The shipper can also rely on *ex-post* balancing by the TSO and choose to pay balancing charges for his recorded imbalances ($\dot{V}imb$, Mm^3/h).

gas markets: GASFLEX. TME Working paper series. University of Leuven (KU Leuven) Energy Institute [144].

[52] The quantities, listed here in physical power units, are consistent with energy since the flow rates have to be interpreted as averages over the time step that have to be multiplied with this time step, which is one hour (*h*), returning energy units, Mm^3.

[53] Note that spot-market transactions also have a flat flow rate over the duration of the contract. So, buying gas for delivery the next day means a constant flow rate throughout the next day, but shorter term products, e.g., delivery the next hour, can be used for modulation purposes by the shipper.

3.2.2.1 Shipper model

The shipper-profit function, Eq. (3.1), consists of revenues from sales minus acquisition costs, *ex-ante*-flexibility costs and *ex-post*-balancing costs:[54]

$$\max profit = \begin{pmatrix} \sum_h ps_h \cdot \dot{V}sell_h - \sum_h cb_h \cdot \dot{V}buy_h \\ -\sum_h cf_h \cdot \dot{V}flex_h - imbcost \end{pmatrix} \tag{3.1}$$

These balancing costs (*imbcost*) are dependent on the settlement mechanism and are further defined below in Eq. (3.11). The unit prices of selling and buying gas are represented by ps_h (EUR/m^3) and cb_h (EUR/m^3), respectively, and cf_h (EUR/m^3) gives the unit cost of *ex-ante* flexibility.

Every time step h (usually the time step is an hour) conservation of energy has to hold, meaning that the shipper portfolio has to balance as in Eq. (3.2):

$$\dot{V}buy_h + \dot{V}flex_h - \dot{V}sell_h = \dot{V}imb_h \tag{3.2}$$

Where:

$\dot{V}buy_h$	shipper's called supply rate [Mm^3/h] in period h
$\dot{V}sell_h$	shipper's demand rate [Mm^3/h] in period h
$\dot{V}flex_h$	shipper's called *ex-ante* flexibility [Mm^3/h] in period h, positive for upward flexibility, negative for downward flexibility
$\dot{V}imb_h$	shipper's reliance on *ex-post* flexibility [Mm^3/h] in period h, positive for surplus, negative for deficit

In Eq. (3.2), the imbalance term reflects surplus gas buffered by the TSO if it is positive and a gas deficit covered by the TSO when it is negative. In the same way but with opposite signs, positive values of $\dot{V}flex$ reflect upward flexibility for the shipper, e.g., withdrawing gas from storage, whereas negative values represent downward flexibility, e.g., injecting gas into storage for later use.

Gas sales have to meet exogenous *demand*: either the expected demand (*E(demand$_h$)* with "*E*" standing for expected) in the "unit-commitment" phase (UC), as expressed by Eq. (3.3), or the actual demand during the "power-dispatch" phase (PD), shown in Eq. (3.4).

$$UC\ phase:\ \dot{V}sell_h = E(demand_h) \tag{3.3}$$

$$PD\ phase:\ \dot{V}sell_h = demand_h \tag{3.4}$$

[54] Only short-run variable costs are considered on the operational horizon of this model, meaning that possible capacity-reservation costs are assumed to be sunk costs that have been paid beforehand, e.g., as socialized costs in the general transport-capacity tariff.

The supply contract is modeled by Eqs. (3.5)-(3.6), which enforce a flat supply profile throughout the gas day, with the flow rate between the contractual minimum (*buy_min*) and maximum (*buy_max*), respectively. *card(H)* represents the total number of time steps within the gas day and equals 24 for hourly time steps.

$$\dot{V}buy_H = \frac{\sum_h \dot{V}buy_h}{card(H)} \tag{3.5}$$

$$buy\_min \leq \dot{V}buy_h \leq buy\_max \tag{3.6}$$

Flexibility is available within the limits of the flexibility contract. In the case of storage flexibility, the stored volume (*Vstock*, Mm^3) is limited by the booked storage capacity:

$$0 \leq Vstock_h \leq flex\_cap \tag{3.7}$$

With:

$Vstock_h$ shipper's level of stored gas [Mm^3] at the end of period *h*

The flexibility rates cannot exceed contract limits for injection (*flex_min*) and withdrawal (*flex_max*):

$$flex\_min \leq \dot{V}flex_h \leq flex\_max \tag{3.8}$$

In the case of storage, the flexibility flow rate also represents the change of the flexibility volume between time steps *h* and *h–1*:

$$Vstock_h - Vstock_{h\text{-}1} = \dot{V}flex_h \tag{3.9}$$

Similarly, Eq. (3.10) relates the hourly imbalance changes ($\dot{V}imb$) to the imbalance-account positions (*Vimbacc*, Mm^3) at time steps *h* and *h–1*. Therefore, this imbalance account reports the cumulative use of the balancing mechanism throughout the day, with the final value (*h=card(H)*) representing the end-of-day imbalance of the shipper.

$$Vimbacc_h - Vimbacc_{h\text{-}1} = \dot{V}imb_h \tag{3.10}$$

$Vimbacc_h$ level of cumulative imbalance [Mm^3] by the shipper at the end of period *h*

Imbalance costs for the shipper depend on the settlement mechanism that defines the cash-out fees and due penalties because of imbalanced positions:

$$imbcost = \begin{pmatrix} F1 \cdot Vimbacc_H + \sum_h F2_h \cdot \dot{V}imb_h \\ + F3 \cdot \max_h(Vimbacc_h) + F4 \cdot \min_h(Vimbacc_h) \end{pmatrix} \tag{3.11}$$

In Eq. (3.11), *F1* to *F4* stand for imbalance-tariff fees for the end-of-day imbalance (*F1*), the hourly imbalances (*F2*) and fees for peak cumulative long (*F3*) and peak cumulative short (*F4*) positions, respectively. Behind these tariffs can be stepwise cost functions, e.g., offering a tolerance for the first part of the imbalance and increasingly higher penalties for bigger imbalances (see section 1.2.3). The actual imbalance-cost function, thus, depends, on the tariff structure of the modeled settlement mechanism.

3.2.2.2 Model application

The output of this shipper optimization serves as input for the technical model that is the subject of the next section. Indeed, the aggregated shipper nominations make up the *a priori* nominations and *a posteriori* allocations for entry and exit in the gas network. The *a priori* optimization is done by the shipper to decide on the "unit commitment", meaning the amount of gas to be called from the supply contracts to meet expected demand, which is the best forecast available. Further optimizations are then carried out accounting for this committed gas, meaning that only flexibility can be used to adapt to better demand forecasts. The final optimization of the shipper, then, concerns the actual "gas power dispatching" when no more changes are possible to the nominations. Indeed, nominated quantities become allocated quantities that are used by the TSO for imbalance settlement.

3.2.3 TSO-system optimization: technical

The TSO receives the hourly flow programs of the individual shippers (output of the shipper optimization discussed in the previous section) and has to execute the requested transport services using the compressors and the pipelines.

The network model is basically composed of nodes *i*, *j*... and pipelines *a(ij)* connecting the nodes *i* and *j*. First, the network and time constraints of the gas system are presented, followed by the technical relationships that describe the gas dynamics. Next, the shipper-related constraints are introduced and the objective function is defined.

3.2.3.1 Network and time constraints

The transportation of gas is subject to the law of conservation of mass. Therefore, nodal balance is enforced by Eq. (3.12), which states that for every node *i* and for every period *h*, gas leaving a node (left-hand side) is equal to gas entering that node (right-hand side):

$$\begin{aligned} &\dot{V}ex_{h,i} + \dot{V}flexdown_{h,i} + \dot{V}inj_{h,i} + \sum_{h,j}^{A^{out}(i)} \dot{V}i_{h,a(ij)} \\ &= \dot{V}en_{h,i} + \dot{V}flexup_{h,i} + \dot{V}wd_{h,i} + \sum_{h,j}^{A^{in}(i)} \dot{V}j_{h,a(ji)} \end{aligned} \tag{3.12}$$

Where:

$\dot{V}en_{h,i}$	gas-entry rate [Mm^3/h] at node *i* in period *h*, e.g., production
$\dot{V}ex_{h,i}$	gas-exit rate [Mm^3/h] at node *i* in period *h*, e.g., demand
$\dot{V}flexup_{h,i}$	upward flexibility [Mm^3/h] at node *i* in period *h*, gas is added to the pipeline system (e.g., activation of interruptible demand)
$\dot{V}flexdown_{h,i}$	downward flexibility [Mm^3/h] at node *i* in period *h*, gas is removed from the pipeline system (e.g., injecting in a storage facility)
$\dot{V}inj_{h,i}$	storage-injection rate [Mm^3/h] at node *i* in period *h*
$\dot{V}wd_{h,i}$	storage-withdrawal rate [Mm^3/h] at node *i* in period *h*
$\dot{V}i_{h,a(ij)}$	volume-flow rate [Mm^3/h] leaving node *i* on line *a(ij)* during period *h*
$\dot{V}j_{h,a(ji)}$	volume-flow rate [Mm^3/h] entering node *i* on line *a(ji)* during period *h*
$A^{in}(i)$	subset of pipelines *a(ji)* arriving in *i*
$A^{out}(i)$	subset of pipelines *a(ij)* departing from *i*

Besides a spatial balance, the gas system is also subject to a temporal balance by means of line-pack balance and storage balance, defined in Eqs. (3.13) and (3.14), respectively.

$$Vlp_{h,a(ij)} - Vlp_{h\text{-}1,a(ij)} = \dot{V}i_{h,a(ij)} - \dot{V}j_{h,a(ij)} \tag{3.13}$$

$$Vsto_{h,i} - Vsto_{h\text{-}1,i} = \dot{V}inj_{h,i} - \dot{V}wd_{h,i} \tag{3.14}$$

Where:

$Vlp_{h,a(ij)}$	line-pack level [Mm^3] of pipeline *a(ij)* at the end of period *h*
$Vsto_{h,i}$	level of physically stored gas [Mm^3] in node *i* at the end of period *h*

Both constraints state that the buffered level of gas, either in the pipeline or in a storage facility, at the end of a period is equal to the level at the end of the previous period plus the net inflow into the buffer. Starting levels (*h*=0) have to be fed to the model to determine the start state; and boundary conditions for the end state (*h*=*card(H)*) of the line pack and storage can easily be added as well.

3.2.3.2 Model of gas dynamics

The pipeline-flow dynamics is modeled in a similar way as has been done in [163], but GASFLEX also borrows from the formulation in [159]. Note that the model of the gas dynamics incorporates some simplifications that are explained below.

a. Flow dynamics

The steady-state equation for isothermal gas flow states that the squared volumetric flow rate is proportional with the difference of the squared pressures at both ends of the pipeline section as shown in its most basic form in Eq. (3.15) [81; 100; 101]. Hence, the flow rate in a pipeline *a(ij)*, connecting nodes *i* and *j* (expressed in m^3/s or Mm^3/h) reads:

$$\dot{V}_{a(ij)} = k\_flow_{a(ij)} \cdot \sqrt{p_i^2 - p_j^2} \;, \tag{3.15}$$

where $k\_flow_{a(ij)}$ is defined as:

$$k\_flow_{a(ij)} = \sqrt{c\_flow \cdot \frac{T_{st}}{p_{st}} \cdot \left(2 \cdot \log \frac{3.7 * D_{a(ij)}}{\varepsilon}\right)^2 \cdot \frac{D_{a(ij)}^5}{Z \cdot T \cdot L_{a(ij)} \cdot \delta}} \tag{3.16}$$

The proportionality factor $k\_flow_{a(ij)}$ of Eq. (3.16) incorporates pipeline length L (m), diameter D (m), relative density δ (-), gas temperature T (K), roughness ε (m), compressibility number Z (-), standard temperature (T_{st} in K) and pressure (p_{st}), and a factor *c_flow* dependent on the units chosen for pressure p_i (Pa or bar) and flow rate $\dot{V}_{a(ij)}$ (m^3/s or Mm^3/h).[55] For practical applications, pressure is most often expressed in bar and flow rate in Mm^3/h.

Nodal pressures can only vary between upper (p_max_i) and lower (p_min_i) pressure limits:

$$p\_min_i \le p_i \le p\_max_i \tag{3.17}$$

Steady-state flow assumes inflow and outflow to be the same. Therefore, it is typically used for longer time steps such as a day. For shorter time steps, inflow and outflow tend to deviate causing some transient effects [102]. However, full transient development of gas flow is beyond the needs of the model. Rather, an approximation is required that balances technical accuracy and economic applicability.

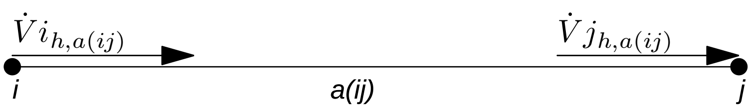

Figure 19. Flow convention: flow rate at node i ($\dot{V}i_{h,a(ij)}$) and flow rate at node j ($\dot{V}j_{h,a(ij)}$) over pipeline a(ij), forward flow from i to j has positive values for $\dot{V}i_{h,a(ij)}$ and $\dot{V}j_{h,a(ij)}$, backward flow from j to i, has negative values for $\dot{V}i_{h,a(ij)}$ and $\dot{V}j_{h,a(ij)}$

[55] Values for different equations can be found in, e.g., Coelho and Pinho [101], De Wolf and Smeers [159], Eberhard and Hüning [81] or van der Hoeven [102]. In this thesis the equation from [159] has been applied with *c_flow* = 1.668 10^{-16} for Mm^3/h, ε = 0.00005, Z = 0.8, T = 281.15 and δ = 0.616, but alternative formulations could have been used. For a comparison of possible flow equations, which are all approximations as actual parameters can only be determined *a posteriori*, see [101].

Figure 19 shows a pipeline *a(ij)* between nodes *i* and *j*. On this pipeline, two flow rates are defined, $\dot{V}i_{h,a(ij)}$ and $\dot{V}j_{h,a(ij)}$, which can be physically interpreted as the flow rate at node *i* and node *j*, respectively. According to this convention, the flow at node *i* is the pipeline inflow for a forward directed pipeline *a(ij)*; whereas this flow rate represents the outflow for a backward directed line (*j* to *i*).
According to Eq. (3.15), both flow rates in line *a(ij)* correspond to a certain pressure drop between *i* and *j*. However, a node cannot have two distinct pressure levels at the same time. Therefore, the steady-state pressure drop over the pipeline needs to be corrected for the varying flow rate at the pipeline inlet and outlet in period *h*.

The development of pressure within a pipeline provides clues on how to change the equation. Table 19 lists the change in line pack and the development of pressure caused by non-steady-state flow. Intuitively, the non-steady-state pressure drop over the pipeline should remain between the steady-state pressure drops for $\dot{V}i_{h,a(ij)}$ and $\dot{V}j_{h,a(ij)}$, respectively.[56]

Table 19. Intuitions on pressure development and line-pack caused by non-steady-state flow

Possible difference in flow rates	*Pressure change*	*Line-pack change*
$\dot{V}i_{h,a(ij)} = \dot{V}j_{h,a(ij)}$	$p_i - p_j$ defined by Eq. (3.15)	Steady state: no line-pack changes
$\dot{V}i_{h,a(ij)} > \dot{V}j_{h,a(ij)}$	Initially, entry pressure p_i remains at same level, exit pressure p_j starts building up because no further offtake is happening; next, a pressure wave propagates towards the entry, eventually raising entry pressure	Line-pack build-up as pressure starts rising near the exit, and, eventually, also near the entry
$\dot{V}i_{h,a(ij)} < \dot{V}j_{h,a(ij)}$	Initially, entry pressure p_i starts dropping from its initial level, next, the decreasing pressure level propagates towards the exit of the pipeline	Injection does not compensate for ongoing offtake so line-pack starts to be depleted downstream

The intuitions developed in Table 19 are further confirmed by Figure 20. The squared-pressure drops *dp2* (p_i^2-p_j^2 expressed in bar^2) for the flow rates at node *i* and node *j*, respectively, act as reference values (and limits) for a steady-state approximation of the non-steady-state pressure drop when $\dot{V}i_{h,a(ij)}$ and $\dot{V}j_{h,a(ij)}$ differ.

[56] Also neglecting shock-wave like pressure fluctuations due to possible large sudden perturbations.

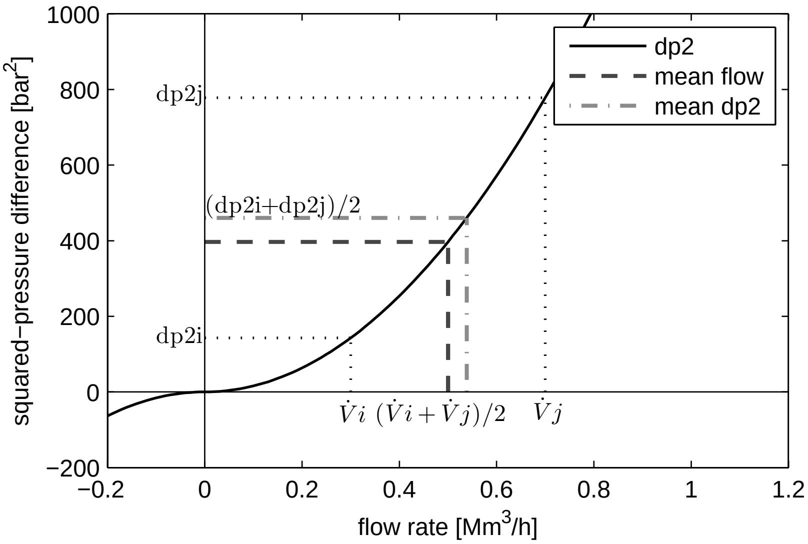

Figure 20. Squared-pressure difference dp2 [bar²] as a function of the flow rate V̇ [Mm³/h] (solid line) according to Eq. (3.15). The dashed lines mark the pressure drop corresponding to the average of inflow (V̇i) and outflow (V̇j), while the dash-dotted lines indicate the flow rate corresponding to the averaged squared-pressure difference. Using the mean-flow in the pipeline to determine the pressure drop returns a pressure difference that slightly underestimates the average of the pressure drops corresponding to the effective inflow and outflow and is an acceptable approximation of the pressure in a non-steady-state pipeline since the non-linearity is relatively limited near the average of the in- and outflow rates.

Figure 20 illustrates well that the squared-pressure drop corresponding to the mean flow rate, Eq. (3.18), along the pipeline does not deviate much from the flow rate that corresponds to the mean squared-pressure drop, defined in Eq. (3.19). Therefore, the mean flow rate over *a(ij)* in a period is used to determine the squared-pressure difference from which the nodal pressures in *i* and *j* can be derived as done by Midthun [147] and resembling the finite-difference method presented in Chaudry et al. [163]:

$$mean\ flow = \frac{\dot{V}i + \dot{V}j}{2} \tag{3.18}$$

$$mean\ squared\text{-}pressure\ drop = \frac{dp2i + dp2j}{2} \tag{3.19}$$

The flow equation in Eq. (3.15), then, is replaced by Eq. (3.20) for non-steady-state flow, as follows:

$$\left(\frac{\dot{Vi}_{h,a(ij)} + \dot{Vj}_{h,a(ij)}}{2}\right)^2 \leq sign_{h,a(ij)} \cdot k\_flow^2_{a(ij)} \cdot \left(cr^2_{h,i} \cdot p^2_{h,i} - cr^2_{h,j} \cdot p^2_{h,j}\right) \tag{3.20}$$

In Eq. (3.20), $sign_{h,a(ij)}$ indicates the flow direction with 1 for a forward directed line and -1 for backward flow and is determined using a binary variable as in [159] (further information on defining flow direction is provided in Appendix B). In line with operational practice, the physical flow direction cannot change intra-day. Equation (3.20) is a binding constraint except for situations when there is no flow in a pipeline. In that case the pressure difference can still deviate from zero, meaning that the nodes can have different pressures depending on the other connecting pipelines.

The compression ratio $cr_{h,i}$ (dimensionless) determines how the pressure of gas entering the pipeline following the compressor relates to the pressure of the gas before entering the compressor. Evidently, compression can only occur in nodes with a compressor and only at the inflow side of the pipeline, in all other cases *cr* equals one.

Compression requires primary energy (*Ecr*), which is typically provided by gas or electric power. The energy requirement (kWh or Mm^3) for adiabatic gas compression during one hour (time interval) is structurally defined in Eq. (3.21) and basically relates the energy use to the efficiency of the compression process, the flow to be handled and the actual compression ratio [100]:

$$Ecr_{h,i} = \left[k\_cr \cdot \frac{1}{\eta_{comp}} \cdot \frac{1}{\eta_{mech}} \cdot \frac{\gamma}{\gamma - 1} \cdot T \cdot Z \cdot \sum_{i \in a(ij)} \dot{Vi}_{h,a(ij)} \cdot \left(cr_{h,i}^{\frac{\gamma-1}{\gamma}} - 1\right)\right] \tag{3.21}$$

In Eq. (3.21), η_{comp} stands for the adiabatic compression efficiency and η_{mech} for the mechanical efficiency of the compressor, γ is the isentropic exponent and *k_cr* a factor depending on the units chosen.[57] The other symbols have been defined before.

The main reason to deviate from true steady-state flow is to account for the pipeline storage potential by using the line-pack flexibility. The line pack (Mm^3) is the total amount of gas present in the pipeline [100; 163] and is directly proportional to the average pressure ($\bar{p}_{h,a(ij)}$) over that pipeline as defined by Eq. (3.22):

$$Vlp_{h,a(ij)} = k\_lp_{ij} \cdot \bar{p}_{h,a(ij)} \tag{3.22}$$

[57] The following values have been considered: η_{comp} = 0.85, η_{mech} = 0.98, γ = 1.3 and *k_cr* = 8.48 for energy expressed in Mm^3.

The constant *k_lp* depends on the geometrical volume of the pipeline, the referenced standard conditions and a factor *c_lp* to account for the chosen units [81]:[58]

$$k\_lp_{ij} = c\_lp \cdot \frac{T_{st}}{p_{st}} \cdot \frac{1}{Z*T} \cdot D^2_{a(ij)} \cdot L_{a(ij)} \tag{3.23}$$

The average pressure, however, is not the arithmetic mean, but is calculated according to Eq. (3.24) in order to correct for the non-linear pressure development over a pipeline along the distance as is illustrated in Figure 11 [81]:

$$\overline{p}_{h,a(ij)} = \frac{2}{3} \cdot \left(p_{h,i} + p_{h,j} - \frac{p_{h,i} \cdot p_{h,j}}{p_{h,i} + p_{h,j}} \right) \tag{3.24}$$

b. Storage dynamics

Next to flow dynamics, the model of the gas system should also take into account technical aspects of traditional underground gas storages. Storages have three defining characteristics: the working volume $Vsto_{h,i}$ (Mm^3), the injection rate $\dot{V}inj_{h,i}$ (Mm^3/h) and the withdrawal rate $\dot{V}wd_{h,i}$ (Mm^3/h). Storage rates (injection and withdrawal) are dependent on the current working volume and the amount of base gas ($Vbase_i$ expressed in Mm^3) in the storage facility in a non-linear way.[59] Intuitively, higher withdrawal rates are expected when more working gas is available for extraction, whereas injection is inversely related with the storage level because of the pressure level in the storage. Thompson et al. [164] derived the relations, Eqs. (3.25) and (3.26), to link the effective storage-flow limits to the current level of stored gas. Furthermore, they computed *k_wd*, *k_inj_1* and *k_inj_2*, which are proportionality factors that represent the characteristics of the storage. Note that both flow rates are mutually exclusive: either gas is physically injected or withdrawn.

$$\dot{V}wd_{h,i} \leq k\_wd_i * \sqrt{Vsto_{h,i}} \tag{3.25}$$

$$\dot{V}inj_{h,i} \leq k\_inj\_1_i * \sqrt{\frac{1}{Vsto_{h,i} + Vbase_i} + k\_inj\_2_i} \tag{3.26}$$

The non-linear limits are plotted in Figure 21 with the solid line representing the withdrawal limit for different levels of the working volume and the dashed line representing the corresponding injection limit. These non-linear storage constraints often cause scaling problems. Therefore, linear approximations can be used instead: linear cuts can replace the convex withdrawal function, but for the non-convex injection a piecewise-linear approximation with *special ordered sets of type 2*

[58] *c_lp* = 7.855 10^{-10} for units expressed in Mm^3.

[59] Base gas is the amount of gas that has to remain in the storage for operational reasons like cavern stability and pressure maintenance.

(SOS2)-variables can be used. The details of these linearization methods can be found in Appendix B.

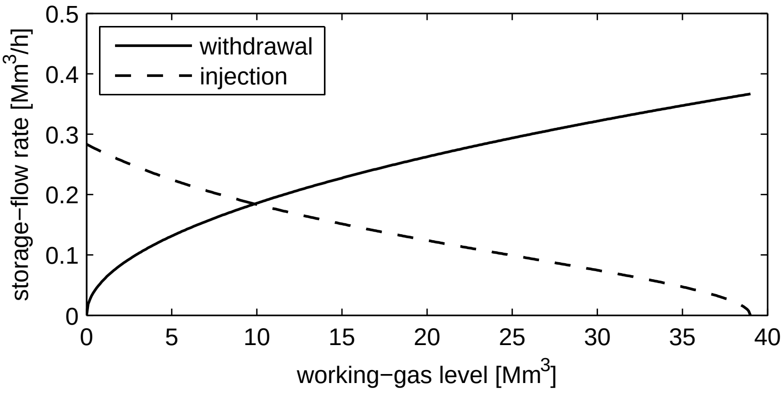

Figure 21. Withdrawal and injection limits [Mm³/h] according to the level of working gas in storage

3.2.3.3 Shipper related constraints

Gas entry and exit are exogenous as these are the result of the aggregation of all individual shippers' nominations:

$$\dot{V}en_{h,i} = \sum_{shippers} \dot{V}buy_{h,i} \tag{3.27}$$

$$\dot{V}ex_{h,i} = \sum_{shippers} \dot{V}sell_{h,i} \tag{3.28}$$

If *ex-ante* flexibility has been nominated by the shipper, that flexibility is to be taken into account as well. The modeling of this is similar to Eqs. (3.27) and (3.28).

3.2.3.4 Objective function

The constraints above just define the solution space with (physically) feasible solutions. The outcome of the model, then, is determined by the objective function, which can take different forms like maximizing throughput, minimizing fuel costs etc. In this thesis, the objective of the TSO is to minimize balancing costs, meaning operational costs related to the management of the network, costs of line pack and procurement and dispatching costs of flexible gas:

$$\min \ balancingcost = fuelcost + lpcost + flexgascost \tag{3.29}$$

Only net costs are considered, therefore, the TSO implicitly "buys" all gas entering the system and "sells" all gas leaving the system at the day-ahead price on the spot market.

The *fuelcost* is related to the energy required for compression of gas to a pressure level consistent with transport needs and line-pack flexibility needs:

$$fuelcost = \sum_{h,i} cfuel_{h,i} \cdot Ecr_{h,i} \tag{3.30}$$

This energy has a unit cost ($cfuel_{h,i}$ expressed in EUR/m^3) that is dependent on the used fuel, e.g., gas. Evidently, *fuelcost* cannot be attributed completely to the balancing of the system as compression is also necessary for provision of transport services. Any attempt to disentangle these mixed-use costs has been disregarded to simplify the analysis. Moreover, the compression costs are much smaller than the other costs. So, their full inclusion is not distorting (too much) the effects that are the subject of research in this thesis.

Line-pack costs (*lpcost*) values the use of line-pack at its unit cost *clpflex* (EUR/m^3). This cost represents the operational and, if applicable, the capacity cost of using line-pack. *lpcost* is then defined by Eq. (3.31) in which the hourly line-pack changes are aggregated for all pipelines and then multiplied with the net cost for all periods:

$$lpcost = \sum_{h} clpflex_{h} \cdot \left(\sum_{a(ij)} \left(\dot{V}i_{h,a(ij)} - \dot{V}j_{h,a(ij)} \right) \right) \tag{3.31}$$

Hence, *lpcost* is an alternative for the compressor cost as both valuate the use of the pipeline flexibility. In general, *clpflex* is close to zero if it represents just operational costs as is the case in this work.

Procurement costs of flexible gas are dealt with in a similar way as line-pack costs:

$$flexgascost = \begin{pmatrix} \sum_{h,i} cflexup_{h,i} \cdot \dot{V}flexup_{h,i} \\ + \sum_{h,i} cflexdown_{h,i} \cdot \dot{V}flexdown_{h,i} \end{pmatrix} \tag{3.32}$$

The net costs *cflexup* (EUR/m^3) for upward flexibility and *cflexdown* (EUR/m^3) for downward flexibility represent operational costs of flexible gas and can be thought of as a mark-up and mark-down on the day-ahead price of gas in a market-based merit-order mechanism (see further in Chapter 6). Suppose a day-ahead price amounting to 0.15 EUR/m^3 and a bid price for upward flexible gas amounting to 0.17 EUR/m^3, then the net cost of the flexibility to be taken into account is actually 0.02 EUR/m^3.

Note that capacity costs have been omitted from this operational study of flexibility because they can be considered sunk costs in the absence of a functioning capacity market. But such costs can easily be added when longer horizons allow capacity decisions to be included, or to reflect the opportunity cost of capacity when a market allows trading capacity.

3.2.4 Algorithm

The actual optimization of the gas-system model is carried out with commercial solvers that are called through the GAMS optimization platform [165] with most input and output handling done by Matlab [166]. The complete translation of the model introduced in this chapter is referred to as GASFLEX. It is further composed of GASFLEX-shipper and GASFLEX-TSO, both of which are discussed below.

3.2.4.1 GASFLEX-shipper

The optimization related to the shipper's nominations (GASFLEX-shipper) is a straightforward mixed-integer-linear-programming (MILP) problem consisting of Eqs. (3.1)-(3.3) and Eqs. (3.5)-(3.11) during the unit commitment when the shipper uses demand forecasts and all *ex-ante* flexibility is available. During the power-dispatching phase, Eq. (3.3) is replaced by Eq. (3.4) as demand is known in that phase.

Data are fed to GAMS, which in turn calls the CPLEX optimizer. Next, results are returned to GAMS and read out into Matlab. Multiple optimizations can be looped, changing data or parameters as desired. The final output of this model serves as input for GASFLEX-TSO. The program logic is illustrated in Figure 22.

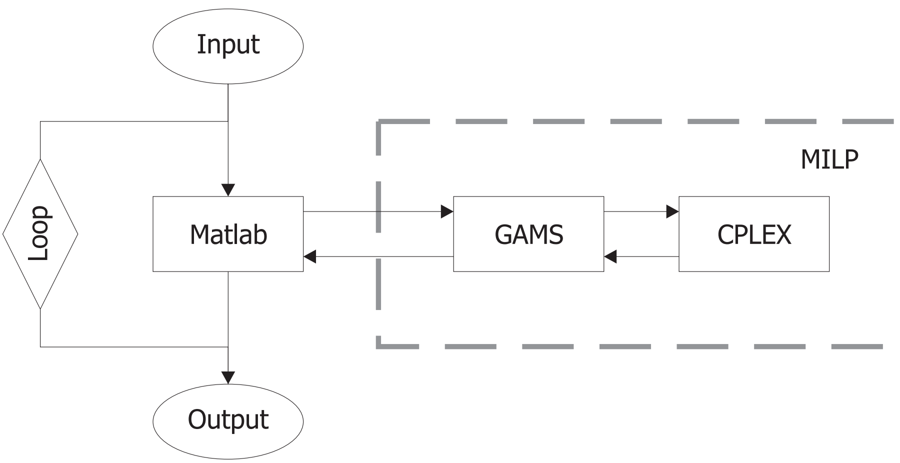

Figure 22. GASFLEX-shipper logic: input and output are handled by Matlab, which subsequently calls GAMS for the optimization of the mixed-integer-linear problem (MILP) by the CPLEX solver; a loop can be used for scenario analysis or iterative algorithms, e.g., "unit commitment" followed by "power dispatching"

3.2.4.2 GASFLEX-TSO

Due to the combination of non-linear equations and integer variables, mixed-integer-non-linear-programming (MINLP) techniques are required to compute a feasible and at least locally optimal solution for the TSO-balancing problem. However, to improve the MINLP solver's chances of finding good solutions, two support problems are solved. A MILP problem allows computation of a globally optimal integer solution for a relaxed problem statement compared to the master MINLP problem. Next, the non-linear constraints are solved with non-linear programming (NLP) using values for the integer variables obtained in the MILP support problem. Overall, the complete optimization follows the steps that are illustrated in Figure 23.

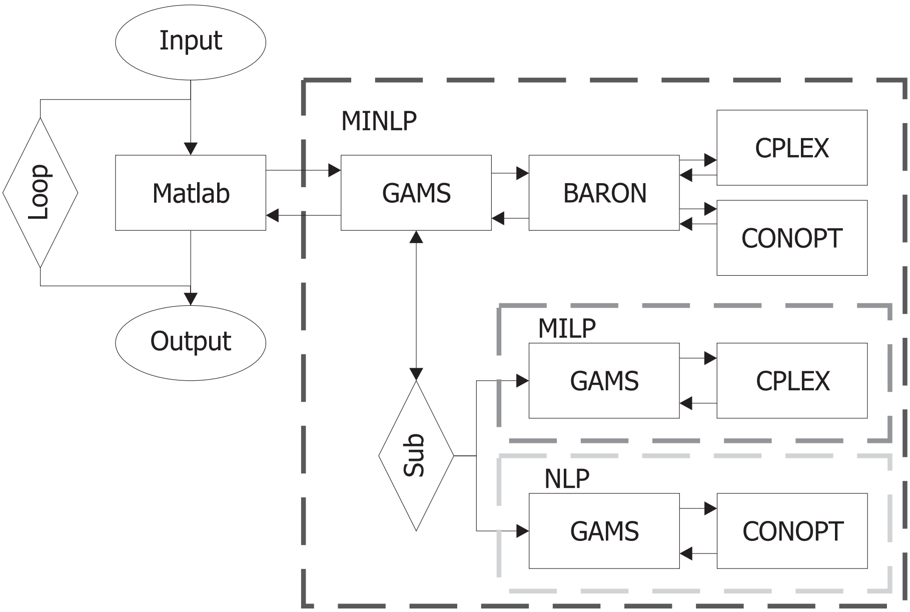

Figure 23. GASFLEX-TSO logic: input and output are handled by Matlab, which calls GAMS; within GAMS two support problems are solved, first, CPLEX solves a mixed-integer-linear problem (MILP) to determine initial values for the integer variables, and, second, CONOPT solves the non-linear constraints as a non-linear-programming (NLP) problem using the integer variables as parameters; the obtained values for the variables provide an initial feasible solution for the mixed-integer-non-linear programming (MINLP) model that is subsequently solved by BARON, which also uses CPLEX and CONOPT in subroutines

a. Master MINLP

The master MINLP model consists of constraints defined in Eqs. (3.12)-(3.14), Eqs. (3.16)-(3.17) and Eqs. (3.20)-(3.29). Usually, a MINLP solver only guarantees local optimality of a found solution. *BARON* [167; 168], however, is a global optimizer which can return a proven global optimum if certain conditions are met.[60]

[60] According to the *Baron* manual [167] global optima can be obtained if a good (i.e. easy to solve) relaxation exist of the initial problem because all local optima have to be considered.

Furthermore, *BARON* calls sub-solvers *CPLEX* [169] and *CONOPT* [170; 171] for MILP and NLP relaxations, respectively.[61]

To improve the efficiency of *BARON* (tight) upper and lower bounds are required for all variables and constraints. The better the bounds, the more efficient the problem can be solved by the solver's algorithms.

To further enhance the efficiency of *BARON*, the solver benefits from a feasible starting solution as an initial point for the optimization algorithm. To determine such a feasible solution two supporting optimizations are carried out: a MILP relaxation and an NLP with the integers fixed based on the MILP solution.

b. Support MILP

The MILP relaxation provides initial values for the integer variables with reference to the direction of gas flow (*bin* and related *sign*) and the Special Ordered Sets of type 2 (SOS2)-variables for the linear approximation of the storage-injection rate.[62]

CPLEX is a very efficient MILP solver, but adding more integer variables to the problem has a severe impact on computational time. Therefore, the size of the studied problems needs to be managed carefully.

The MILP consists of Eqs. (3.12)-(3.14) and Eqs. (3.25)-(3.29). The objective function, however, omits the compression related *fuelcost*, and the non-linear Eqs. (3.25) and (3.26) are replaced with their linear approximations (see Appendix B).

c. Support NLP

The integer values obtained from the MILP relaxation are subsequently submitted as parameters to the NLP support problem. The flow directions, therefore, are fixed in this problem. The NLP solver (*CONOPT*) provides values for all variables, but only if a feasible solution exists for the flow path that has been determined by the MILP support problem.

The NLP support problem consists of the same equations as the master problem, but the binary variables are fixed. NLP solvers can only guarantee a local optimum, though.

The combined set of solution values for the integer variables and the other variables found by the MILP and NLP support problems constitutes a feasible initial solution for the master MINLP problem.

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[61] *CPLEX* uses branch-and-bound methods for MILP and *CONOPT* applies generalized reduced gradient (GRG) methods for NLP.

[62] Special Ordered Sets of type 2-variables are used to define piecewise linear functions. Only two SOS2-variables can be positive and these variables have to be adjacent (only ordered sets can be used). If the sum of the variables equals 1, a linear interpolation between given breaking points (for which the function values are known) can be defined.

Furthermore, in many cases the network state obtained from the MILP and NLP will be (sufficiently) optimal for the applications considered in this thesis and no need exists to call the computationally challenging and time consuming MINLP.

3.2.5 Model validation

The model validation has been twofold. On the one hand, GASFLEX is able to reproduce the results of the single-period multi-nodal gas-transport problem introduced by De wolf and Smeers [159], and it obtains the same results for the examples introduced by Midthun [47]. The technical storage constraints have been verified for the examples in Thompson et al. [164]. On the other hand, GASFLEX has been tested rigorously on its internal logic, making sure that every constraint does what it is supposed to do. To this end, GASFLEX has been verified for simple test cases (two periods, two nodes and one pipeline), for which analytical solutions could be computed.

Unfortunately, no standardized test problems exist for this kind of multi-period gas modeling and calibration data were only limited available.[63] Moreover, global optima are only found for a limited number of cases, meaning that the model output needs a cautious approach as only local optimality is guaranteed, even if this local optimum is actually a global optimum. Feasibility of the model is partly dependent on the starting conditions, e.g., for line pack and storage. These starting values are determined based on a preceding optimization run by the TSO using available flow-schedule information.

The non-linear and non-convex problem is computationally intensive and numerical instabilities can occur, especially if the problem instances become big. So, improvements on the modeling side are possible, but the current models are sufficient for the problems investigated here. It should also be noted that the non-steady-state approximation is sufficient for the economic problems discussed in this work, but it should not be used, e.g., for determining optimal operational control of a transient pipeline system.

3.3 Case study: problem description

To study the conceptual impact of wind-power unpredictability (forecast errors) on the balancing of the gas network, a simplified hypothetical electricity and gas system is considered with wind participation levels between 15 and 25 percent of generated electricity. An example of a case study on the operational impact of massive wind-power integration in the future UK system can be found in [136]. In that study by Qadrdan et al., it is shown that gas-network operations and the electricity-generation

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[63] The publication of selected gas-network data by European TSOs has only become mandatory from 2012 onwards and could not be included in this thesis.

mix are affected by the interactions between wind and gas for electric power generation. The case study in this thesis looks beyond that operational impact, and focuses on the impact of wind-power unpredictability on the organization of gas balancing.

3.3.1 Electricity system: assumptions and data

The assumed electricity-generation system consists of 600 MW wind power in a single wind farm and four CCGT plants of 400 MW each. All CCGT plants are identical with respect to their characteristics, e.g., for minimum uptimes and downtimes and efficiency rates at different working points.[64] No electrical network is taken into account as it is the production of electric power by CCGTs that is relevant to the gas system.

A scaled generic electricity-demand profile for a typical day in Northwest Europe serves as the exogenous input for the power-plant unit-commitment and economic power-dispatching optimization [172]. The average electric power demand amounts to 1370 MW with a fairly limited variability of the power-demand profile as measured by its standard deviation of 118.8 MW. Note that this variability includes peak and off-peak differences. Wind power is then taken into account by subtracting it from the considered electricity-demand profile, which gives the net electric power demand to be met by CCGTs. The unpredictable fluctuations of wind power are accounted for by imposing four deterministic wind-power forecast-error profiles on the real-time wind-power output profile, which is the same in all examined cases.[65] In other words, the variability of wind is the same in all cases and is rather small; hence, the wind-power profile is rather flat in the perfect-forecast case. The differences between profiles depend on the unpredictable fluctuations. It is the effect of these fluctuations on the gas-system balancing that is of interest in this study.

Additionally, a no-wind scenario serves as benchmark to understand the flexibility needs with and without wind. With reference to the electric power demand, demand-side uncertainty is disregarded to simplify the analysis. The 0 MW-wind scenario should therefore return similar outcomes to the perfect-forecast scenario because in both scenarios wind is equally reliable as gas at the supply side. All remaining differences between the perfect-forecast case and the no-wind case, e.g., with regard to intra-day flexibility, can be attributed to differences in variability.

[64] A priority rule is applied whenever multiple optimal dispatching solutions exist: in that case plants could be substituted at zero cost and the obtained solution would otherwise depend on the solution path of the algorithm.

[65] Wind-power profiles are derived from wind-power data published by the Belgian electricity-transmission-system operator, Elia [173], and prediction errors have been generated according to the method introduced by Brand en Kok [174] and have been calibrated on historical forecast and real-time wind-speed data of the Royal Dutch Meteorological Institute [175].

Table 20 provides an overview of the wind-power scenarios that are examined. The average predicted electric power to be generated by CCGTs and the variability of the predicted gas-fired electric power generation are reported under μ (MW) and σ (MW), respectively.

Table 20. Summary of examined wind-power scenarios based on different forecast errors for wind-power output and a benchmark scenario with no wind: μ represents the average, and σ the standard deviation, of predicted electric power generation by CCGTs

Scenario	Description	μ [MW]	σ [MW]
perfect forecast	wind-power output is predicted perfectly and dispatching follows unit commitment	1100	106.4
small errors	small prediction errors require some corrective dispatching decisions	1099	98.44
overestimation	actual wind-power output much less than predicted and more CCGT power needs to be dispatched	1063	194.9
underestimation	actual wind power output exceeds predictions requiring CCGTs to be regulated down	1141	99.86
no wind	benchmark with zero wind-power output	1370	118.8

Table 21, then, summarizes the average and the standard deviation of the wind-power prediction errors for the four forecast scenarios. E.g., in the overestimation case, 37 MW of predicted wind power was on average not actually available during the dispatching phase. The errors should be compared to the 600 MW of installed wind-power capacity.

Table 21. Summary of wind-power prediction statistics for the four scenarios: mean prediction error [MW] and standard deviation of the prediction error [MW] for 600 MW installed wind-power capacity; actual output compared to predicted output

Scenario	Mean prediction error [MW]	St.dev. prediction error [MW]
perfect forecast	0	0
small errors	–1.5	16.7
overestimation	–37	107
underestimation	40	31.4

Note that the naming of the research cases refers to the wind-power forecast: the underestimation case, then, underestimates wind (too little wind output predicted), but coincides with overestimating gas demand (too much gas committed).

Figure 24 plots the total electricity demand and the forecasted residual gas-fired electric power demand in the upper panel, whereas in the lower panel the wind-power forecasts are illustrated.

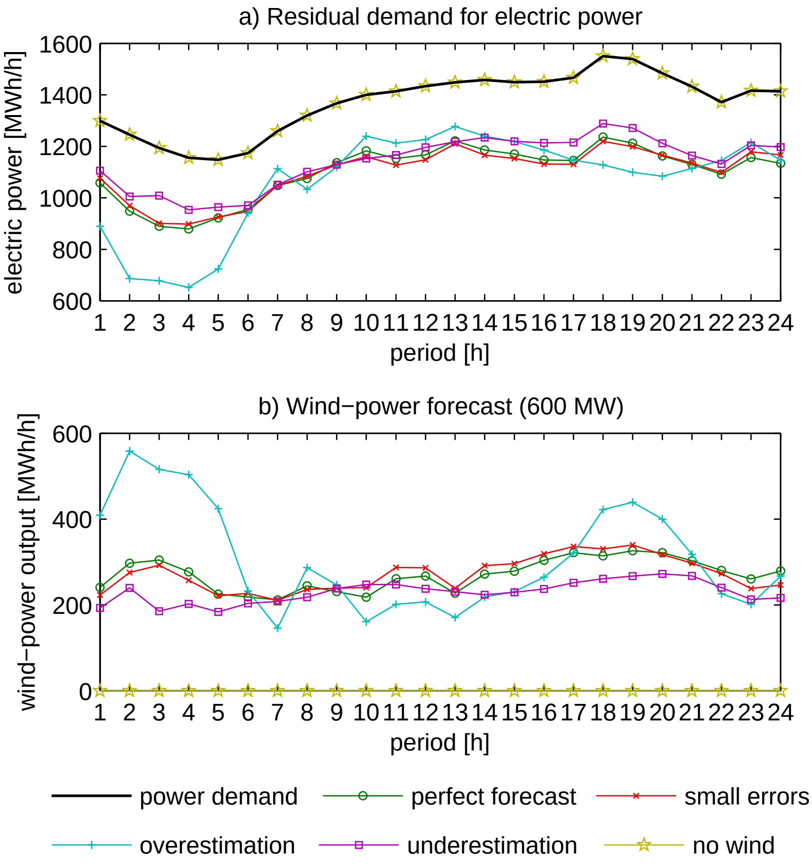

Figure 24. Electric power profiles – a) forecasted residual demand for electric power generation by CCGTs and b) wind-power-output forecasts for different forecast qualities; total electric power demand is represented in the upper panel by the black line

The average predicted wind-power output is obtained by subtracting the average predicted CCGT production (represented by "μ" in Table 20) from the average electric power demand (1370 MW). It varies between approximately 230 MW or about 17 percent of the average electric power demand, and 310 MW or 22 percent of the average electric power demand. The large standard deviation ("σ" in Table 20) for the scenario with overestimated wind power (third scenario in Table 20) indicates a forecast with much more variable wind power than will actually occur in real time.

During the first 8 hours, for instance, much more wind-power output is predicted than actual wind output will be, as can be observed in the difference between the overestimation case and the perfect-forecast case. Furthermore, the electric-power-demand profile and the no-wind profile provide the same information, hence their overlap in Figure 24.a.

The electricity model explicitly takes into account a part-load efficiency profile for the four CCGTs as defined by Delarue [172]. Thus, the CCGTs have multiple working points with different efficiencies in order to get a stepwise cost function for the power plants. The first and last working points refer to the minimum and maximum working points of the CCGT plant, respectively.[66] Efficiencies between the working points have to be calculated from the stepwise cost function [172].

First, the power-plant unit commitment (UC) is solved by minimizing costs (start-up costs and fuel costs) of the electricity-generation system. In this step of the electricity-system optimization, input is based on the forecasts for the wind-power output and the resulting forecasted net demand for gas-fired electric power generation. The second part of the optimization deals with the actual economic power dispatching (PD) of the CCGTs based on the actual hourly wind-power output and the CCGT costs. In this stage, the on/off state of the power plants is fixed as determined in the UC stage. More details about the modeling of the electricity-generation system can be found in [172].

Because of the efficiency profile and the inclusion of other dispatching constraints such as start-up costs, minimum uptime and downtime of the power plants, the CCGT UC and PD return an operationally realistic generation profile. Indeed, two CCGT running at half power is preferred over having one CCGT at full power and another switching on and off.

Figure 25 illustrates the unit commitment based on a negative forecast error (fourth case in Table 20) for wind-power output, so that mainly CCGT1 and to a lesser extent CCGT2 had to be regulated down in the power-dispatching phase. Figure 26, on the other hand, shows the unit commitment and the power dispatch when forecasted wind-power output is overestimating (positive forecast error) actual wind power (third case in Table 20). In this scenario, CCGT4 remains switched off during the first part of the day. The unavailable wind power is then covered by ramping up CCGT1, which has to be dispatched at full power all the time, and dispatching CCGT2 more variably than compared to its initial commitment. It should be noted that the power dispatching is optimal taking into account the decisions made in the unit-commitment stage, but is not necessarily the optimal outcome if these decisions could be changed.

[66] A minimum working point entails that if a plant is switched on, it should generate at least that amount of electric power, e.g., 120 MW.

In order to investigate the flexibility of the gas network, hourly electric power production of the CCGTs has to be translated into an hourly gas-flow rate. The CCGT gas power demand ($P_{gas,CCGT}$ expressed in MW_{gas}) is calculated by dividing the electric power production ($P_{el,CCGT}$ expressed in MW_{el}) by the dynamic efficiency (η_{CCGT}) of that CCGT plant at that output level:[67]

$$P_{gas,CCGT} = P_{el,CCGT} / \eta_{CCGT} \tag{3.33}$$

Conversion of power units (MW) into volume-flow rates (Mm^3/h) is carried out with an assumed gross caloric value (GCV) of 0.0115 MWh/m^3.

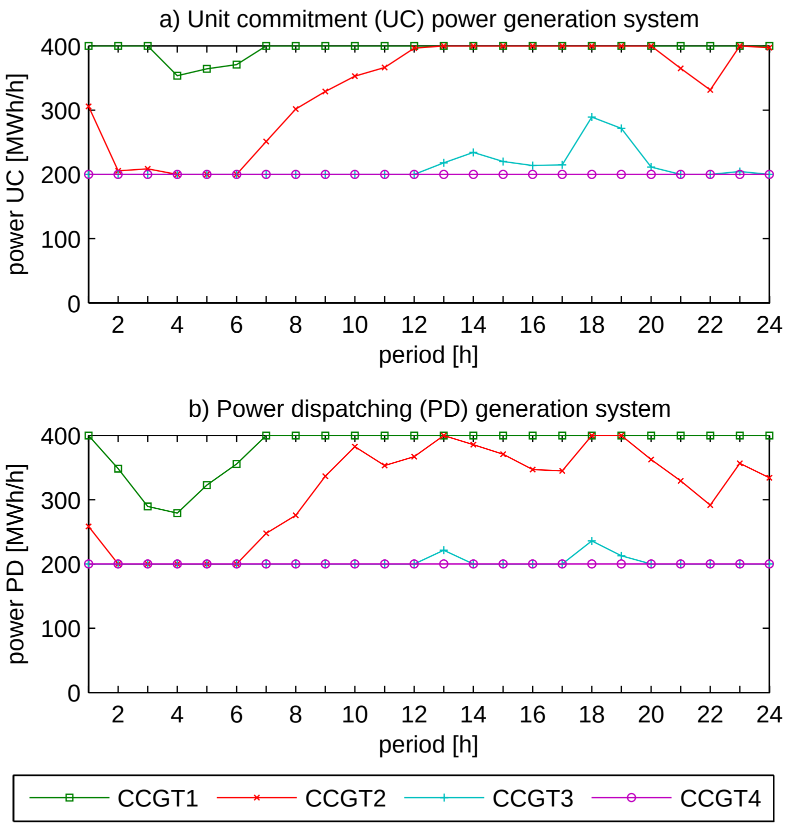

Figure 25. CCGT-generation profiles for underestimated wind – a) unit commitment based on forecasts and b) power dispatching based on actual wind-power output, CCGT1 and CCGT2 are ramped down several times to compensate for more dispatched wind power than was predicted

[67] The dynamic efficiency is obtained as the ratio of the total electric power output over the total gas power input: $\eta_{CCGT} = \Delta P_{el,CCGT} / \Delta P_{gas,CCGT}$.

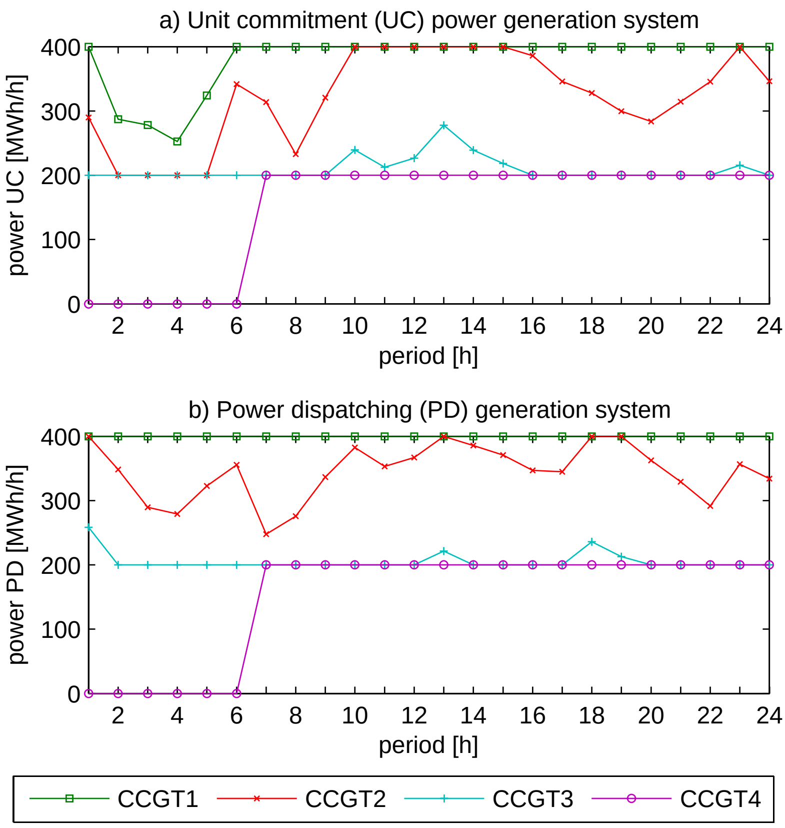

Figure 26. CCGT-generation profiles for overestimated wind – a) unit commitment based on forecasts and b) power dispatching based on actual wind-power output – CCGT1 is running all the time and CCGT2 is ramped up several times to cover for less wind-power output than was predicted, especially in the first part of the day; CCGT4 has not been committed and is thus not available in the dispatching phase for the first part of the day

3.3.2 Gas system: assumptions and data

The hypothetical gas-pipeline system, illustrated in Figure 27, consists of five demand nodes divided over four CCGT plants and one industrial consumer. Next, gas enters the network through two production/import nodes, supply A and supply B, and one storage site can be used to inject and withdraw gas. The nodes are connected by seven pipelines without gas compression (thus, compression occurs outside the modeled system). The flow direction of bidirectional pipelines is determined within the model and is labeled according to the convention explained in

Figure 19.[68] In Figure 27, for instance, the flow on line CCGT2 – storage physically flows from the storage to CCGT2, hence the negative sign. Furthermore, the figure illustrates supply and demand (**bold**, Mm^3/h) and pipeline inflow and outflow rates (*italic*, Mm^3/h) for the 6th hour of the overestimation case. All supply from node B (0.0875) is injected in line B – CCGT3 (*0.0875*), but less gas is taken from the line (*0.0771*). As a result, the line-pack buffer of that pipeline is loaded. Part of the gas is used to meet local demand of CCGT3, whereas the remaining gas is injected on the connecting pipelines industry – CCGT3 and CCGT3 – CCGT4. Other numbers and nodal and line balances are explained similarly. More technical details (e.g., pressure limits and pipeline geometry) are provided in Appendix C.

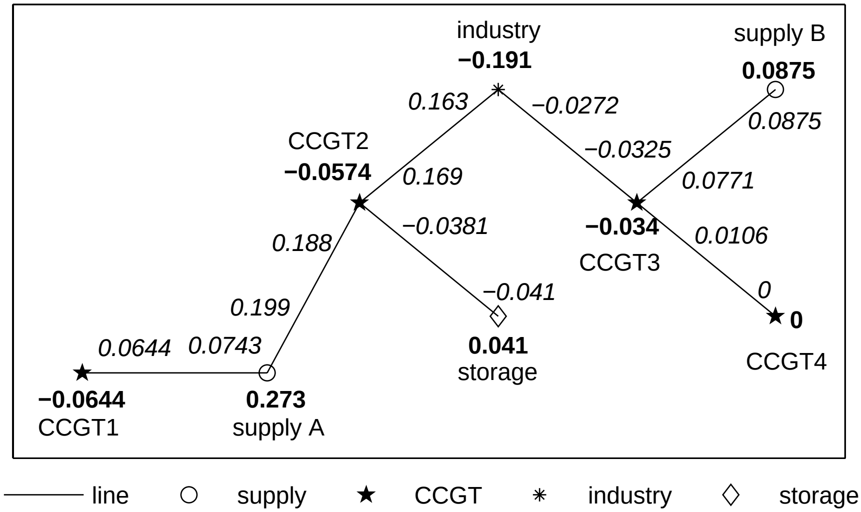

*Figure 27. Gas network with 2 gas-supply nodes (o), 1 storage node (◇), 1 industrial-demand (*) node and 4 CCGT-demand nodes (★) – numbers [Mm^3/h] for the 6th hour of the overestimation case, italic numbers represent flows in and out of a pipeline with negative numbers indicating backward flow, numbers in **bold** indicate supply and demand (including storage)*

As explained in Chapter 2, the pipeline capacity offers flexibility services at the cost of reducing transport services. In other words, capacity should be designed taking into account a peak-flow service and a peak-flexibility service. The connecting pipelines, therefore, have been defined in terms of pressure limits and diameter in

[68] Bidirectional gas pipelines allow physical flow in both directions, but the actual flow direction depends on the net nominated flow and the ability of compressors to support flow compression in both directions. An actual decision to physically change the flow direction will only be taken for longer periods, e.g., several days of sustained net flow nominations in that direction, even though the switching process takes less than a day [176].

such a way that the pipeline capacity does not limit the flow rates demanded by the CCGTs. The bundled line-pack flexibility provides time flexibility to the TSO, the kind of flexibility needed to deal with sudden changes like intermittent gas demand. Underground storage makes up a second source of system flexibility in the hypothetical gas system. On the shippers' side, the gas-supply contract is assumed not to provide intra-day modulation and other *ex-ante* flexibility is disregarded to focus on *ex-post* balancing. As a consequence of these assumptions, all flexibility to deal with unpredictable fluctuations has to come from the TSO. And the shipper optimization can only use *ex-post* flexibility to modulate supply to match (predicted) demand.

The optimization with GASFLEX is first conducted for the committed CCGT plants in every hour based on the wind-power prediction (this is the gas "unit commitment"). Subsequently, the actual hourly gas dispatch is optimized taking into account wind-forecast inaccuracies for the CCGT gas demand (the gas "power dispatching"). In that second phase, the gas supply at the import nodes is fixed at the flat levels committed in the UC. Indeed, this supply fixing simulates the unpredictability of gas demand that is dependent on the wind-power forecast error. Therefore, the obtained imbalances can be considered exogenous to the dispatching phase.

It is possible to consider re-nominations to some extent, e.g., up to two hours before real time, as better short-term wind-speed forecasts become available. Such an approach lowers the financial balancing needs if a shipper can use *ex-ante* flexibility on short notice. However, this option has not been implemented here because the fundamental dynamics would not change. It is important to understand that when, e.g., storage is used as ex-ante flexibility, the contractual flows (rights to gas) and the physical injection or withdrawal are separate matters with different actors responsible for either of them. In fact, only the net storage flow has to be physically injected or withdrawn by the end of the day.

3.3.3 Problem setting

The hypothetical problem setting further consist of two shippers of about equal size in total demand over the horizon: a shipper with just CCGTs in his demand portfolio, hereafter "wind shipper", and a shipper with an industrial-demand profile, hereafter "historic shipper". With regard to the physical balancing of the system, the TSO has access to line-pack flexibility and underground storage.

Balancing costs have to be recovered from unbalanced shippers through the settlement mechanism. Two distinct design options are examined: a non-market-based mechanism and a market-based mechanism. The former stands for a design in which an imbalance is cashed out at a price that is determined disregarding the imbalance position of the gas system. By definition, for non-market-based settlement, the imbalance fee (F_{imb}) is independent of the system imbalance (imb_{sys}):

$$\frac{\partial F_{imb}}{\partial imb_{sys}} = 0 \tag{3.34}$$

A market-based mechanism, on the other hand, implicitly or explicitly links the imbalance fee to the system imbalance or the TSO's deployment of flexible gas as expressed by the non-zero derivative of the imbalance tariff to the system imbalance in Eq. (3.35):

$$\frac{\partial F_{imb}}{\partial imb_{sys}} \neq 0 \tag{3.35}$$

Figure 28 illustrates the dynamics behind this market-based settlement of *ex-post*-balancing services. The TSO can dispatch an amount of upward or downward flexibility to correct for a gas system in deficit or in surplus, respectively. The sources of flexibility are ranked according to their marginal costs and the cheapest sources are used first. Only if additional flexibility is required, more expensive flexible gas is used. The imbalance tariff per unit of imbalance, then, can be related to the system imbalance and the cost of the marginal unit of system flexibility.

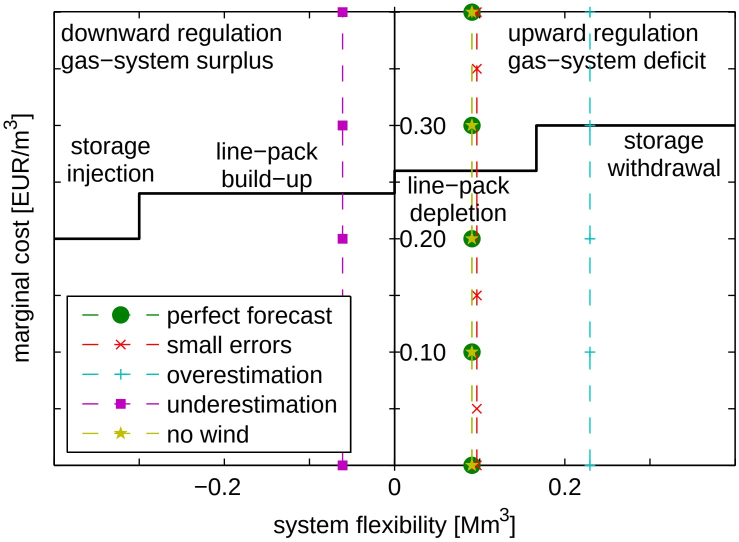

Figure 28. Merit-order curve for system flexibility for five wind-power scenarios when the historic shipper is short: upward (downward) regulation to correct gas-system deficit (surplus), the system-imbalance lines determine the effective marginal cost of system flexibility; the "no-wind" and "perfect-forecast" lines overlap

In Figure 28, the gas reference price is assumed to be 0.25 EUR/m^3. Furthermore, operational costs have been considered for line-pack flexibility (0.01 EUR/m^3) and storage flexibility (0.05 EUR/m^3). These operational costs for flexibility have to be added to, or subtracted from the reference price, e.g., the day-ahead price, for gas to obtain the marginal cost of flexible gas.

However, the merit-order curve is dependent on the actual gas-system operation because availability and dispatching of line-pack flexibility is only determined dynamically within GASFLEX. Therefore, Figure 28 only shows one possible merit curve that is obtained from the optimization. The dynamic limit for upward line-pack flexibility amounted to approximately 0.17 Mm^3 (about 50 percent of total hourly demand or 2 percent of total daily demand). Furthermore, Figure 28 shows the gas-system imbalances for the five examined cases from Table 20. The lines indicating the no-wind and the perfect-forecast cases coincide almost perfectly because the wind-power output is perfectly predicted in the UC stage in both cases and the remaining intra-day variability is small and very similar. Note that line-pack flexibility has been included in the merit order; whereas in current practice, line-pack flexibility is must-use flexibility that is subtracted from the TSO demand for flexibility to obtain the residual demand for flexible gas that has to be procured from balancing-services providers. A single reference price is assumed for all actors, disregarding the strategic use of the balancing mechanism by shippers to, e.g., dump cheap gas from long-term contracts capitalizing on a large reference-price difference.[69]

The settlement-design options have been discussed in Chapter 1. Nevertheless, the main points of attention are emphasized again. Ultimately, only four situations can occur for end-of-period imbalance settlement (Table 22). First, an individual shipper can be short when the system is also short (Q1 in Table 22). In that case the shipper is instigating the system imbalance. Another shipper can be long when the system is short (Q2 in Table 22). That shipper actually mitigates the system imbalance. When the system is long, short shippers will be settled according to Q3. Finally, Q4 represents the applicable imbalance tariff for long shippers in a long system.

Table 22. Settlement mechanism: four distinct quadrants according to individual shipper imbalance and system imbalance

Shipper imbalance	System imbalance	
	Short	Long
Short	Q1	Q3
Long	Q2	Q4

[69] If the shipper's contract price amounts to 0.18 EUR/m^3 and the balancing reference price is 0.25 EUR/m^3, the shipper can dump gas in the balancing mechanism even taking into account net imbalance charges of, e.g., 20%; this is especially true for non-market-based balancing because the charges are in that case independent from the state of the system.

Each quadrant, thus, represents a system-shipper combination with a distinctive imbalance tariff. However, most currently applied settlement mechanisms have no connection between the system position and the applicable tariff, using the same for both situations (Q1 = Q3 and Q2 = Q4).

Several options exist to determine tariffs from the merit-order curve and the system imbalance. The most basic example consists in using the price coinciding with the used amount of balancing energy for both long and short shippers. The underestimation case in Figure 28, for instance, has a marginal cost of 0.24 EUR/m^3 for system flexibility – or net cost of 0.01 EUR/m^3 when the reference price of gas is taken into account. This kind of tariff system rewards shippers that help the system with a mitigating opposing imbalance position, whereas it penalizes shippers who further instigate the system imbalance.

So, market-based settlement depends on an implicit or explicit merit-order curve for flexible gas. The merit-order-derived marginal cost of balancing, then, provides better signals to the market players with reference to the real costs of flexibility and the need for further investment in these instruments. A non-market-based tariff, on the other hand, does not take into account the overall state of the gas system and the actually used flexibility. Therefore, this settlement design does not provide efficient signals.

Actual settlement mechanisms become very complex, as has been demonstrated in Chapter 1. The subsequent analysis of wind-power unpredictability on gas balancing does not include these complex settlement designs, but rather uses basic settlement designs to understand the fundamental principles. The main findings, though, remain valid for more complex designs because the latter are just combinations of the basic design options that are examined.

3.4 Effects of wind unpredictability on gas balancing

The impact assessment of wind-power unpredictability on gas balancing is split in two parts. The first subsection deals with the impact of unpredictability on the physical flexibility requirements of the gas system. The cost recovery by means of the settlement mechanism is subject of a second subsection.

3.4.1 Physical gas balancing

Because of prediction errors, the wind shipper commits too much or too little gas during the UC, resulting in unavoidable imbalances in the dispatching phase. This wind-shipper imbalance is combined with the imbalance of the historic shipper, for whom both negative and positive forecast errors have been assumed. The TSO, then, anticipates the (intra-day) flexibility needs based on the information received during the UC, e.g., building up a buffer when shippers expect to be short during the day.

a. Historic shipper: short imbalance position

Figure 29 shows an example of deterministic imbalance profiles of the wind shipper and the historic shipper for the four examined forecast errors.[70] In the examples, the historic shipper has committed too little gas as he has underestimated industrial gas demand.

Evidently, when the wind-power output is perfect (Figure 29.a), the gas dispatching mirrors the gas committed by the wind shipper and the system imbalance equals the historic shipper's deficit. Small forecast errors (panel b) only cause minor physical changes and the system state still reflects the unavoidable historic imbalance. In both cases the limited flexibility needs are covered with line-pack. However, if the quality of forecasting is low, the physical impact of the wind shipper's imbalance on the state of the gas network is substantial. This is illustrated in Figure 29.c and Figure 29.d. The impact on the line-pack buffer for these low-quality forecasts depends on the respective signs of the individual shipper imbalances.

Figure 29.c, then, shows that when wind-power output is overestimated (thus CCGT gas demand underestimated) and industrial demand underestimated, the planned buffer build-up in the unit-commitment stage proves to be insufficient during the dispatching and the line-pack ends up substantially depleted to the extent that gas is withdrawn from the more expensive storage in order to keep the CCGTs, the industrial site and the pipeline system running. Indeed, the TSO has to control line pack with an eye on both the current intra-day needs and the contingency needs of the next gas day. When the historic shipper and the wind shipper have opposing positions, the net outcome depends on the dominant imbalance in this 2-shipper gas market. In the example of Figure 29.d, the historic shipper is actually helping the TSO to balance the system, whereas the wind shipper instigates the system imbalance.

[70] The no-wind case has a similar profile as the perfect-forecast case, except for the intra-day imbalance position of the wind shipper. At the end of the day, committed gas for CCGTs meets the gas consumed by the CCGTs in those cases.

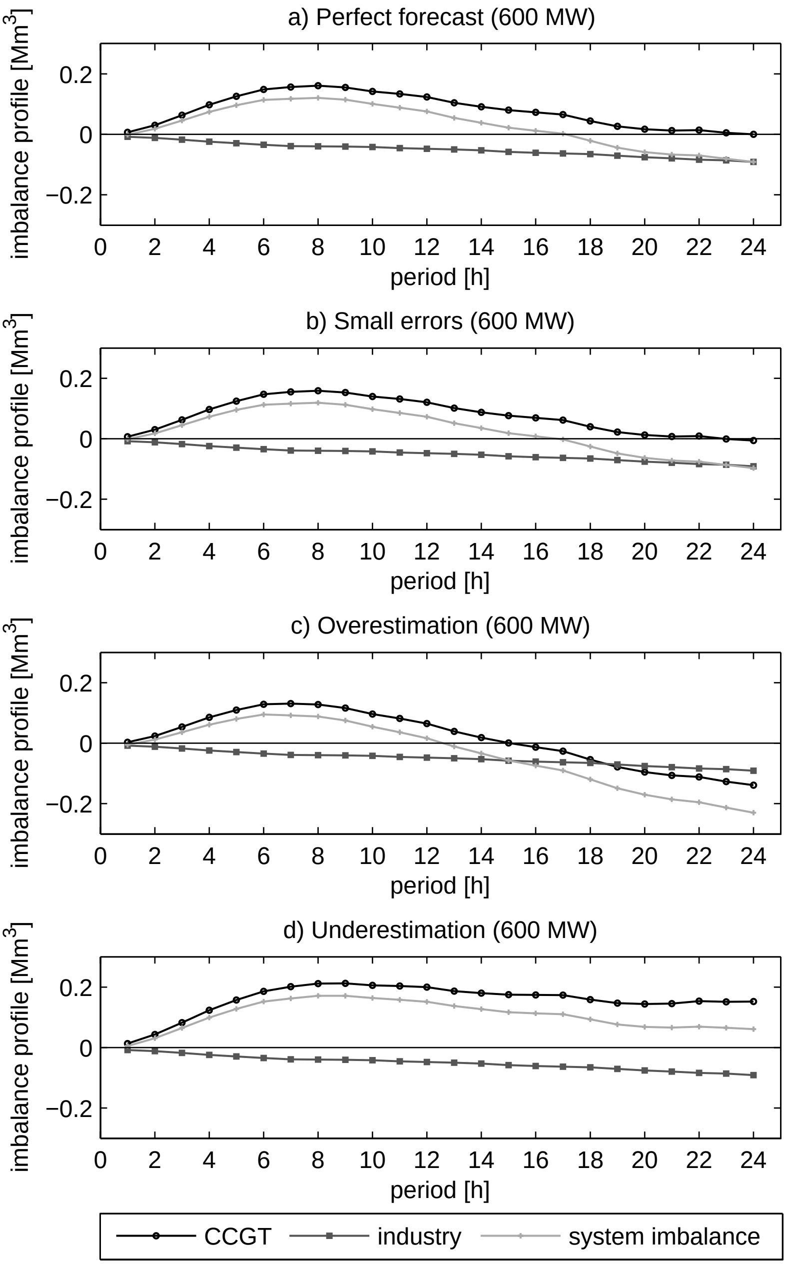

Figure 29. Shipper-imbalance and system-imbalance profiles after dispatching for short historic shipper (industrial demand exceeds supply) – The system imbalance represents the physical intra-day and end-of-day flexibility needs to be covered with line-pack flexibility and storage

Table 23 gives an overview of the dispatched flexibility on a net daily basis (end-of-day flexibility). Note that negative numbers indicate that gas is withdrawn from the line-pack or the storage (upward flexibility), whereas positive numbers indicate an increase of the buffered gas in the pipeline or in the underground storage.

Table 23. Dispatching of flexibility (daily net amount [Mm^3]) assuming a short historic shipper; positive: line-pack buffer / storage inflates; negative: line-pack buffer / storage decreases

	Perfect forecast	Small error	Over-estimation	Under-estimation	No wind
Line pack [Mm^3]	–0.091	–0.097	–0.176	0.061	–0.091
Storage [Mm^3]	0	0	–0.054	0	0

If insufficient gas is supplied because forecasts indicated low gas demand, the buffers are called upon to provide flexibility. This is the case for the first three forecast scenarios and the no-wind scenario of Table 23. The underestimation case (column 4 in Table 23), on the other hand, results in a net surplus of gas because the wind-shipper surplus exceeds the deficit of the historic shipper (Figure 29.d). In this scenario, the opposing imbalance positions actually help the overall system.

The net system-balancing costs are displayed in Figure 30. These net balancing cost are obtained by multiplying all used flexibility (related to maximum intra-day swing) with its respective variable cost.

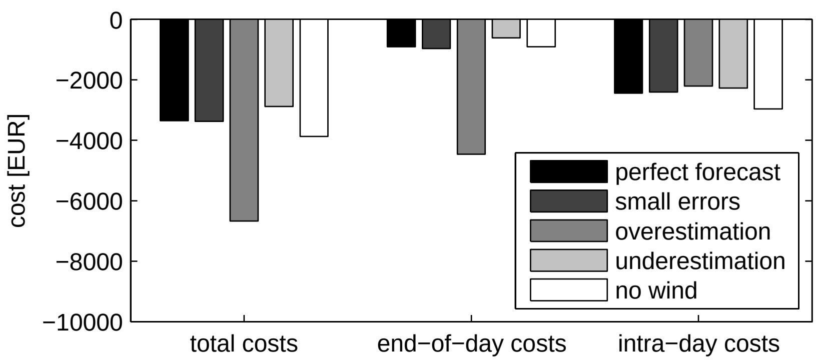

Figure 30. System-balancing costs [EUR] for one gas day (short historic shipper) – total costs are made up of intra-day balancing costs and end-of-day balancing costs; end-of-day costs are attributed to the unbalanced shippers, but intra-day costs are typically recovered outside the settlement mechanism, the relative division between the two cost types depends on the variability and unpredictability of demand

The balancing costs are more or less equal for all cases, except for the overestimation scenario, which has higher costs due to the dispatching of more expensive flexibility (see the merit order in Figure 28 for cost data and Table 23 for dispatching of flexibility). The balancing costs, then, are further broken down into "end-of-day costs" and "intra-day costs". The former represent the costs of the end-of-day system imbalance, meaning the costs that can be associated with unpredictability of gas demand. If shippers can predict demand perfectly, these costs would be avoided. The intra-day costs, on the other hand, reflect the flexibility that is used to cover temporary imbalances that are corrected by the aggregated shippers before the end of the balancing period. Indeed, shippers can, e.g., inject gas in the line-pack buffer during the night to use it during the morning. As such, these costs relate to the variable nature of the gas demand and the inherent mismatch between demand and supply in the shipper portfolio. The difference between the perfect-forecast case and the no-wind case entirely comes down to differences in variability as the end-of-day system imbalances are equal. Whether the intra-day costs or the end-of-day costs are dominant, depends entirely on the time patterns of supply and demand and the *ex-ante* flexibility in the portfolio of the shipper. In the end, both costs are transferred to the shippers either as balancing charges for unbalanced shippers or partly socialized in the tariffs for all shippers.

b. Historic shipper: long imbalance position

Similarly, Figure 31 reports the net balancing costs for an example in which the historic shipper overshoots actual demand and commits too much gas, resulting in a long imbalance position.

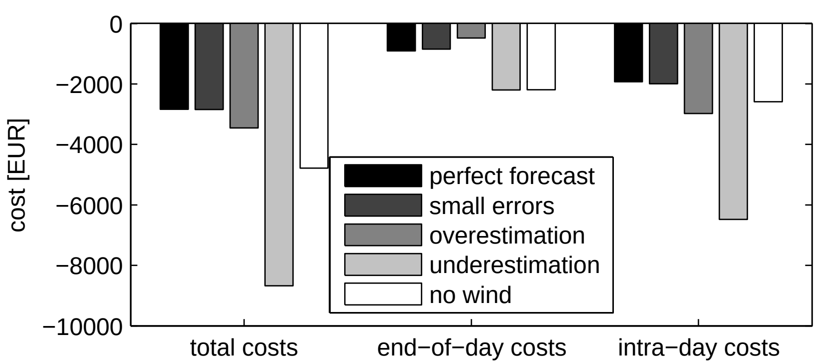

Figure 31. System-balancing costs [EUR] for one gas day (historic shipper is long) – total costs are made up of intra-day balancing costs and end-of-day balancing costs; end-of-day costs are attributed to the unbalanced shippers, but intra-day costs are typically recovered outside the settlement mechanism, the division between the two cost types depends on the variability and unpredictability of demand

This time, the balancing costs of overestimating wind are not problematic because the opposing imbalance positions reduce the overall system imbalance, avoiding the dispatching of expensive flexible gas. The costs of balancing when the wind power is underestimated, on the other hand, have exploded because both shippers have committed too much gas, resulting in the injection of gas into more expensive underground storage (Table 24). In the other scenarios, the line-pack buffer provided sufficient flexibility to ensure gas-system integrity.

Table 24. Dispatching of flexibility (daily net amount [Mm^3]) assuming a long historic shipper; positive: line-pack buffer / storage rises; negative: line-pack buffer / storage decreases

	Perfect forecast	Small error	Over-estimation	Under-estimation	No wind
Line pack [Mm^3]	0.091	0.085	−0.047	0.110	0.091
Storage [Mm^3]	0	0	0	0.133	0

Figure 32 shows the dynamically obtained merit order for the cases with a surplus for the historic shipper. The higher marginal costs of flexible gas in the underestimation case can be observed on the left-hand side. Note that system imbalances are long in four of the five cases because the historic shipper is now long.

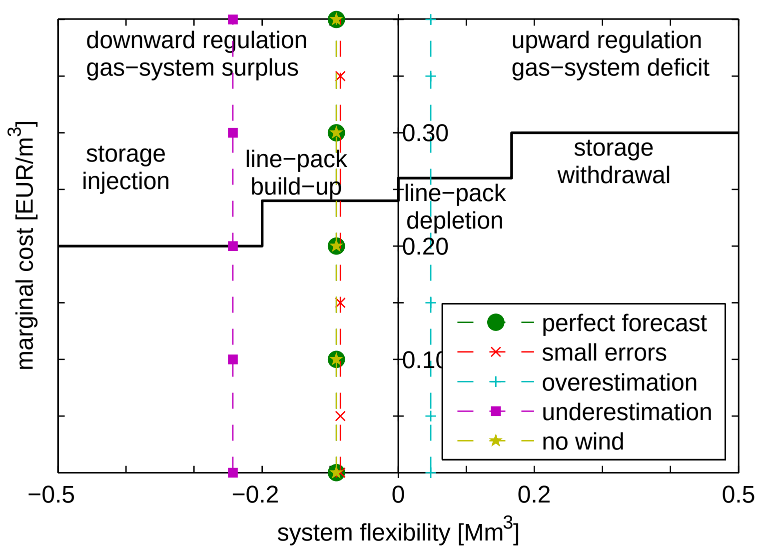

Figure 32. Merit-order curve for system flexibility (historic shipper is long): upward (downward) regulation to correct gas system deficit (surplus), the system-imbalance lines determine the effective marginal cost of system flexibility. The "no-wind" and "perfect-forecast" lines overlap.

c. Conclusion on effect of wind unpredictability on physical balancing

More important than the actual numbers, which depend on assumptions and hypothetical data, are the qualitative effects that are observed. The physical impact on the gas network depends on the relative positions of the shippers. If both commit too much gas, the network buffer can become exhausted and the TSO has to turn to more expensive resources. Historic gas demand is well understood, making forecasting future demand easier. Residential demand, for instance, is temperature dependent, but rather than relying on the predicted temperature of just the next day, it is common practice in the gas industry to make heating-demand forecasts using an equivalent temperature that takes into account the predicted average temperature for the next day as well as average-temperature data of previous days.[71] By experience the shippers know the accuracy of that prediction method. The transfer of wind-power unpredictability and variability, on the other hand, is a new phenomenon.

The actually available line-pack flexibility depends strongly on the starting conditions. Therefore, unpredictability makes system management harder. Furthermore, end-state limitations for the next-day contingency also affect the use of line-pack flexibility and whether or not more expensive flexible gas has to be dispatched. The balancing costs were observed to depend strongly on the starting conditions. Indeed, in many simulations the system was able to deal with the imbalances using just line-pack flexibility. It should be noted, however, that the TSO takes preemptive actions based on the unit commitment submitted by the shippers. These anticipatory actions can be contrary to what would have been done if all information had been correct, e.g., increasing the buffer because shippers are expected to go short intra-day when in real time the shippers have committed too much gas, further inflating the buffer. The TSO can only act on the same information as the shippers and is thus subject to erratic information. These situations, where the unpredictability and the low-quality information affect both the shipper and the TSO, are challenging the balancing of the network.

Taking the hypothetical network (Figure 27) under scrutiny, the pipeline between CCGT2, the industrial site and CCGT3 determines to a large extent the dynamics of the network as it forecloses supply from either A or B to a part of the gas system. One part of the system might have abundant cheap line-pack flexibility, whereas the other part might be forced to relying on more expensive storage gas. This problem, however, will only arise if there is physical congestion, which was not examined.

[71] This equivalent temperature is further linked to the degree-day concept that is frequently used in the heating sector as a measure for heating-services demand. The number of (equivalent) degree days is then obtained by subtracting the equivalent temperature from the predefined base temperature above which no heating is expected.

Evidently, the identified dynamics has existed before the introduction of massive wind power. Indeed, in the no-wind scenario, it can be observed that line-pack flexibility covers the within-day variability of demand in the same way as the scenario with perfect forecasting of wind-power output. However, wind-power unpredictability that is transferred to the CCGT gas demand creates additional challenges for the gas-system balancing. Therefore, wind-power unpredictability has a strong impact on the physical balancing of the gas system and its flexibility tools. And this impact is likely to increase in the future.

3.4.2 Imbalance settlement

Balancing occurs over a 24-hour interval in the EU and covers the actual gas dispatching. Balancing charges, then, are levied proportionally to the contribution of each individual shipper to the system imbalance. These balancing charges should be cost covering: either the total balancing costs or only the end-of-day costs that have been shown in Figure 30 and Figure 31. Balancing charges should also reflect actual costs and offer incentives to balance *ex ante*. First, a non-market-based design is examined, followed by a market-based design.

3.4.2.1 Non-market-based settlement

In case of non-market-based settlement, shipper imbalances are typically settled against a price referring to the local or an adjacent spot market for gas. Additionally, a penalty term often provides an incentive for the shipper to balance *ex ante*. Appropriate penalty levels are derived below for an imposed cost-neutrality by the TSO with regard to balancing costs. Strictly speaking, a penalty is neither cost reflective nor meant to recover costs, even though it can "unintentionally" help recover costs. But in the context of the analysis in this chapter, the break-even penalties serve as mark-ups on the reference price to achieve cost neutrality. Thus, the TSO recovers the system-balancing costs from the unbalanced shippers and he defines a break-even mark-up on the reference price to achieve this goal.

a. Historic shipper: short imbalance position

Table 25 shows the break-even penalties for the cases with a small deficit for the historic shipper. This break-even penalty is calculated by dividing the applicable balancing cost (see Figure 30) by the imbalance basis and the reference gas price. This imbalance basis, then, is the sum of the absolute values of the individual shipper imbalances. It has been explained before that settlement mechanisms often do not make a distinction between those who instigate the system imbalance and those who help the system with an opposite mitigating imbalance position. Therefore, both have to contribute to the recovery of the TSO's balancing costs.

Table 25. Non-market-based imbalance tariffs: break-even penalty (expressed as a percentage of the reference gas price) to achieve cost neutrality with regard to the total balancing costs or only the end-of-day costs for the case of the short historic shipper

Cost-neutral penalty	Perfect forecast	Small error	Over-estimation	Under-estimation	No wind
Total balancing cost	14.7%	13.9%	11.9%	4.75%	17%
End-of-day cost	4%	4%	7.73%	1.01%	4%

Intra-day costs are often socialized in the transmission tariff for all gas-network users. If that is the case, only the end-of-day balancing costs have to be recovered by means of the break-even penalty (second line in Table 25). The cost-neutral end-of-day penalties range between 1 percent and about 8 percent and are thus fairly low. If intra-day costs are not socialized, on the other hand, and all balancing costs have to be covered by a break-even penalty, this total penalty becomes two to four times as high as the end-of-day penalties, ranging from almost 5 percent till over 15 percent (first line in Table 25). A closer examination of the forecast scenarios reveals low penalty levels in the underestimation case. These particular levels are explained by the opposite imbalance positions of the historic shipper, who mitigates the system imbalance, and the wind shipper, who instigates the system imbalance (Figure 29.d). Their opposing positions reduce the aggregated system imbalance and lower balancing costs, on the one hand, and the imbalance basis is large because both shippers have an end-of-day imbalance, on the other hand. So, lower costs are divided over a larger imbalance basis; thus, requiring a small break-even penalty.

In the perfect-forecast and no-wind scenarios, the break-even penalties to recover total balancing costs are high compared to the scenarios with forecast errors. These high penalties indicate another problem of settlement design: in both scenarios the CCGT demand is perfectly predictable and the wind shipper balances over the day, resulting in an imbalance basis of zero. In other words, all balancing costs – including the intra-day costs caused by the wind shipper – are to be recovered from the historic shipper.

b. Historic shipper: long imbalance position

Table 26 summarizes the break-even penalties for the examined forecast scenarios if the historic shipper has committed too much gas. The interpretation of the penalties is similar to that made in the preceding subsection: the first line of Table 26 represents mark-ups to pass on all balancing costs to unbalanced shippers, whereas the end-of-day penalties recover only the end-of-day costs while the intra-day costs are socialized.

Table 26. Non-market-based imbalance tariffs: break-even penalty (expressed as a percentage of the reference gas price) to achieve cost neutrality with regard to the total balancing costs or only the end-of-day costs for the case of the long historic shipper

Cost-neutral penalty	Perfect forecast	Small error	Over-estimation	Under-estimation	No wind
Total balancing cost	12.5%	11.7%	6%	15.7%	15.4%
End-of-day cost	4%	3.51%	0.8%	12.8%	4%

End-of-day penalties range from below 1 percent to over 12 percent depending on the forecast scenario. The mark-ups that cover all balancing costs vary from 6 percent to almost 16 percent. This spread is again explained by the dynamics of the imbalance basis and the actual balancing costs. E.g., in the underestimation scenario, both shippers instigate the system imbalance. Even though the imbalance basis is large, the dispatching of expensive flexibility (Table 24) increases balancing costs to such a degree that the end-of-day and the total break-even penalties become high compared to the respective penalties in the other forecast scenarios. The overestimation case in Table 26 is similar to the underestimation case in Table 25: both shippers have opposing and non-zero imbalances reducing balancing costs while both shippers are contributing to the recovery of those costs.

c. Conclusion on effect of wind unpredictability on non-market-based settlement

The difficulty in determining a proper break-even mark-up for non-market-based balancing mechanisms consists in ensuring the mark-up is high enough to pass on either the end-of-day costs, if intra-day costs are socialized, or the total balancing costs, if all costs are allocated to the unbalanced shippers. Yet, these balancing costs depend on unpredictable system imbalances. Thus, the *a-priori* determination of a mark-up that recovers and reflects costs is nearly impossible.[72] The varying penalties for the different forecast cases in, e.g., Table 25 illustrate this statement: in some scenarios a 1-percent mark-up is sufficient, whereas in other, equally likely cases a 7-percent mark-up is required to cover end-of-day costs.

[72] It can be argued that cost recovery should not be accomplished on this very short term, but can be achieved, e.g., by charging a lump sum tariff (or tariff reduction) to all network users independent of the amount of used flexibility. However, such a lump sum fails to allocate costs to those causing them. Therefore, cost neutrality of the TSO should be achieved as close as possible to the balancing period because otherwise the link between cause (imbalance) and consequence (costs), or in other words, cost reflection is lost.

Slightly overshooting the break-even level, though, can still be justified in order to provide balancing incentives to shippers. Indeed, cost-neutral penalties are not efficient in providing incentives. However, in current settlement mechanisms the single penalty level is fixed and independent of the actually used flexibility. More-unpredictable gas demand will result in more occurrences of the low-quality-forecast cases, leading to inappropriate penalty levels burdening shippers or failing to recover balancing costs.

A risk-averse system operator might be tempted to overshoot the break-even penalty rather than end up with an inadequately low mark-up. This might be the case for Belgium, where penalty levels of 40 percent of the reference price and higher are charged. Either the actual costs of system flexibility are very high, perhaps including some kind of (pipeline) capacity cost, or the penalty just serves as deterrence for shippers. Either way, the Belgian (and other countries') penalties are not transparent. For the shipper, on the other hand, a fixed penalty allows an easy comparison of the *ex-post* exposure to imbalance charges to the costs of *ex-ante* flexibility.

3.4.2.2 Market-based settlement

However, European TSOs are changing their settlement-mechanism design toward market-based settlement. This settlement mechanism implies that market dynamics determines the price of flexible gas. A merit-order curve for flexible gas offered to the TSO, e.g., Figure 28 or Figure 32, can be used for balancing and to derive imbalance tariffs from. The flexible gas is then acquired from balancing-services providers (in the framework of this chapter, it is irrelevant whether this is the TSO or other, competitive flexibility providers) who have to be paid an appropriate fee. The TSO, then, has multiple options to charge unbalanced shippers. One option consists of charging the average cost of these services. This is equivalent with the outcome of the cost-neutral penalties determined in the preceding section. Or, as a second option, the charges can be linked to the cost of the marginal unit of either upward or downward balancing energy.[73] Marginal-cost pricing of imbalances can result in profits for the TSO, but it can be more efficient as it provides better incentives to both the shippers and the TSO regarding flexibility needs. In the following subsections, this marginal-cost pricing is used as the pricing rule for *ex-post* balancing.

a. Historic shipper: short imbalance position

Table 27 summarizes the results of market-based settlement for the cases where the historic shipper is short. The upper two rows in Table 27 report the cost contributions

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[73] Tariffs can be derived from the balancing merit-order curve in many different ways; the examples presented here are just two options that contain the principles of a market-based tariff.

(EUR) of the wind shipper and the historic shipper, respectively.[74] The final two rows in Table 27, then, display the degree of balancing-cost recovery (%) by the market-based charges, both with respect to the total balancing cost and the end-of-day cost. This degree, thus, indicates to what extent the balancing costs are passed on to the unbalanced shippers.

Table 27. Market-based imbalance tariffs (historic shipper has deficit): individual shipper contribution in terms of net balancing charges (EUR) and degree of balancing-cost recovery (%) of total market-based balancing charges

	Perfect forecast	Small error	Over-estimation	Under-estimation	No wind
Wind shipper contribution	EUR 0	EUR 58.7	EUR 6936.3	EUR 1520.7	EUR 0
Historic shipper contribution	EUR 909.8	EUR 909.8	EUR 4549.2	EUR 909.8	EUR 909.8
End-of-day cost coverage	100%	100%	259%	398%	100%
Total balancing cost coverage	27%	29%	168%	84%	24%

Compared to the single penalty of a non-market-based mechanism, marginal-cost-based imbalance tariffs ensure full recovery of at least the end-of-day costs associated with unpredictability in all cases: cost coverage is 100 percent or above (third line in Table 27). Furthermore, the unbalanced shippers receive clear signals with reference to the cost of *ex-post* balancing: they pay substantially higher imbalance charges if the marginal cost of flexibility increases. This is the case for the overestimation scenario. Indeed, both short shippers are cashed out at the higher marginal cost of dispatched upward flexibility from storage (Table 23): the historic shipper pays about 4500 and the wind shipper almost 7000. For both shippers this amount is much more than they pay in the other forecasts scenarios in which no expensive flexibility has been dispatched. The TSO even makes a profit as evidenced by the degree of cost coverage that is well above 100 percent for both recovery of end-of-day costs and recovery of total balancing costs. This profit can be used for the benefit of all network users by making investments in flexibility or by reducing the general transport tariffs that cover intra-day flexibility.

In the underestimation case, end-of-day unpredictability costs are also more than covered (398%), but the short historic shipper ends up paying for a system imbalance that he actually helped mitigate. If shippers are allowed to pool individual

[74] Note that these values are costs for just 24 hours of balancing and that the comparison of the values between different forecast-cases is more important than the exact numbers.

imbalances *ex post*, they can cooperate to reduce their exposure to balancing charges. For the TSO, on the other hand, such pooling would reduce the imbalance basis from which balancing costs can be recovered.

b. Historic shipper: long imbalance position

Table 28 reports the imbalance charges for the historic shipper and the wind shipper, and the degree of cost recovery of end-of-day costs and total costs for the case of a long historic shipper. The shippers face the higher marginal cost of dispatched storage flexibility (Table 24) if they are both long. Again, efficient prices are charged to the unbalanced shippers and these prices cover at least the end-of-day imbalances. In some scenarios, also the total balancing cost is covered by the market-based charges, but this is not a structural result.

Table 28. Market-based imbalance tariffs (historic shipper has surplus): individual shipper contribution in terms of net balancing charges (EUR) and degree of balancing-cost recovery (%) of total market-based balancing charges

	Perfect forecast	Small error	Over-estimation	Under-estimation	No wind
Wind shipper contribution	EUR 0	EUR 58.7	EUR 1387.3	EUR 7603.4	EUR 0
Historic shipper contribution	EUR 909.8	EUR 909.8	EUR 909.8	EUR 4549.2	EUR 909.8
End-of-day cost coverage	100%	114%	481%	156%	100%
Total balancing cost coverage	32%	34%	66%	127%	26%

c. Conclusion on effect of wind unpredictability on market-based settlement

If unpredictability increases, all shippers instigating larger system imbalances end up paying the high marginal cost of more expensive flexible gas; even if a shipper's contribution is limited. In the overestimation case of Table 27, the historic shipper's share of the system imbalance is about 33 percent (this can be visually confirmed in Figure 29.c) and he pays about 4500 euro or five time the amount of the no-wind case. But, if the wind shipper had avoided his massive forecasting error, the historic shipper would have paid about four times less as evidenced by the charges due by the historic shipper for the perfect-forecast and the overestimation case in Table 27.

Therefore, shippers with small imbalance positions of the same sign as the imbalances of dominant shippers dealing with massive unpredictability, such as gas demand related to intermittent wind power, are penalized by marginal-cost-based balancing because the small shipper pays a higher cost. And this cost is actually caused by the dominant shipper. The actions of such dominant shippers affect the price of flexibility and the assumption of price-taking shippers no longer holds.

Another peculiarity that has been observed in some simulations is the dispatching of expensive upward intra-day flexibility when the end-of-day imbalances of the system and the shippers were all positive. In that case, the shippers would only pay the marginal cost of downward flexibility instead of the expensive upward flexibility. This anomaly is dependent on the design of the settlement mechanism and can be remedied by making a distinction between those instigating and those mitigating the system imbalance at the time of the dispatching of expensive flexibility, or by reducing the balancing interval (e.g. hourly or every quarter-day) to better allocate costs.

3.5 Summary and conclusions on the effect of interactions with RES on gas-balancing design

This chapter has served a dual purpose. First, it has introduced an operations-research model to study shipper-portfolio optimization and subsequent optimal network balancing by the TSO, taking into account gas dynamics. Second, this model has been applied to studying the effect of increasing unpredictability on gas-balancing-mechanism design. GASFLEX is a versatile model and it is further applied to other balancing problems in the next chapters, but further improvements and extensions are possible.

Furthermore, this chapter has underlined how the integration of intermittent wind power poses challenges not only for the electricity system, but also for the gas system. Indeed, the two energy systems are becoming more and more interconnected. This impact has been studied by applying the electricity-generation concepts of "unit commitment", "power dispatching" and "forecast error" to the gas balancing problem.

Physically, the network flexibility and flexible gas need to cover potentially very large deviations of several percent of the (scaled) demand between gas "unit commitment" and gas "power dispatching". These deviations originate from the unpredictability of wind and the resulting forecasting error on the gas demand. System flexibility has to cover this imbalance, with increasing unpredictability leading to the dispatch of more expensive flexible gas to cover the physical swing. Therefore, unpredictability raises the costs of system balancing.

The impact on financial gas balancing is closely related to the increased physical swing: large prediction errors cause large gas-system imbalances, requiring more expensive flexible gas in a market-based-balancing framework. Such a balancing mechanism provides clear incentives to balance the system *ex ante* because the more unbalanced the system, the less favorable the *ex-post* balancing charges become. The downside of this mechanism is a risk that massive uncontrollable and unpredictable wind increases gas-system imbalances and thus deteriorates the balancing conditions for all other users, who cannot be held responsible for the gas matching problems of the wind shipper. Indeed, dominant shippers with an unpredictable portfolio could become price setters instead of price takers.

The non-market-based settlement, that is currently the main design in Europe, is not really affected by wind-power integration because this kind of system is to a large extent independent of gas-balancing dynamics.[75] Yet, the main difficulty consists of determining an appropriate fixed penalty that results in passing on balancing costs and at the same time does not harm shippers by being excessive.

Both settlement-mechanism designs, however, fail to recover the full cost of balancing, meaning the costs associated with intra-day and end-of-day imbalances. Indeed, the intra-day costs are absorbed by the TSO and socialized by means of the general transport tariffs, confirming the findings of Chapter 2. Better and more efficient cost allocation is achieved if shorter balancing intervals are used.

Policy makers advocating renewable energy sources like wind power are sometimes aware of the impact on the electricity system, but are almost never aware of the consequences on the gas system. Certainly, from a regulatory point of view, the gas system is impacted by the transfer of intermittency. This has been demonstrated in this chapter with regard to the physical balancing of the gas system and the settlement of imbalances afterwards.

The analysis presented here is an *a posteriori* study of the impact of wind power on gas. Other methods should be applied to make an *a priori* assessment taking into account interactions between the gas actors, especially in the market-based case. This would require another class of models: equilibrium modeling. Evidently, real balancing designs are substantially more complex and try to remedy some of the fallacies of simple designs, but the main findings are general enough to hold because complex designs still use the basic building blocks. For instance, the addition of *ex-ante* flexibility would allow the shipper to modulate demand and reduce imbalances, but prediction errors would still be present on a very short term.

Furthermore, the study in this thesis is the first to explicitly associate the challenges of designing gas-balancing mechanisms to the issue of wind-power integration, or more in general, increasing unpredictability of gas demand. It provides a first step in a field where further research is needed to streamline the operation of future closely interconnected electricity-and-gas systems.

[75] At the time of writing of this thesis, non-market-based settlement is the dominant design, but designs are changing towards market-based settlement.

PART 3

Cross-border aspects of gas balancing

4. FUNDAMENTALS OF CROSS-BORDER BALANCING

The liberalization of the gas markets in the EU also aims for market integration and, in the end, a common gas market. Therefore, the playing field has changed from the national level to the European level. Indeed, competitive market players are active in different geographical regions, maximizing profit using a transnational approach towards optimal allocation of their resources. At the same time, and despite the third regulatory package of the EU liberalization effort [6; 7], the network regulation remains predominantly national. As a result, the balancing rules defining the gas-balancing mechanism show a great diversity. This has been illustrated in Chapter 1.

The previous parts of this thesis focused on effects of balancing-mechanism design and network regulation in a national or "single-zone" context. This third part, then, explicitly deals with transnational issues of gas balancing. Cross-border balancing can be investigated from two viewpoints. The design of a multi-region gas market is a first approach and is discussed in the first subsection, but is not further investigated in this thesis. A second approach consists in looking at the coordination of rules in a postulated multi-region context. A second subsection introduces this second approach to cross-border balancing. It is this final approach that is further used in the subsequent chapters of this third part.

4.1 Design of a multi-region gas market

Although the objective of the EU legislation is to create a common market for gas, the EU gas market is not a single market. Indeed, borders remain present within the area covered by that EU legislation. For historical reasons, these demarcated zones correspond mainly to national markets or smaller geographical areas that have been controlled by a historic monopolist utility company. As a result, these demarcated geographical regions often have no economic or technical justification and the presence of a multitude of (too) small zones, e.g., with regard to the consumption or the amount of traded gas, has been found to hamper new entry [177]. At the same time, removing all barriers to create a single market area is not achievable at this time due to technological, e.g., pressure management and congestion, and possibly also organizational limitations and costs.

Therefore, the design and organization of the multi-region gas market, including the sizing of market areas and balancing zones has been, and still is a topic of interest for the regulators, TSOs and other gas-market participants. Different possible gas-market models have been developed by, e.g., Ascari [178], Glachant [179], Moselle and White [180], Clingendael [181], and Frontier Economics et al. [182]. Note that these models represent target models to be achieved on a horizon of 10-15 years and that they represent different visions on the market design. Ascari [178], for instance, presents a market model, that draws from the organization of the US gas market and is relying on the interactions between market forces – as in the US gas-commodity *and* gas-transport markets – and regulation to organically achieve a functioning organization of the EU gas market, whereas the other models remain closer to the present institutional framework of the EU gas market.[76] For a discussion on the main differences between the models see, e.g., [183] and [184].

Finally, the European regulators have published their vision on a European target model for the gas market [185]. This CEER target model reflects the main principles of the MECOS (Market Enabling, COnnecting and Securing) model developed by Glachant [179; 184]. In the discussion below, the focus is on those aspects of the MECOS model that are relevant to the organization of balancing. The full details of the model, however, should be consulted in the original work.

With regard to the sizing of market regions, and balancing zones, the MECOS model suggest two ways of rethinking the currently too small market regions to obtain functioning wholesale markets. A functioning gas market is then defined as "*a single price zone that is accessible to incumbents and new entrants on equal terms and where trading is liquid…*" [179, p. 13]. Furthermore, a number of key indicators to estimate the functionality of a market are presented: e.g., a Hirschmann-Herfindahl Index (HHI) of below 2000, participation of at least three producers and a great many gas consumers combining for a total consumption of about 20 BCM, and presence of at least three entry points into the zone.[77]

A first design option to obtain functioning markets consists of the "market area model". In this model, well connected transmission and distribution networks in a geographical area are organized in a single entry-exit zone. This single zone serves then as a virtual market place and has a single balancing mechanism with one set of rules for the area.

The alternative design option consists of the "trading region model".[78] In this model, a number of TSOs establish a common entry-exit zone on the supranational transmission level, while keeping national balancing zones for the end users. The common entry-exit zone, again, serves as a virtual trading point for both the supranational and national levels. With regard to balancing, this second model does not require a single set of balancing rules in the different balancing zones.

[76] The US gas market has been discussed more extensively in Chapter 1.
[77] HHI is a measure of market concentration obtained by adding the squared market shares, expressed in percentage points, of the market players.
[78] Note that "region" in the MECOS model means "supranational", whereas throughout this thesis region refers to a geographical area with a particular set of balancing rules.

Furthermore, the participating TSOs could establish a single balancing entity or the TSOs keep separate accounts of trades on the supranational level. The balancing of shippers is then effectively carried out on the level of the national balancing zone.

The choice for either of the design options and the number of remaining borders – or, alternatively, the size of the market regions – will be the result of a cost-benefit analysis with regard to the organizational and physical reality that has to be dealt with. Furthermore, the two design options can co-exist in the resulting multi-region gas market.

However, the sizing of market regions and balancing zones is not further dealt with in this thesis because the study of that topic requires an investigation of the market design well beyond just balancing.

4.2 Efficiency in a cross-border context

Cross-border balancing can also be looked at as the coordination of market players by multiple sets of balancing rules in a postulated multi-region market design. Because this approach focuses on the efficiency objective of the EU gas-market reforms, the efficiency of multi-region balancing is examined using a self-developed methodology based on "welfare" benchmarking.

Welfare is an important economic concept that is used extensively to assess effects of policy and regulatory decisions [186]. The welfare definition is traditionally based on consumer surplus and producer surplus, reflecting utility of all citizens who offer and demand products in a region. In this thesis, however, a deviating definition is used based on efficiency. Indeed, a surplus function is defined for the shippers (profit maximization) and the TSOs (cost minimization), respectively. The shipper surplus is similar to the classic producer surplus of profit-maximizing competing businesses. The role of the TSO, on the other hand, should not be limited to his functioning as the regulated monopolist who operates the network. Indeed, in light of the efficiency objective, the TSO should be interpreted as an agent representing a great many gas consumers and should be regulated accordingly. Hence, cost minimization as a goal for the TSO is justified as the TSO's costs are in the end borne by the gas consumers.

Next, "welfare", i.e. the sum of the shipper surplus and the TSO surplus is calculated, first, in autarky, when regions operate autonomously without interactions, and, second, under assumption of market integration, when cross-border interaction is possible. Costs are calculated using the multi-period GASFLEX model that has been introduced in Chapter 3 and is extended here to deal with multiple gas regions.

In an imperfectly integrated gas market that is still built on national rules, it is not ensured that the cross-border welfare is optimized because of differing regional interests. In this work, however, it is investigated how the overall efficiency in the integrated gas market can increase. Thus, the TSOs represent the respective gas consumers in their region, but it is the total efficiency that is optimized, in line with the common-market philosophy that is the capstone of the EU project.

4.2.1 Shipper-driven efficiency

As far as the shipper is concerned, cross-border balancing affects the settlement of imbalances. Indeed, shippers that are active in geographically adjacent regions optimize their nominations taking into account the different settlement rules in the regions. The effects of cross-border operating shippers on the settlement of imbalances and the costs of balancing the respective gas networks are examined in Chapter 5. Cross-border imbalance settlement has been investigated for electricity and is found to potentially induce market distortions because what is profitable for an individual shipper can harm the system as a whole if imbalance movements oppose movement of TSO-procured flexibility [77].

4.2.2 TSO-driven efficiency

TSOs, on the other hand, can cooperate on the procurement of flexible gas and the exchange of line-pack flexibility. Vandezande [77] has identified two cooperation mechanisms regarding cross-border electricity balancing: either balancing-services providers offer their services directly to multiple transmission-system operators (TSO-BSP cooperation), or TSOs in geographically adjacent control areas trade the balancing services they have contracted or are able to acquire individually (TSO-TSO cooperation). The most complete form of such TSO-TSO trading, still according to [77], is the use of a single merit order with all offers for balancing services in the combined control area. Each mechanism imposes transaction costs regarding implementation. And TSO-BSP-implementation costs are expected to be lowest. Indeed, current balancing-mechanism design can be continued in that framework, but the individual TSOs can procure from domestic and foreign flexibility providers. TSO-TSO cooperation, on the other hand, implies some sort of coordinated approach to balancing-mechanism design. The possible efficiency gains of TSO-TSO cooperation regarding procurement of flexible gas are investigated in Chapter 6.

The approaches of Chapter 5 and Chapter 6 can also be combined: having TSOs who efficiently procure flexibility and price *ex-post* balancing services accordingly, and transnational shippers responding to these efficient prices. This problem setting is not effectively modeled, but it is reflected upon at the end of Chapter 6, where cross-border settlement is discussed.

5. FORUM SHOPPING FOR BALANCING RULES: CROSS-BORDER SETTLEMENT[79]

This chapter assesses the effects of gas-market integration with regard to cross-border settlement. In the integrated EU gas market, competitive shippers are active in different regions that still apply different balancing rules. The profitability of "forum shopping" is then demonstrated for settlement-mechanism designs that are not aligned across borders.[80]

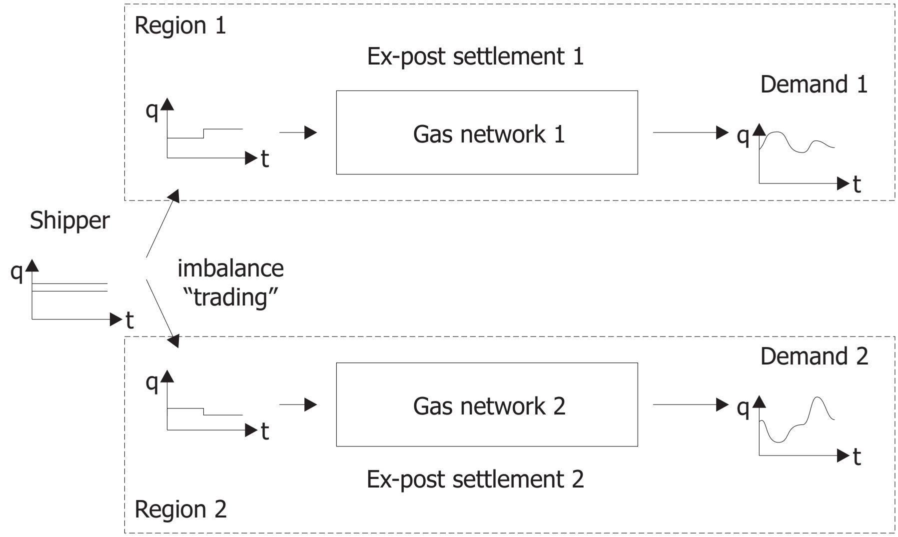

Figure 33. Schematic overview of cross-border settlement as viewed by the shipper (stage 1): the transnational shipper faces portfolio matching problems, but can "trade" imbalances between regions by adapting his entry nominations; imbalances are moved towards regions that offer cheaper settlement of ex-post-balancing services; in the graphical illustrations of demand and supply, "q" stands for an amount [Mm^3/h, to be integrated over the length of a period] and "t" stands for the hourly time periods [h]

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[79] The material in this chapter has been submitted for publication: Keyaerts, N., D'haeseleer, W., 2012. Forum shopping for *ex-post* gas-balancing services [187].

[80] "Forum shopping" is a concept originally used in the legal world and refers to the practice of choosing the jurisdiction to affect the expected outcome of a ruling [188]. This thesis transposes the concept to the gas system referring to the behavior of shippers to move imbalances to the system with the more lenient balancing mechanism.

Figure 33 provides a schematic overview of the problem from the perspective of the shipper. A transnational shipper has gas-sales contracts in two regions and has a gas-supply contract to deliver gas in both regions. For matching supply and demand the shipper relies on *ex-post*-balancing services. Because the settlement of these services is handled differently in the two regions, the shipper can arbitrate between the two settlement mechanisms. Indeed, the shipper can modulate his supply and "trade" imbalances between the regions to maximize profit.

The second stage of the forum-shopping problem deals with the respective TSOs and is schematically illustrated in Figure 34. The TSOs have to balance their regional system using domestic resources. Balancing costs in the respective regions, then, depend on the efficiency of the TSOs to balance their respective system, but also on the imbalance that is attracted to the respective regions through the comparative settlement costs for the shippers.

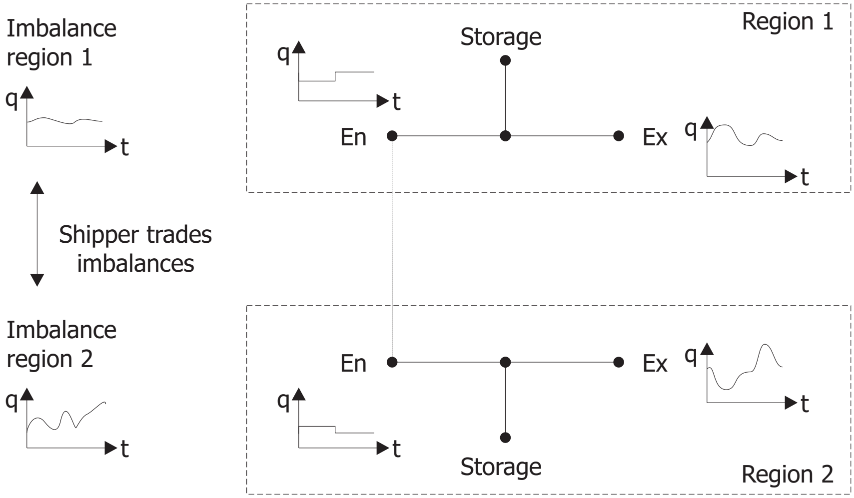

Figure 34. Schematic overview of cross-border settlement as viewed by the TSO (stage 2): the regional TSOs face system imbalances that depend on the incentives that are provided through the respective settlement designs; TSOs rely on domestic network and storage flexibility; in the graphical illustrations of demand, supply and imbalance, "q" stands for an amount [Mm^3/h, to be integrated over the length of a period] and "t" stands for the hourly time periods [h]

The chapter is organized as follows. First, the problem setting is introduced. Next, the self-developed methodology is explained, followed by a discussion of the results with respect to the shipper efficiency and the TSO efficiency. The chapter ends with a summary of the findings and the main conclusions regarding balancing design.

5.1 Introduction: cross-border operating shippers in imperfectly integrated gas markets

The balancing mechanism acts as an interface for the recombination of different gas-market functions in the liberalized and unbundled market. At the same time, national gas markets are connected by border capacities. Thus, shippers are enabled to ship gas between different sets of rules, providing incentives for profit-maximizing shippers to commit to "forum shopping" for imbalance-settlement rules. In other words, the shipper chooses the most lenient settlement mechanism. This incentive is investigated by modeling different imbalance-settlement mechanisms and comparing the costs of *ex-post* balancing, which in the end should represent the worst case balancing conditions. Indeed, any shipper can turn to the TSO-balancing mechanism for flexibility, independent of his access to *ex-ante* flexibility.

It has been shown that current European balancing rules regulate line-pack flexibility inefficiently [48]. Thus distorting both the competitive and non-competitive parts of the gas market. The balancing period was identified as a main distorting factor because its current definition allows for cross-subsidization of heavy users of *ex-post*-balancing services by smaller users of network flexibility. Indeed, intra-period imbalances are often completely covered by the TSO and these costs are carried by all network users instead of the users causing the flexibility needs.

So, differences in formal and effective balancing periods create opportunities for arbitrage. Indeed, shippers can move imbalances to gas regions that have longer balancing periods or that are more lenient towards intra-period imbalances. This movement of imbalances affects both the shipper profitability and the costs of gas-system balancing.

First, the perspective is taken of a profit-maximizing shipper who relies on *ex-post*-balancing services to match demand and supply. Three demand profiles are considered: volatile residential demand, gas for electric power generation and fairly flat industrial demand. A typical shipper will have a mixed customer portfolio, but to have a range of demand-profile characteristics, only unmixed generic demand profiles are looked at.

In a second step, the viewpoint of the system-balancing TSO is taken. TSOs face differences in local efficiencies of the balancing instruments and, thus, differences in balancing costs. If geographically adjacent regions apply settlement mechanisms that provide wrong incentives, the combined efficiency of the regional TSOs can reduce as the costs increase. This TSO-efficiency loss is possible if a region that has abundant cheap flexibility, nevertheless implements a stringent settlement mechanism to deter shippers from having imbalances. These shippers turn to more lenient settlement mechanisms that might have less-efficient flexibility. Policy makers and gas-market regulators should be concerned about these efficiency losses and strive to harmonize or at least make balancing mechanisms compatible across borders and have them provide correct cross-border incentives.

The exemplary case studies in this chapter are in part hypothetical because data, mainly on network costs, were not sufficiently available. In order to correctly capture the range of possible effects, multiple cases are examined. The settlement designs, however, are modeled according to real practice and market-price data for different regions are based on real market prices in different regions. The developed methodology, however, can be used to study and compare real balancing-mechanism-arbitrage opportunities in adjacent gas markets if the actual data are available.

5.2 Welfare methodology

The developed methodology calculates the efficiency gains of the shipper and the TSO when shippers apply a forum-shopping strategy (FS) compared to the benchmark autarkic strategy (AUT). In autarky, the shipper follows a national strategy excluding any movement of imbalances across borders. The forum-shopping strategy, on the other hand, concerns a cross-border optimization by the shipper, moving imbalances to the more lenient settlement mechanism. Both strategies assume nationally operated systems. Therefore, the respective TSOs can only rely on domestic sources of system flexibility.

5.2.1 Welfare and efficiency definitions

Shippers engage into forum-shopping behavior if this is a profitable strategy. The efficiency surplus of the shipper in the combined region ($\Delta S_{shipper,R1+R2}$) is, therefore, defined as the difference between the profit applying the forum-shopping strategy and the profit using the autarkic strategy in the separate regions:

$$\Delta S_{shipper,R1+R2} = \left(profit_{FS,R1} - profit_{AUT,R1}\right) + \left(profit_{FS,R2} - profit_{AUT,R2}\right) \tag{5.1}$$

Profit has been defined in GASFLEX (Chapter 3) as the revenues of selling gas minus the costs of importing gas and the imbalance costs (and costs of *ex-ante* flexibility if applicable).

The TSO-efficiency function ($\Delta S_{TSO,R1+R2}$) in the combined region, then, is defined as the sum of the regional costs of balancing the system when shippers nominate according to the FS-strategy minus the balancing costs in the case that the shippers nominate according to the benchmark AUT-strategy:

$$\Delta S_{TSO,R1+R2} = \begin{pmatrix} \left(balancingcost_{FS,R1} - balancingcost_{AUT,R1}\right) \\ +\left(balancingcost_{FS,R2} - balancingcost_{AUT,R2}\right) \end{pmatrix} \tag{5.2}$$

Note that *balancingcost* are negative numbers, ensuring that positive surpluses correspond to efficiency gains for the TSO, whose costs affect all gas-network users. Hence, a negative TSO surplus is a loss for the whole community of gas-market actors. The TSO surplus refers to costs only as the TSO-efficiency criterion since it is not the objective of the TSO to make a profit with his balancing activities.

To know the impact of forum shopping on the net welfare, thus the change in total efficiency in the combined region (ΔW_{R1+R2}), the total shipper-efficiency surplus and the total TSO-efficiency surplus have to be added:

$$\Delta W_{R1+R2} = \Delta S_{shipper,R1+R2} + \Delta S_{TSO,R1+R2} \tag{5.3}$$

5.2.2 Gas pipeline systems

The comparative efficiency benchmarking requires the modeling of two distinct gas systems in geographically adjacent regions. Indeed, a physical interconnection must be present to allow forum shopping. Furthermore, a single shipper is assumed to be active in both regions. In other words, the shipper optimizes entry and exit nominations in the most profitable way accounting for the two sets of balancing rules.

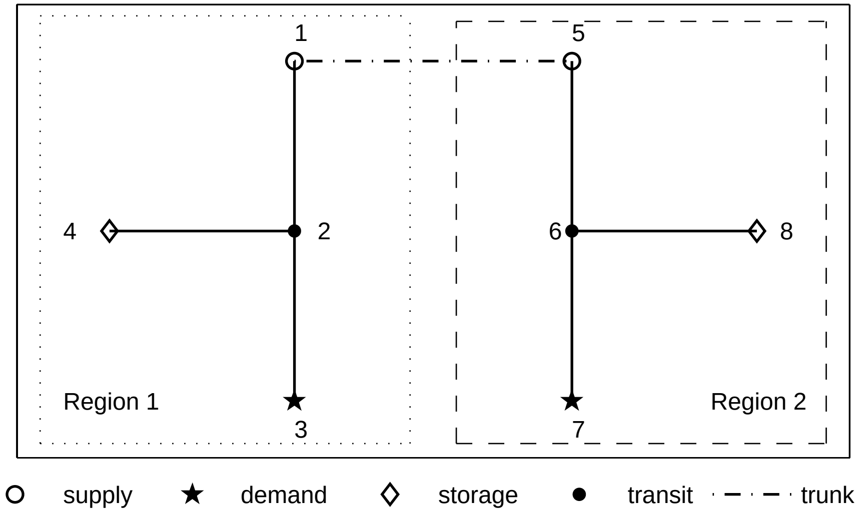

Figure 35. Hypothetical gas-pipeline systems in two geographically adjacent and physically interconnected regions, region 1 equals nodes 1-4 and region 2 nodes 5-8, the networks consist of gas import nodes (1 and 5, o), gas demand nodes (3 and 7, ★), storage nodes (4 and 8, ◇) and transit nodes (2 and 6, ●). Compressors are stationed in nodes 1 and 5. The physical interconnection (dash-dotted line) has to be interpreted as a big trunk line passing through nodes 1 and 5 from which both regions draw gas.

Figure 35 plots the hypothetical gas networks in region 1 and region 2. Each gas system consists of an entry node (nodes 1 and 5) through which gas is imported. Next, gas is consumed downstream in nodes 3 and 7. Besides pipeline storage, the systems each have an underground storage to provide flexible gas (nodes 4 and 8). The other nodes are just for transit, connecting multiple pipelines. The physical interconnection between the regions can be interpreted as a trunk line from which both regions draw gas, allowing the shipper to move imbalances by changing entry nominations in both regions. Finally, compressors are located in both entry nodes. Further technical details on the gas network are provided in Appendix C.

5.2.3 Data and assumptions

To isolate the effects of the settlement-mechanism design on the shipper behavior, *ex-ante* flexibility is disregarded in the model. The introduction of *ex-ante* flexibility would decrease imbalance costs at the cost of having to contract and deploy other flexibility like storage or flexible production. However, the focus in this chapter is on the arbitrage possibilities between different sources of *ex-post* flexibility provided through the settlement mechanisms.

5.2.3.1 Demand

Three generic demand profiles are considered: a) residential demand, b) GFPP demand and c) industrial demand. The demand profiles are scaled to an average hourly demand of 1 Mm^3/h and cover two gas days, adding up to 48 hours, as illustrated in Figure 36.

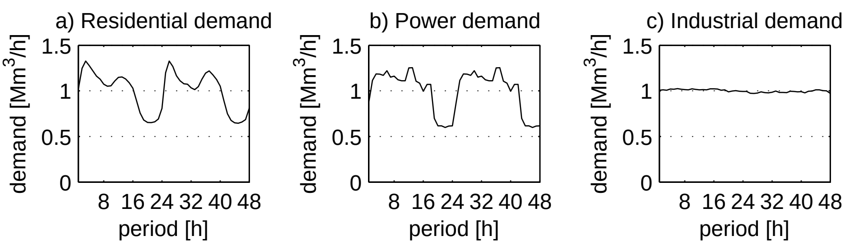

Figure 36. Generic demand [Mm^3/h] profiles for residential users, electric power generation and industry for two gas days; the average hourly demand has been scaled to 1 Mm^3/h

5.2.3.2 Supply

The supply side is assumed to be rigid in both regions. Indeed, the shipper has a major import contract for both regions and just chooses where to move the gas to. Furthermore, once an amount of gas is committed for a day, the amount cannot change. Re-nomination of gas between regions, on the other hand, is assumed possible. In fact, this re-nomination is the driver behind moving imbalances.

So, committed gas is entered ($\dot{V}buy_{r,h}$) in each region *r* throughout the day based on forecasted demand for the respective regions. The effective demand ($\dot{V}sell_{r,h}$) deviates from the forecasted demand according to a supposed forecast error. Because no *ex-ante* flexibility is considered, shippers rely completely on the *ex-post*-balancing mechanism for inevitable intra-day imbalances. In the absence of *ex-ante* flexibility, the daily portfolio imbalance in autarky comes down to the difference between the purchase contracts and the sales contracts for a region:

$$\sum_h \dot{V}buy_{r,h} - \sum_h \dot{V}sell_{r,h} = \sum_h \dot{V}imb_{r,h} \qquad (5.4)$$

Where $\dot{V}imb_{r,h}$ represents the hourly regional imbalance in the shipper portfolio.

When shippers pursue a forum-shopping strategy, Eq. (5.4) is replaced by Eq. (5.5). In that equation, cross-border movement ($M_{r,h}$ expressed in Mm^3/h and positive for import into region *r*) is added to represent the possibility of imbalance trade.[81]

$$\sum_h \dot{V}buy_{r,h} - \sum_h \dot{V}sell_{r,h} = \sum_h \dot{V}imb_{r,h} - \sum_h M_{r,h} \qquad (5.5)$$

To have a range of relevant cases, 11 forecast errors (FE) are applied on the generic demand profiles for each of the three demand types (Figure 36), resulting in 33 (3x11) supply profiles ranging from underestimating demand at 85 percent, so 15 percent short, over perfect forecasting to overestimating demand at 115 percent, meaning 15 percent of surplus gas is injected in the system on a daily basis.[82]

5.2.3.3 Settlement mechanism

Different settlement-mechanism designs are the main driver for forum shopping. As a case study, the settlement mechanisms of Belgium and the United Kingdom are revisited (see Chapter 1 for more examples). These mechanisms serve as excellent illustrations of the different settlement-design options. Moreover, these two gas systems are effectively adjacent and connected by a physical infrastructure, making forum shopping a real possibility.

The UK applies daily imbalance settlement with a double-price mechanism. Indeed, the UK's TSO uses a different spot-market-based price [51] for buying gas from shippers facing long positions and selling gas to shippers facing short positions. The spread between the system marginal prices for buying (SMP_{buy}) and selling (SMP_{sell}) gas compared to the average price constitutes an implicit penalty for unbalanced shippers.[83] Furthermore, the TSO does neither impose fees for intra-day imbalances,

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[81] The straightforward interpretation of this "movement" is the re-nomination of entry in the respective regions.
[82] The superimposed forecast errors on the daily demand range from -15% to +15% in steps of 3 percentage points: -15%, -12%, -9%, -6%, -3%, 0%, +3%, +6%, +9%, +12%, +15%.
[83] The definitions of the system marginal prices can be simplified to: the "SMP_{buy}" is the highest price paid for a balancing action for the day; whereas the "SMP_{sell}" is the lowest price offered for a balancing action for the day [53].

nor are any tolerances granted. Details of the UK balancing mechanism can be found in the UK's network code [53].

Mathematical imbalances (Mm^3), meaning the mathematical difference between gas entered ($\dot{V}buy_{r,h}$) and gas withdrawn ($\dot{V}sell_{r,h}$) over a period *h* in region *r*, are transformed into economic imbalances (Mm^3). These transformations are made for modeling reasons and they account for nominations, applicable tolerances and penalties. The imbalance fee in euro is then obtained by multiplying the different economic imbalances with the applicable reference price(s). Thus, it is the economic imbalance that serves as a corrected basis for levying imbalance charges.

Table 29 summarizes the transformations for the UK. Mathematical hourly and cumulative-hourly imbalances are transformed to 0 and, therefore, do not give rise to any penalty charges. With regard to the end-of-day imbalance, a distinction is made – for modeling reasons – between the (possible) imbalance penalty and the cash out. The UK settlement mechanism does not impose an explicit daily penalty; so, the end-of-day imbalance is in that case transformed into an economic imbalance of 0. For the cash out, on the other hand, the shipper is accountable for his full mathematical imbalance. Hence, the economic imbalance for daily cash out is the same as the shipper's mathematical imbalance. For short shippers, then, the applicable reference price is the SMP_{buy} and for long shippers the SMP_{sell}.

Table 29. UK – Transformation of mathematical imbalances (nominations) into economic imbalances (nominations, tolerances and penalty part) that serve as a basis to charge balancing fees

UK transformations	Mathematical imbalance [Mm^3]	Economic imbalance [Mm^3]
Hourly penalty	$\dot{V}buy_h - \dot{V}sell_h$	0
Cumulative penalty	$\forall$ h: $\sum_h (\dot{V}buy_h - \dot{V}sell_h)$	0
Daily penalty	$\sum_h (\dot{V}buy_h - \dot{V}sell_h)$	0
Cash out (daily)	$\sum_h (\dot{V}buy_h - \dot{V}sell_h)$	$\sum_h (\dot{V}buy_h - \dot{V}sell_h)$

Belgium, on the other hand, has a much more complex balancing mechanism as demonstrated by Table 30. The formal balancing interval is one day, but hourly short positions are also penalized, and the peak cumulative imbalances within the day give also rise to an imbalance charge. Furthermore, shippers receive tolerances pro rata of their booked transport capacity and penalties are further charged according to a stepwise-linear function for long and short shipper positions.

Table 30. Belgium – Transformation of mathematical imbalances (nominations) into economic imbalances (nominations, tolerances and penalty part) that serve as basis to charge balancing fees

Belgian transformations	Mathematical imbalance [Mm^3]	Economic imbalance [Mm^3]
Hourly penalty	$\sum_h (\dot{V}buy_h - \dot{V}sell_h)$	Long: 0
		Short: $\dot{V}buy_h - \dot{V}sell_h - Tol\text{-}H$
Cumulative hourly penalty	max($\forall$ h: $\sum_h(\dot{V}buy_h - \dot{V}sell_h)$)	0→Tol-CH: 0
		Tol-CH→2Tol-CH:
		0.4 $\sum_h (\dot{V}buy_h - \dot{V}sell_h - Tol\text{-}CH)$
		2Tol-CH→3Tol-CH:
		0.6 $\sum_h (\dot{V}buy_h - \dot{V}sell_h - 2Tol\text{-}CH)$
		3Tol-CH→…:
		0.8 $\sum_h (\dot{V}buy_h - \dot{V}sell_h - 3Tol\text{-}CH)$
Daily penalty	$\sum_h (\dot{V}buy_h - \dot{V}sell_h)$	0→Tol-D: 0
		Tol-D→2Tol-D:
		0.4 $\sum_h (\dot{V}buy_h - \dot{V}sell_h - Tol\text{-}D)$
		2Tol-D→3Tol-D:
		0.6 $\sum_h (\dot{V}buy_h - \dot{V}sell_h - 2Tol\text{-}D)$
		3Tol-D→…:
		0.8 $\sum_h (\dot{V}buy_h - \dot{V}sell_h - 3Tol\text{-}D)$
Cash out (daily)	$\sum_h (\dot{V}buy_h - \dot{V}sell_h)$	$\sum_h (\dot{V}buy_h - \dot{V}sell_h)$

Note 1: transformations are symmetrical if no distinction is made between short and long

Note 2: tolerances are symmetrical, but of opposite sign for short and long positions

Note 3: *max* becomes *min* for negative cumulative imbalance

For instance, a daily penalty of 0 is applied for imbalances within the limits of the daily tolerance (*Tol-D*), 40 percent of the reference price is due for the part of the imbalance between *Tol-D* and two times *Tol-D*, 60 percent between twice *Tol-D* and triple *Tol-D*, and, finally, 80 percent beyond three times the daily tolerance level. The cumulative penalties, which are due for the peak positive and peak negative cumulative imbalances, are determined in a similar way. The cash out of the end-of-day imbalance in Belgium uses the full imbalance as a settlement basis as shown in the last row of Table 30. In the case of hourly imbalances, only gas deficits beyond the hourly tolerance level (*Tol-H*) give rise to penalties, whereas hourly gas surpluses are transformed to 0.

The Belgian settlement mechanism uses a basket of prices rather than a single market price to establish an RMP. Interestingly, in addition to the DJ Zeebrugge Index Gas (ZIG) this basket includes the SMP_{buy} (short) and SMP_{sell} (long) prices that are also applicable in the UK.

As far as price data are concerned, the intra-day SMP_{buy} and SMP_{sell} are used for the UK, whereas the ZIG is applied for Belgium. Additionally, other price scenarios have been examined to show that it is the settlement design rather than diverging market prices in different regions that incentivize shippers to do forum shopping. Cross-border trade that is the result of price differences is a relevant topic, but is not part of the present study.

5.2.3.4 Shipper information

The shipper has perfect information with regard to the design of the regional settlement mechanisms, but he still faces some uncertainty concerning, e.g., the effective RMPs and the exact demand by his customers. This uncertainty is disregarded in the results discussed in section 5.3. Note, however, that demand uncertainty decreases throughout the day as new information becomes available and the shipper's transaction costs to adapt his strategy are limited as well. Indeed, a transnational shipper usually has border capacity available and collects all necessary information like regional market prices regardless of any forum shopping for balancing rules. Moreover, the driving forces behind the forum-shopping strategy are the known settlement-design differences such as absence or presence of intra-day constraints, rather than mere diverging RMPs. Thus, the considered shipper strategy of moving imbalances between regions by nominating accordingly is realistic, but the perfect foresight assumption might result in an overestimation of the strategy's profitability.

5.3 Results of welfare benchmarking

5.3.1 Shipper surplus

Figure 37 shows the net shipper costs for acquiring *ex-post*-balancing services from the TSOs in the benchmark case (AUT) and the forum-shopping case (FS). Note that the results are ordered on the horizontal axis according to the forecast error (FE): underestimating demand with 15 percent means that the shipper has an end-of-day deficit of 15 percent in the combined region because too few gas has been committed.

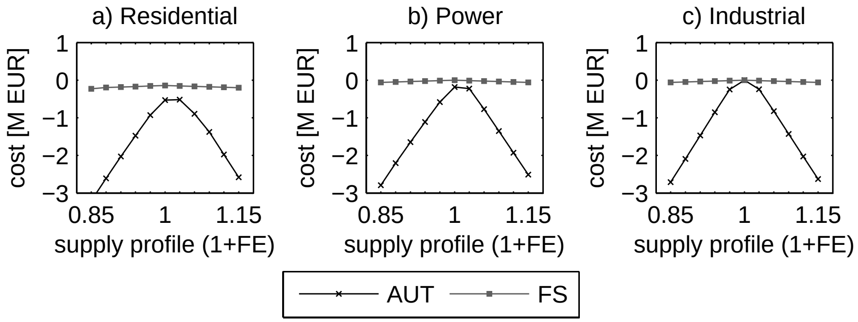

Figure 37. Shipper imbalance costs [M EUR] in the combined region (BE+UK) for the benchmark case (AUT) and the cross-border case (FS) and for a) residential demand, b) electric power sector demand and c) industrial demand; the supply profiles are ranked according to their respective forecast error (FE)

In autarky, the combined costs in the Belgian and UK regions are much bigger and have a stronger dependency on the forecast error. The costs in the forum-shopping case, on the other hand, are much smaller and less dependent on the forecast error. These observations are explained by the settlement-design differences between the two regions that have been established by Table 29 for the UK and Table 30 for Belgium. In autarky, the dominant Belgian settlement costs determine to a large extent the shipper's costs for *ex-post* flexibility. By trading imbalances to the UK in the FS-case (see further), the costs are predominantly determined by the more lenient UK settlement design. If the separate autarkic imbalance costs of the Belgian and the UK region would have been plotted, the AUT line would almost coincide with the Belgian autarkic settlement costs and the FS line would resemble more or less the autarkic UK costs. Comparing the three panels, the residential-demand profiles return slightly higher settlement costs due to the presence of larger intra-day variation than for the assumed power-sector and industrial-sector profiles. Nevertheless, the demand type seems to have little effect on the costs in the examined cases.

For all investigated scenarios, forum shopping proves to be a profitable strategy for a shipper, as illustrated in Figure 38. Indeed, moving imbalances between regions saves money for the transnational shipper as *ex-post* flexibility becomes less costly. Clearly, the absolute shipper surplus (Figure 38.a) is dependent on the quality of the demand forecast as for good-quality forecasts (middle profiles) the surplus is much lower than for the cases in which demand is much more underestimated (left-hand side) or overestimated (right-hand side). This observation suggests that shippers have no incentive to improve demand forecasts as long as they can transfer imbalances to a balancing mechanism that is lenient for intra-day imbalances. Indeed, shippers will only invest in forecasting, or *ex-ante* flexibility, if the reduced costs by avoided imbalances in the cheapest settlement mechanism exceed the costs of better forecasting or contracting flexibility. Furthermore, Figure 38.a shows that absolute shipper surpluses are slightly higher for demand types that have more intra-day variation, especially when demand has been underestimated (negative forecast error). The asymmetry in the Belgian imbalance charges regarding hourly imbalances explains why a similar outcome for overestimated demand is not observed. Indeed, hourly shortages are subject to a penalty, whereas hourly surplus positions are not (Table 30).

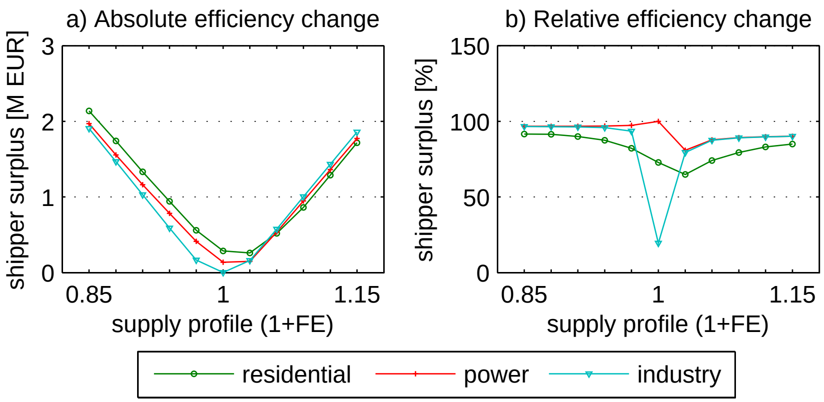

Figure 38. Absolute [M EUR] and relative [%] shipper surplus by forum shopping (FS) for balancing rules compared to separate balancing in the UK and Belgium (AUT) for 3 characteristic demand profiles and 11 supply profiles (1+FE) that are based on assumed demand forecast errors (FE)

Figure 38.b shows that the shipper-profit changes are also substantial in relative terms comparing the shipper-imbalance cost reductions with the benchmark costs in autarky. An asymmetry is observed between the supply profiles that underestimate demand and those that overestimate demand with the former resulting in slightly higher relative reductions compared to the latter. As before, this is explained by asymmetries in the settlement designs. Furthermore, differences can be observed between the different customer profiles with the residential demand profile having lower relative-surplus potential than the other demand types, which have almost overlap. This is due to the intra-day variation: residential demand is subject to higher costs in absolute terms for autarky as well as for forum shopping. Hence, the denominator in the relative surplus is a higher cost than for the other demand types.

Looking at the direction of gas movement in Figure 39, gas is exported from the UK to Belgium when demand is underestimated, on the one hand; and the UK imports gas from Belgium when demand is overestimated, on the other hand. Both movements correspond to reducing the exposure of the shipper to the more penalizing Belgian balancing mechanism. Indeed, if demand is substantially underestimated, the shipper is likely to be in a short position in both gas systems. However, by exporting gas from the UK to Belgium, the shipper increases exposure to the UK balancing mechanism by further shorting, whereas the imported gas decreases the open imbalance position in Belgium. Imports do not differ much between demand types; hence, the almost overlapping lines in Figure 39.

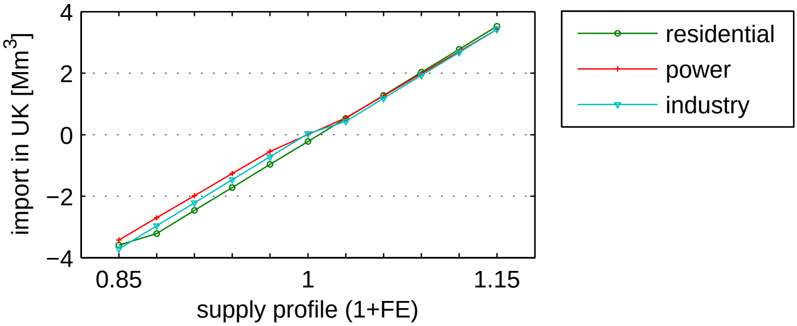

Figure 39. Imbalance trade [Mm^3]: import (>0) of gas in the UK from Belgium or export (<0) from the UK to Belgium – 11 supply profiles (1+FE) based on assumed demand forecast errors (FE); surplus gas in Belgium is exported to the UK; if the shipper is short in both regions, gas is exported from the UK to Belgium to reduce exposure to the penalizing settlement-mechanism

Figure 40 shows a similar analysis of shipper surplus for a range of RMPs for the UK and Belgian regions and for residential demand. The shipper surplus again rises with increasing forecast errors. Long positions provide less profit opportunities because of the asymmetry in the Belgian settlement mechanism, which only penalizes hourly short positions. For short imbalances (negative forecast error) the range of outcomes is dependent on the difference between the UK RMP and the Belgian RMP. The more the Belgian RMP exceeds the UK RMP, the higher the potential surplus becomes. If the UK RMP, on the other hand, exceeds the Belgian RMP, the surpluses are smaller. A similar trend cannot be observed for positive forecast errors. Indeed, the surplus remains fairly stable for the different RMP cases. Furthermore, the absolute profit opportunities are dependent on the absolute level of the Belgian RMP because the penalties are directly related to that price. Hence, the low surplus for negative forecasts is explained by the Belgian RMP being much lower than the UK RMP (RMP UK >> BE in Figure 40), but also by the low absolute value that was considered in that particular case.

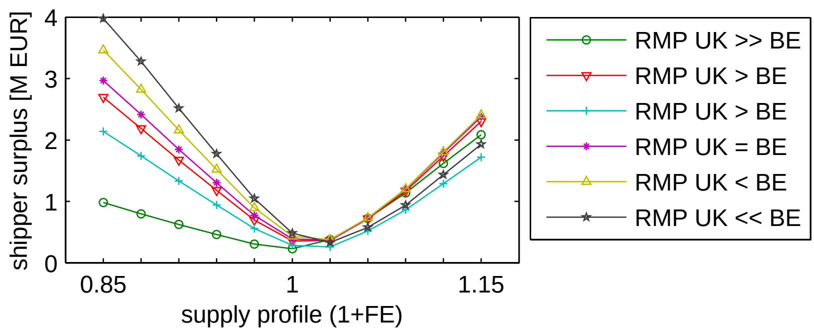

Figure 40. Shipper surplus [M EUR] (residential demand) by forum shopping (FS) compared to an autarkic strategy (AUT) for 11 supply profiles based on assumed demand forecast errors (FE) and for different values of the respective RMPs in both regions: short positions offer bigger profits than long positions because of the asymmetry in the Belgian settlement mechanism regarding hourly imbalances; the more the UK RMP exceeds the Belgian RMP, the lower the surplus for short positions (negative FE), and that same surplus increases the more the Belgian RMP exceeds the UK RMP; a similar trend is not observed for positive FE

The results presented above suppose that the shipper can access an unlimited amount of *ex-post*-balancing services in each region. However, trade restrictions, like border capacity, limit the accessibility of cross-border services. In that case, the surpluses remain positive, but are topped off for large forecast errors because the shipper can only move imbalances up to a pre-determined level that is lower than the optimal level of imbalance trades. Five different border capacities, listed in Table 31, have been considered. It should be noted that the largest considered capacity in Table 31 amounts to 15 percent of the scaled average hourly demand and it will be shown below that this capacity is not binding and thus corresponds to the unrestricted case that has been discussed above.

Table 31. Considered border capacities [Mm^3/h] for trade between the regions

Capacity 1 [Mm^3/h]	Capacity 2 [Mm^3/h]	Capacity 3 [Mm^3/h]	Capacity 4 [Mm^3/h]	Capacity 5 [Mm^3/h]
0.03	0.06	0.09	0.12	0.15

Figure 41 shows the shipper surplus for the different levels of trade capacity from Table 31 (y-axis). Only the generic residential demand is considered here, but the results for the electricity-sector and industry-sector demand are similar. The more restricted the trade opportunities, the lower the actual surplus that can be captured by the transnational shipper. The trade restrictions become only relevant if there is a substantial positive or negative forecast error. Otherwise, there is no advantage for the shipper to move imbalances across borders. This is shown in Figure 41 by the flat zone for supply profiles that have a forecast error close to zero.

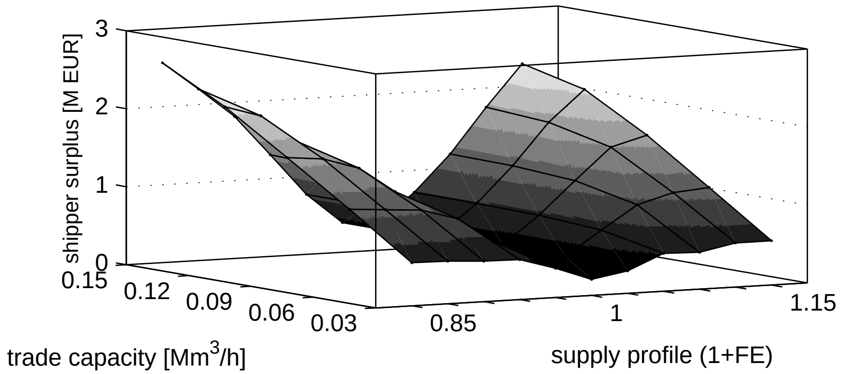

Figure 41. Shipper surplus [M EUR] FS compared to AUT (residential-demand case) – Imbalance trade limited by border capacity – x-axis: 11 supply profiles (1+FE) based on forecast errors (FE); y-axis: 5 levels of trade capacity [Mm^3/h]; forum-shopping restrictions limit the surplus that can be captured by the shipper

Figure 42, then, shows the import of imbalances into the UK region for different trade-capacity levels. Positive numbers indicate the import of gas into the UK, whereas negative numbers correspond to export of gas (equivalent to importing a deficit) from the UK to Belgium.

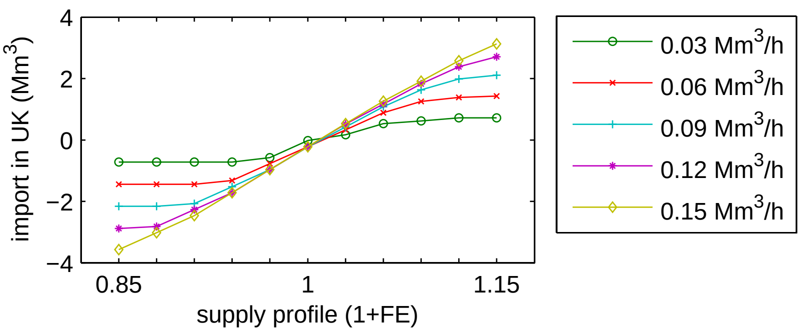

Figure 42. Imbalance trade [Mm^3] (residential-demand case): import (>0) of gas in the UK from Belgium or export (<0) from the UK to Belgium – Limited ex-post-balancing services offered by TSO – for 11 supply profiles (1+FE) based on assumed demand forecast errors (FE) and different levels of trade restrictions – the more restricted forum shopping becomes, the more imbalance exchange deviates from the optimal level without any restrictions

The diamond markers represent the optimal trade strategies for the different forecast errors if there is no binding restriction on trade. The more restricted the trade opportunities become, the more actual trade deviates from those optimal levels.

Repeating the analysis for lower and higher daily demand, both by scaling and by adding a constant demand, returned similar results to the ones presented here. Therefore, shippers gain from shopping for balancing rules and arbitrating between a lenient mechanism with reference to intra-day imbalances (UK), and a more penalizing mechanism (Belgium). So, adapting intra-day nominations to move imbalances to the less-costly settlement mechanism is a profitable strategy for the shipper. In fact, the shipper cannot do worse than the autarky strategy, since that strategy remains available. The shipper could lose on a wrongfully pursued forum-shopping strategy if he is not a price taker. Indeed, if the movement of imbalances affects the imbalance tariff in one region or in both, the shipper profit could reduce. This could happen, for instance, if dumping surplus gas in the UK system results in a lower market value of the shipper's gas in the UK region.

5.3.2 TSO surplus

The TSOs face the system imbalances caused by the shipper in their respective region. To accommodate the imbalance in his region, a TSO can rely on domestic flexibility sources: line-pack flexibility and conventional storage. The operational cost of line-pack flexibility comes down to compression costs to control the pressure in the system and the valuation of the line-pack change. In reality, operational line-pack costs are negligible compared to the capacity cost of pipeline storage, but the amount of gas stored in a pipeline affects the required pressure levels to keep the system running. Hence, when compression occurs in the local gas network, the compressor's fuel cost serves as an operational cost for pipeline flexibility. If no local compression is available or required, on the other hand, pipeline flexibility comes at no operational cost. Indeed, the responsibility to provide adequate pressure at the entry node lies outside the local gas system in such cases. Note that compressors offer a bundled service of transport and flexibility and that, in practice, the fuel cost of the compressor cannot be attributed entirely to the balancing of the system. Any attempt to disentangle that mixed use has been disregarded here to simplify the analysis and the full compression cost is attributed to the flexibility service of the pipeline.

Operational storage costs have been considered for injection and withdrawal. Because of the short-term horizon of the analysis, capacity costs for storage, and compression are disregarded. Table 32 lists exemplary cost parameters for the efficient region and the expensive region. The cost parameters are hypothetical, but the orders of magnitude have been derived from bid-ladder data published by the Dutch TSO [50]. Compression costs, then, are approximated by the cost of fuel gas.

Table 32. Operational costs [EUR/m^3] for storage and compression in the efficient and expensive regions, respectively (sample values inspired by actual bid-ladder data [50])

	Efficient region cost [EUR/m^3]	Expensive region cost [EUR/m^3]
Storage injection (downward flexibility)	0.02	0.06
Storage withdrawal (upward flexibility)	0.02	0.06
Compression cost	0.12	0.15

The effects of increasing cost-efficiency differences between the regions, then, are investigated with four relative-efficiency (RE) scenarios (Table 33). These scenarios consider increasing flexibility costs in the expensive region, while the costs in the efficient region are kept constant. RE1 then represent the smallest, and RE4 the largest cost difference.

Table 33. Relative efficiency (RE) scenarios: expensive region costs for storage services (efficient region costs are kept constant to the levels provided in Table 32)

	RE1 [EUR/m^3]	RE2 [EUR/m^3]	RE3 [EUR/m^3]	RE4 [EUR/m^3]
Storage injection	0.06	0.18	0.30	0.42
Storage withdrawal	0.06	0.18	0.30	0.42

Two mutually exclusive situations can occur. Either the settlement mechanisms are designed in line with the effective balancing costs in the respective regions (right incentive) or the settlement mechanisms provide wrong incentives. A right incentive is provided if the more lenient settlement mechanism has the more efficient tools for balancing. If the lenient settlement mechanism relies on the more expensive balancing instruments, a wrong incentive is provided to the shippers. The previous subsection has demonstrated that shippers prefer the lenient UK settlement mechanism over the Belgian design. Therefore, the right-incentive case supposes that the UK is the efficient region. In the wrong-incentive case, on the other hand, the Belgian TSO is the more efficient region to balance the gas system.

Figure 43 shows the TSO surpluses for the combined UK and Belgium regions for the residential-demand profiles. The left-hand panel plots the results for the right-incentive case (UK more efficient balancing region) and the right-hand panel shows the wrong-incentive case (UK less efficient balancing region).

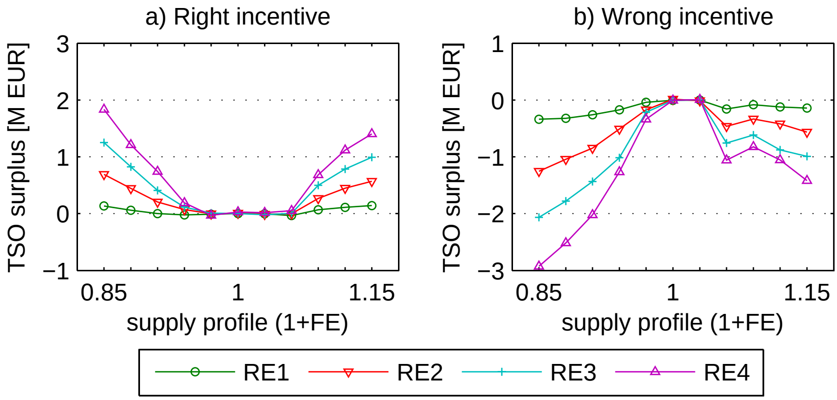

Figure 43. TSO surplus [M EUR] (residential demand) – a) lenient settlement region has more efficient balancing instruments and b) lenient settlement region has more expensive balancing instruments – for 11 supply profiles based on assumed demand forecast errors (FE) and 4 relative-efficiency (RE) scenarios: surpluses become more extreme if ex-post-balancing needs increase (larger forecast error) and if the regional cost difference increases (RE1<<RE4)

The TSO surplus is always positive if the correct incentive is provided, and the more extreme the imbalances become, the more efficiency gains can be captured. The latter is only true to the extent that the UK has an absolute cost advantage, meaning it is the more efficient region to balance independent of the amount of flexible gas that is dispatched. In practice, it can be expected that a hypothetical merit order of all available flexibility in the combined region mixes the regionally available flexibility.[84] Indeed, the first three flexibility instruments in the UK might be cheaper than in Belgium, but the next most efficient source might be located in Belgium followed by another UK source and so on. If the wrong incentive is provided by the relative settlement mechanisms, the TSO surplus is negative and the efficiency of the combined TSOs is reduced (Figure 43.b). Indeed, imbalances are moved by shippers to regions that are less efficient in handling these imbalances. Hence, the demand for *ex-post*-balancing services rises in the expensive region because shippers profit from the lower settlement charges.

The flexibility use in both regions is illustrated in Figure 44 for the fourth relative-efficiency case (RE4 in Table 33) and the residential-demand profile.

[84] The combined merit order is hypothetical because procurement of flexibility is assumed a domestic issue in this chapter.

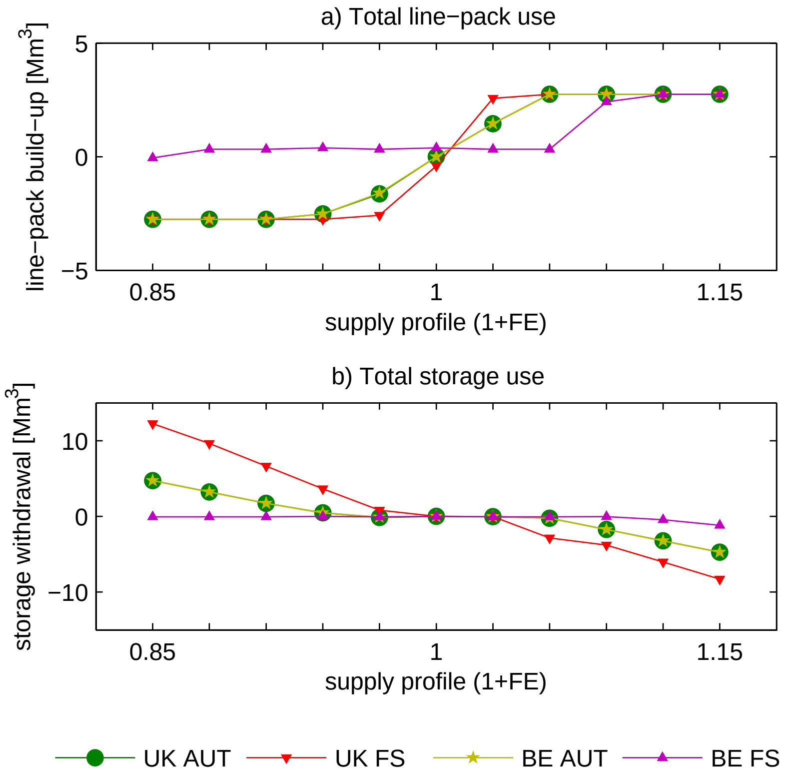

Figure 44. System-flexibility use for autarky (AUT) and forum shopping (FS) in the UK and Belgium (residential demand, RE4) – a) line-pack use [Mm^3] and b) storage use [Mm^3] – for 11 supply profiles based on assumed demand forecast errors (FE) – in the autarky case, both regions use the same amount of flexibility; whereas in the forum-shopping case, the UK attracts the imbalances and dispatches more flexibility and Belgium can reduce its flexibility use

If the shippers follow an autarkic strategy, equal amounts of line-pack flexibility and storage flexibility are used in Belgium and the UK. This specific outcome is caused by the assumed symmetry between the demand and supply profiles in both regions. If the shippers have moved imbalances to the more lenient UK region, on the other hand, the UK dispatches more flexibility compared to the autarky case, and less line pack or storage is used in the Belgian region. Note that only the total net use of flexibility is shown. In fact, the use of flexibility varies throughout the considered time horizon, e.g., buffering gas in the line pack in some periods and withdrawing it in other periods.

Finally, in Figure 43, the outcome of the surpluses in absolute terms clearly depends on the relative efficiency (RE) of the regions. Therefore, the relative efficiency is identified as the major determinant for the TSO efficiency if the shipper nominations have been fixed.

5.3.3 Net surplus: TSO surplus + shipper surplus

The net efficiency gain of the combined region depends on both the shipper surplus and the TSO surplus. Hence, both surpluses are to be accounted for to evaluate the impact of forum shopping on overall efficiency. In absolute terms, the TSO-efficiency change is of the same order of magnitude as the shipper surplus. Hence, if the TSO surplus is negative, the net surplus can also become negative. The actual outcome is dependent on the relative efficiency of the regions. Indeed, if the flexibility-cost difference increases between the efficient and the expensive region, the net result can become negative as illustrated by RE4. If the regional cost difference is small, on the other hand, the TSO surplus can still be negative, but overall efficiency will increase as is illustrated, e.g., by RE2.

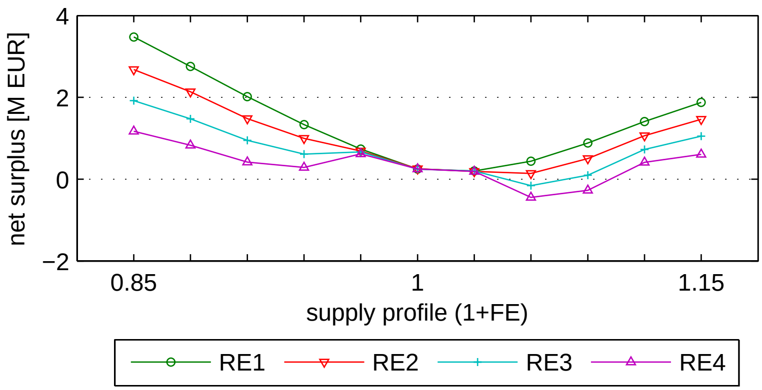

Figure 45. Net surplus [M EUR] for the wrong-incentives case with unrestricted border capacity (residential demand): imbalances are moved to the less efficient region to balance, lowering net efficiency of the TSOs and the shippers in the combined region – for 11 supply profiles based on demand-forecast error (FE) and 4 different relative efficiencies (RE) – if the cost spread between the efficient and expensive region increases, negative net surpluses are possible

In Figure 45, it is demonstrated that the outcome for the wrong-incentive case, indeed, can become negative, reducing total efficiency. Further increasing the flexibility-cost difference would result in more occurrences of negative net surpluses for positive and, then, also negative forecast errors.

5.3.4 Other forum-shopping opportunities

The forum-shopping behavior is induced by differences in the settlement-mechanism design. The UK and Belgium have served as textbook examples, but the same profit opportunities exist at other borders. France, for instance, does not apply any intra-day attribution of flexibility costs, and even allows carry forward of a part of the imbalance. This carry forward implicitly extends the balancing interval beyond a day. Austria, on the other hand, is unique in Europe as it applies hourly settlement, implying that shippers receive an incentive to export imbalances to neighboring regions that apply daily balancing without hourly penalties.

In the past, the Netherlands applied intra-day penalties in a similar way as Belgium, making forum shopping on the border between these two regions a matter of determining the more penalizing region. The new market-based balancing mechanism in the Netherlands links settlement charges to the balancing-market price. As a result, the reference market price is only obtained afterwards as a function of the effectively dispatched flexibility by the TSO. If imbalances are imported into the Dutch balancing region, balancing needs increase, resulting in more expensive flexibility to be called, driving up the balancing price. Forum-shopping shippers, in that case, could become “price setters” if their imbalance trades are substantial. Hence, their actions affect the price of *ex-post*-balancing services.

5.4 Summary and conclusions on settlement-mechanism design in an integrated gas market

This chapter has demonstrated that balancing is no longer an isolated activity in a balancing area in a liberalized gas market encompassing several countries or regions. On the contrary, profit-maximizing transnational shippers can reduce their exposure to imbalance-settlement fees by “forum shopping” for the best balancing mechanism across borders.

The different designs of, e.g., the UK and Belgian settlement mechanisms provide an incentive for shippers to “move” imbalances as much as possible to the more lenient UK. Indeed, both regions have a completely different approach towards intra-day imbalances: in the UK, coverage of intra-day imbalances is free, whereas in Belgium, these imbalances are subject to penalty charges. Other borders between adjacent gas regions provide similar opportunities for transnational shippers.

Using a “welfare”-benchmarking methodology, the impact on efficiency of moving from autarkic strategies to forum-shopping strategies has been demonstrated for the transnational shippers and the national TSOs. The shipper surplus is positive for all investigated cases, independent of the kind of customers the shipper serves. Because shippers can do this imbalance “trading” intra-day, they can only gain from forum shopping. Indeed, they can always revert to their original autarkic strategy. However, trade restrictions, e.g., insufficient border-capacity rights, limit the profits that can be captured by the shippers.

The TSO surplus, on the other hand, is not indisputably positive. If the regional settlement mechanisms give wrong incentives, the combined TSOs see a loss in efficiency caused by the import of imbalances in the more expensive region to balance. Shippers only see the settlement mechanism and do not care for the effective balancing costs in non-market-based-settlement designs. Furthermore, if the relative efficiency of the expensive region compared to the efficient region decreases, the TSO surplus becomes more outspoken. If the right incentive is given, higher efficiency gains are achieved, but if the wrong incentive is provided, the operator loss inflates.

Net efficiency, then depends on the sum of TSO surplus and shipper surplus. If the system-balancing costs are lower for the forum-shopping strategy compared to the system costs for the autarkic strategy, the TSO surplus is positive and net efficiency is certain to increase. Exporting imbalances to less efficient regions with regard to system balancing, however, results in an efficiency loss for the TSO and can result in a negative net outcome. Indeed, both surpluses are of the same order of magnitude in the examined hypothetical cases. This result also holds more generally because, the UK and Belgian settlement mechanisms have been modeled accurately, the hypothetical cost parameters have been derived from real flexibility-cost data and multiple cost and RMP data have been tested. If the relative efficiency of the expensive region is low, forum shopping turns net surplus negative and thus reduces overall efficiency, but the transnational shippers always gain.

Gas-market regulators and policy makers need to be aware of the possibly efficiency-reducing framework of incompatible or non-harmonized non-market-based balancing mechanisms in geographically adjacent gas regions. Indeed, net efficiency should be their primary concern as it is a proxy for the utility of the citizens who are represented by the TSO and the shippers. Introducing market-based cross-border balancing with regard to procurement and settlement solves this problem because settlement is then directly linked to the effective imbalance position of the system. As a result, forum-shopping shippers affect the settlement tariff and while they might initially gain from exporting imbalances, the mechanism will correct itself and prices will provide correct signals to the TSO and the shippers. Steps towards market-based balancing are taken only slowly. One reason might be that the efficiency gain has to be distributed over the participating regions in a fair and coordinated manner. This might be difficult to implement because not all actors profit equally. Until that problem is resolved, shippers face potentially net-efficiency-reducing incentives. Indeed, the shippers can increase their individual profit at the cost of lowering efficiency of other network users, represented by the TSO.

6. CROSS-BORDER PROCUREMENT OF BALANCING SERVICES[85]

This chapter examines the efficiency gains that can be made in the procurement of balancing services across system borders. Indeed, using international-trade-policy theory [190], cross-border market-based merit orders are shown to improve efficiency compared to autarkic-procurement methods.

A schematic overview of the problem at hand is provided in Figure 46 in which two physically interconnected gas regions are considered.

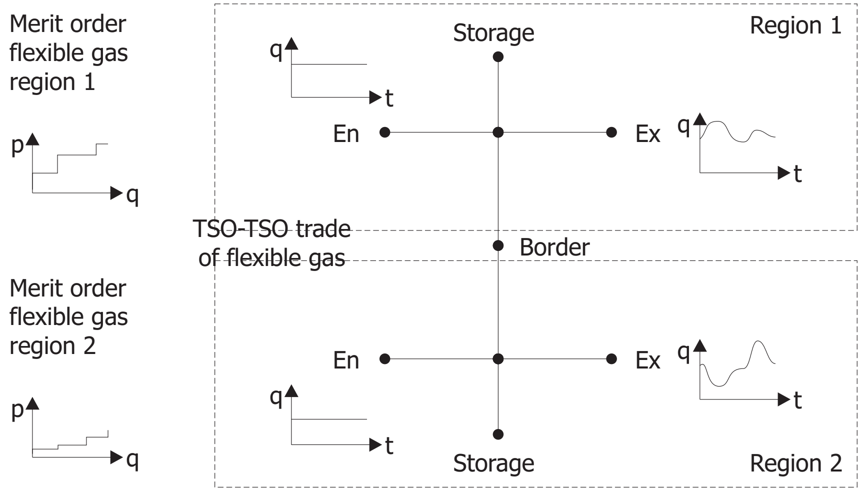

Figure 46. Schematic overview of cross-border procurement of flexible gas: in autarky, a TSO can only rely on domestic sources of flexibility (the domestic merit order) to balance the network in his region; if TSOs cooperate on the procurement of flexible gas (single merit order for combined region), the TSOs can use the most efficient flexibility tool regardless of its regional origin, e.g., flexible gas is cheaper in region 2 and can be exported to region 1 to balance region 1 more efficiently; in the graphical illustrations of demand, supply and imbalance, "q" stands for an amount [Mm^3/h, to be integrated over the length of a period] and "t" stands for the hourly time periods [h]

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[85] The material of this chapter has been submitted for publication: Keyaerts, N., D'haeseleer, W., 2012. Increasing efficiency through market-based cross-border procurement of gas-balancing services in Europe [189].

The respective TSOs have to execute transport services and deal with their regional system imbalance. If the TSOs do not cooperate on the (market-based) procurement of flexibility, they can only rely on the domestic network flexibility and merit order for flexible gas. If, on the other hand, the TSOs engage into cross-border procurement, they can exchange line-pack gas and use the combined merit order for flexible gas. In Figure 46, this cooperation allows the TSO in region 1 to import cheaper flexible gas from region 2.

The efficiency gains of moving from autarkic system balancing towards cross-border procurement are then examined in this chapter. The chapter is further organized in five sections. It starts with a brief introduction of the problem. Next, an analytical framework for international-trade policy is applied to the gas-balancing problem. The third section introduces a methodological approach that extends the international-trade-policy framework theory to include multiple periods and spatial constraints that are present in the gas industry. The results of the efficiency benchmarking are reported in the fourth section. The chapter ends with a summary of the findings and draws conclusions with regard to current balancing-mechanism design in Europe.

6.1 Introduction

The unbundling of the gas market makes physical balancing of the gas system more challenging. At the same time, the gas-market liberalization and subsequent integration creates new opportunities. Indeed, international-trade theory predicts efficiency gains if differences exist in the efficiencies of the regions to produce services. Simply stated, the "market" for balancing services should not be limited to the domestic market; but, services should be acquired where they are produced most efficiently. In terms of the gas-system balancing, "cross-border procurement" refers to the purchase of flexible gas by the TSO at the lowest cost, independent of the regional origin of these balancing services. In other words, balancing services are procured from a larger pool in the combined region. Thus, system balancing can be done more efficiently under a cross-border approach, than under an autarkic approach in which TSOs rely completely on domestic resources. The subsequent efficiency gains are demonstrated using a self-developed "welfare"-benchmarking methodology that is explained below. Note that this chapter discusses the TSO part of balancing and that, in principle, settlement mechanisms do not have to be included in the cross-border cooperation between TSOs. However, building on the market-based procurement of flexible gas, imbalance-settlement charges could be linked to the procurement costs of solving the system imbalance. At the end of this chapter, the possibilities for cross-border settlement are reflected on. Furthermore, the potential pitfalls and barriers to the implementation of cross-border cooperation are defined. Indeed, overall efficiency increases, but the distribution of the surplus over the regions changes as well, raising the need for a compensatory mechanism to overcome this transaction cost.

The potential for efficiency gains in cross-border procurement of electricity-balancing services has been demonstrated by Vandezande [77; 191] for the border between Belgium and the Netherlands. In that work, a procurement mechanism is advocated that is based on real-time energy costs and excludes capacity-reservation costs as much as possible. Notwithstanding technical and institutional differences between electricity and gas, similar efficiency gains should also be attainable in procurement of gas-balancing services across borders.

The potential efficiency gains are examined for two hypothetical regions. The respective TSOs have to balance an exogenous imbalance profile that is the result of injections and withdrawals in the respective pipeline systems. Either the TSOs rely on an autarkic approach and only dispatch domestic flexibility, or the TSOs cooperate across borders by dispatching flexibility from a single combined merit order for flexibility.

6.2 International-trade policy framework applied to the procurement of balancing services

To explain the driving force behind the efficiency gains in the procurement of balancing services across borders, it is necessary to understand, first, the local demand for flexible gas and, second, the offer of these flexibility services. In a next step, the domestic gas system is combined with a foreign system and a cross-border market between the two is introduced.[86]

6.2.1 Demand for balancing services

The gas-transmission-system operator is responsible for the system integrity, but the state of the system is the result of the actions of the gas shippers. Indeed, the shippers inject gas somewhere in the system and withdraw it again at another place. These shipper nominations are subject to matching problems. Gas consumption, on the one hand, is unpredictable, leading to forecast errors that impact the unit commitment at the gas-supply side. The variability of consumption and production/import, on the other hand, differs and requires flexibility for modulating gas supply to meet consumption: a task that is also subject to uncertainty and prediction errors. The aggregation of all individual differences between injections and

[86] The TSO cooperation does not necessarily depend on a competitive market mechanism. Other bargaining mechanisms can be used instead: e.g., implicit or explicit auctioning where BSPs submit bids that are subsequently accepted by the TSO up to the amount of flexibility that is required. The international-trade argument that is developed here, thus, serves as an analogy to explain and visualize the efficiency gains of cross-border cooperation.

withdrawals results in a deficit (short) or a surplus (long) at the system level, meaning, respectively, that the line-pack level drops or surges throughout the day. The flexibility of the line pack, i.e. the ability to use the pipeline as storage, is limited in volume, though, and if the line-pack level reaches an unacceptable level during the day, the transmission-system operator calls for flexible gas. It is, however, important to understand that the operator-controlled line pack, when available, will be used before any other source of flexibility, and, consequently, the demand for flexible gas is a residual demand determined by the cumulative aggregated shipper imbalances throughout the day and the flexibility already offered by using the pipeline storage.[87] Because the line-pack level is also used for system continuity, transmission-system operators try to keep the gas-day end state close to the starting level of that day, also taking into account forecasts for the next gas day. The British TSO, for instance, is incentivized to have the line-pack starting and ending levels close together over a gas day [53].

Because of the short-term nature of the balancing problem and the inevitability of these system imbalances, the demand for balancing energy is supposed to be inelastic to price and exogenous. It is true that the TSO uses the settlement mechanism partly to incentivize shippers to minimize imbalances, but once the shippers have committed their contracts, including *ex-ante* flexibility, the system imbalance becomes fixed.[88] Furthermore, the gas market has no gate closure to distinguish between the wholesale market and the TSO-exclusive market. As a consequence, the TSO has to continuously assess whether an intervention, i.e. a demand for flexible gas, is necessary now or only later in the gas day, while the shippers can also correct their individual positions based on updated information.

6.2.2 Offer of balancing services

The provision of balancing services depends on market players that can offer upward (adding gas to a short system) or downward (accept gas from a long system) flexibility within the time horizon of the balancing problem. KEMA [23] identified a number of tools that can deliver balancing services. Besides line-pack flexibility, which is excluded from the offer considered here for reasons explained above, balancing services can be supplied from (fast-cycling) underground storages, from flexible LNG terminals, from ramping production and from assistance contracts with neighboring systems. The latter represents a form of cross-border cooperation, but it usually concerns help from transit flows or non-market based help from

[87] The line-pack flexibility has a very low variable cost (running the compressor) compared to the substantial investment cost (building a bigger pipeline) per unit of flexibility.

[88] A TSO could choose to keep back some line-pack flexibility for strategic reasons and use this flexibility to affect the residual demand for flexible gas, e.g., when flexibility is exceptionally expensive, introducing some form of price elasticity. Extra line-pack flexibility comes at the cost of reduced transport capacity [48].

geographically adjacent gas systems. Consumers could also offer flexibility by having their consumption interrupted for some time: fuel switching in the electricity sector, for instance, could reduce consumption by GFPPs.

In a market-based framework, the different flexibility providers submit bids, e.g., day-ahead, offering a certain quantity of flexibility against their bid price. The transmission-system operator subsequently calls the needed bids from the composed merit order when flexibility is required. Accepted bids are remunerated either pay-as-bid or all receive the price of the marginal bid. Note that this framework does not assume the presence of an explicit gate closure, but it does suppose a separation between the wholesale market and the balancing merit order that is only accessible by the TSO.

Temporal and spatial constraints, however, complicate the construction of the merit order. Some flexibility can respond as soon as the next hour, whereas other flexibility has a lead time before it can be activated. Therefore, the merit order changes depending on the urgency of the balancing needs. The same applies for the spatial constraint: usually, gas can be added anywhere to restore balance, but sometimes the network can become locally congested, requiring a local intervention, also excluding certain bids.

Table 34 summarizes the main determinants and defining characteristics of the demand for, and provision of, flexible gas.

Table 34. Determinants of demand for, and offer of, flexible gas

Demand for flexible gas	Offer of flexible gas
- residual demand - based on system-imbalance position - and priority use of transmission-system operator-controlled line-pack flexibility - price-inelastic	- different sources: storage, production, LNG, consumption… - providers submit bids (quantity and price) - TSO composes merit order for upward and downward flexibility - spatial and temporal constraints apply

The transmission-system operator continuously monitors the line-pack level taking into account updated predictions for the next few hours and determines the demand for flexible gas. Next, the suitable bids are chosen based on the best offered prices, meaning the lowest prices when gas has to be bought and the highest prices when the TSO sells surplus gas, until the desired quantities are obtained.

6.2.3 Cross-border market for balancing services

When cross-border cooperation for system balancing is considered, the first positive effect lies in the pooling of the regional system imbalances, so that only the net residual imbalance of the combined systems has to be covered with flexible gas. This pooling is actually the exchange of line-pack gas, which has priority over other flexibility.[89] The joining of the separate merit orders into a single merit order that is used in a coordinated way makes up the next step in setting up cross-border market-based procurement of gas-balancing services. Fundamentally, the cross-border procurement of balancing services is not different from any other international trade for services. Therefore, the principles of international-trade theory and policy can be applied to this problem, even though the trade involving two regulated TSOs corresponds imperfectly to completely competitive trade. However, these TSOs are actually agents representing a great many gas consumers and a multitude of flexibility providers.

Two gas systems have been postulated that are physically connected in such a way that gas can be traded between the regions. Figure 47 illustrates the welfare effects of free trade compared to autarky for a single-period and single-node model of the respective gas regions.[90] Region 1 (Figure 47.a) has a demand "D" for flexibility gas and an offer curve "S", whereas region 2 (Figure 47.c) has a demand "D*" and a more efficient merit order "S*". In autarky, the marginal prices are p(a) and p*(a) for regions 1 and 2, respectively. Now, when free trade (noted by "t" in Figure 47 and supposing unrestricted border capacity) is possible, the cross-border price for flexibility reaches p(t) = p*(t) and the amount m(t) is exported from region 2 to region 1. Furthermore, production of flexible gas reduces in region 1 from q(a) to q(t) with an amount equal to m(t) and at the same time production increases by that same amount from q*(a) to q*(t) in region 2. Figure 47.b shows the "international market" that combines the production surplus in region 2 (S*-D*) with the demand surplus (D-S) of region 1 for different price levels on the international market.[91]

[89] This pooling effect or exchange of line pack refers to moving surplus gas from one region to increase the line pack in the other region where the line pack was lower.

[90] The single-period and single-node model disregards the physical gas network and thus the spatial dimension of gas balancing, and only considers a single period, simplifying the temporal effects.

[91] D-S can be interpreted as the willingness to pay for imports on the international market, whereas S*-D* represents the marginal costs of exports to the international market.

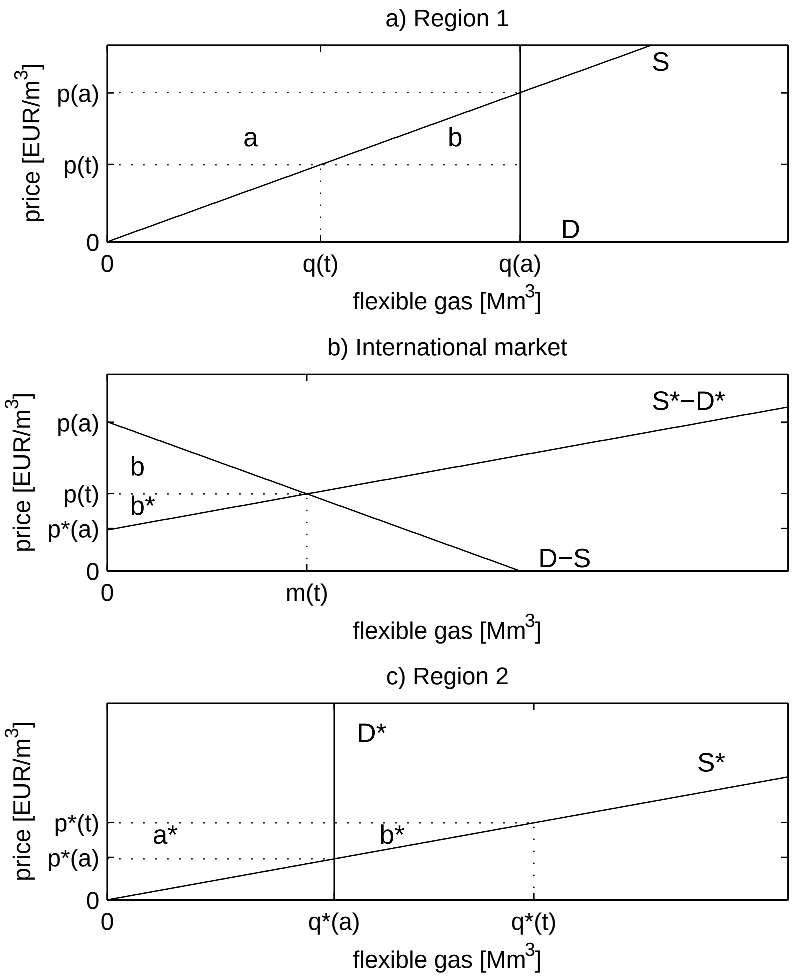

Figure 47. Free trade: welfare impact of free trade (unrestricted border capacity) compared to autarky for procurement of balancing services; welfare change in region 1 equals (+a+b-a), and (+a+b*-a*) in region 2. Net welfare for the combined region rises by (+b+b*).*

The overall impact of free trade or unrestricted cross-border procurement on welfare will be shown to be positive (ΔW in Eq. (6.3)), but not all TSOs and BSPs gain individually. Indeed, welfare in region 1 increases because the TSO gains area +a+b thanks to the lower equilibrium price p(t), whereas the providers of flexible gas gain -b (ΔW_{R1} in Eq. (6.1)). In region 2, on the other hand, the TSO faces a higher price for flexibility than in autarky, gaining -a*, but providers can sell more services at a higher marginal price, gaining +a*+b* (ΔW_{R2} in Eq. (6.2)). From the viewpoint of the

TSOs, the TSO in region 1 gains, whereas the TSO in region 2 loses, suggesting cross-border compensation might be required if they disregard the efficiency gains realized by the BSPs in their respective regions. Such compensation still benefits both TSOs if the gain +a+b exceeds -a*. In the example of Figure 47, the welfare gains are not distributed evenly over the regions as the surplus in region 1, +b, exceeds the surplus in region 2, +b*.

$$\Delta W_{R1} = +a + b - a > 0 \tag{6.1}$$

$$\Delta W_{R2} = +a^* + b^* - a^* > 0 \tag{6.2}$$

$$\Delta W = +b + b^* > 0 \tag{6.3}$$

The full welfare benefits of cross-border trade cannot always be captured because the gas industry is network based and thus dependent on physical capacities. Figure 48 shows the welfare effects for restricted cross-border trade (represented by "r" for restricted border capacity in Figure 48) to, e.g., the amount m(r) that is smaller than the free-trade exchange of flexible gas m(t).

Because of the trade restrictions, region 1 reduces domestic provision of flexible gas to q(r) and faces the price p(r) that is higher than the free-trade price p(t), but still lower than the autarkic price p(a). Compared to free trade, flexibility providers in region1 gain +a, whereas the TSO gains -a-b-c. In region 2, the TSO observes an increase of welfare by +a* because the price of flexibility only rises to p*(r), which is less than the free-trade price p*(t), but higher than the autarkic price p*(a). The providers of flexibility face a welfare change -a*-b*-c* compared to free-trade conditions due to the constrained border capacity. A discrepancy can be observed between the prices for flexibility p(r) in region 1 and p*(r) in region 2. This difference represents the congestion rents for the border capacity (+c+d=+c*+d*). Therefore, overall welfare (ΔW_r in Eq. (6.6)) is decreasing compared to free trade, but the welfare change in the separate regions ($\Delta W_{R1,r}$ in Eq. (6.4) and $\Delta W_{R2,r}$ in Eq. (6.5)) depends on who captures the congestion rent, and whether this rent can cover the negative effects of trade restrictions compared to free trade (d>b or d*>b*). So, either $\Delta W_{R1,r}$ includes the rent +c+d, or $\Delta W_{R2,r}$ includes the term +c*+e*, or the congestion rent might be captured by a third party who owns the border capacity. The congestion rents could, evidently, also be divided among the two transmission-system operators.

$$\Delta W_{R1,r} = -a - b - c + a + (c + d) \tag{6.4}$$

$$\Delta W_{R2,r} = -a^* - b^* - c^* + a^* + (c^* + e^*) \tag{6.5}$$

$$\Delta W_r = -b - c - b^* - c^* + (c + d) \tag{6.6}$$

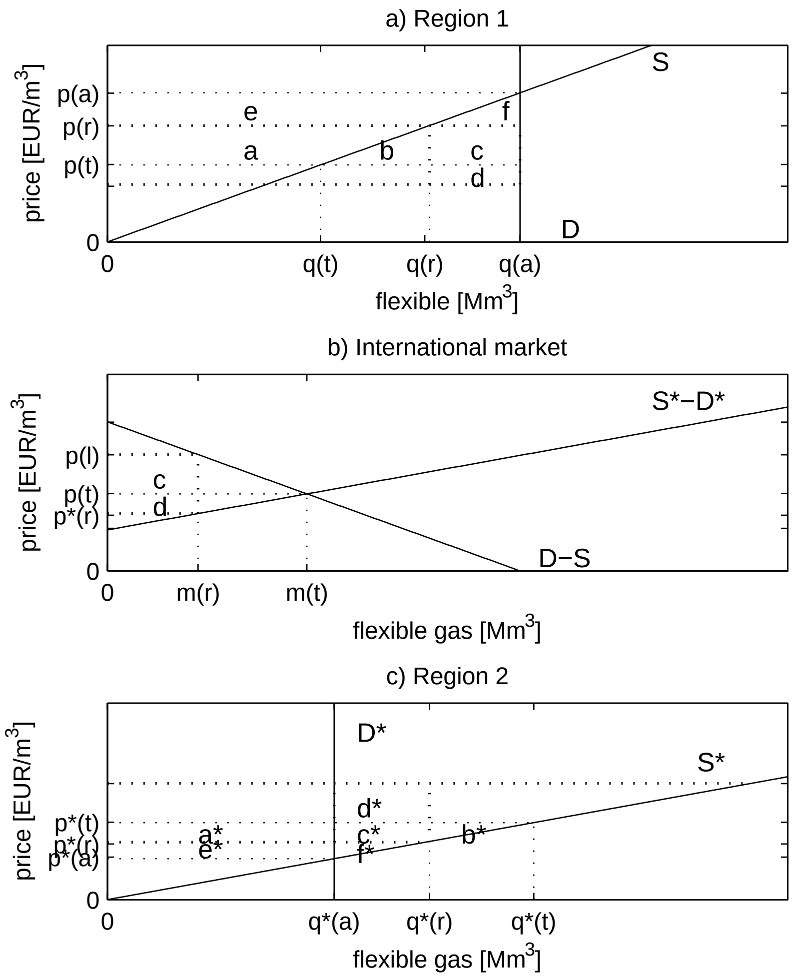

Figure 48. Restricted border capacity: welfare impact of restricted procurement compared to free trade; region 1 gains (-a-b-c+a+c+d) and region 2 gains (-a-b*-c*+a*+c*+e*). The congestion rent (+c+d = +c*+d) can be captured by either region or a third party owning the border capacity depending on the appropriation of the border-capacity rights*

Even if border capacity is limited, cross-border procurement still improves efficiency compared to autarky (+f in region 1, +f* in region 2 and the congestion rents). However, as argued before, distribution of welfare changes dramatically: the transmission-system operator in region 2 sees a higher marginal price for flexible gas. Therefore, a suitable compensatory mechanism might be necessary.

Furthermore, in the analysis above, flexibility is remunerated at the price of the marginal bid that is called. If pay-as-bid pricing is used in an auctioning mechanism, the TSO takes a higher share of the surplus, and the providers of flexibility just capture their bid rate. Balancing-services providers might not reveal their true costs, though, decreasing the efficiency of the pay-as-bid auctioning mechanism.

6.3 Methodological approach to cross-border procurement of flexible gas

For the transmission-system operators the procurement of balancing services is a matter of minimizing balancing costs subject to the operational constraints of the gas network. As pointed out before, gas balancing is a temporal and spatial problem and the gas network plays a crucial role in it. The theoretical model introduced in the previous section, has disregarded the temporal and spatial dimensions of gas balancing. Therefore, in this section, time and space aspects are explicitly taken into account in a multi-period model of the gas network.[92] This technical model of the gas-transport dynamics completes the procurement model. Technical network details can be found in Appendix C and the full details on the modeling have been presented in Chapter 3. For convenience, the main equations, assumptions and simplifications of the operations-research model are reiterated below. Furthermore, the used data have been distilled from publicly available and thus incomplete information. However, a *methodological and conceptual* approach is presented here, rather than a practical case study of current cross-border procurement possibilities.[93] This section discusses, first, the fundamental procurement and balancing model and, second, the assumptions and the data used for the calculations.

The objective of the transmission-system operators is to minimize the costs of residual balancing as expressed in Eq. (6.7):

$$\min balancingcost = \begin{pmatrix} \sum_{r,h,i} cflexup_{r,h,i} \cdot \dot{V}flexup_{r,h,i} \\ + \sum_{r,h,i} cflexdown_{r,h,i} \cdot \dot{V}flexdown_{r,h,i} \\ + \sum_{r,h,a(ij)} clpflex_{r,h,a(ij)} \cdot \dot{V}lpflex_{r,h,a(ij)} \end{pmatrix} \tag{6.7}$$

[92] The gas-transmission speed, however, is not explicitly modelled. Therefore, gas can travel any distance in the considered network in a time period, unless local congestion impedes this.

[93] A study of actual welfare or efficiency changes through cross-border procurement is very difficult because actual data on flexibility are limited and network modeling of real gas networks is a trade-off between technical accuracy and analytical applicability, especially due to the non-linearity and non-convexity of gas transport and pipeline storage.

Where, as before:

$\dot{V}flexup_{r,h,i}$	upward flexibility [Mm^3/h] at node *i* in period *h* in system *r*
$\dot{V}flexdown_{r,h,i}$	downward flexibility [Mm^3/h] at node *i* in period *h* in system *r*
$\dot{V}lpflex_{r,h,a(ij)}$	change of line-pack level [Mm^3] in pipeline *a(ij)* in period *h* in system *r*, $\dot{V}lpflex_{r,h,a(ij)} = Vlp_{r,h,a(ij)} - Vlp_{r,h-1,a(ij)}$
$cflexup_{r,h,i}$	bid price for upward flexibility in node *i* in period *h* in system *r*
$cflexdown_{r,h,i}$	bid price for downward flexibility in node *i* in period *h* in system *r*
$clpflex_{r,h,a(ij)}$	operational cost of line-pack flexibility in pipeline *a(ij)* in period *h* in system *r*

This total cost includes the costs of using line-pack flexibility in system *r* during period *h* and the costs of accepted bids *i* from the merit order in period *h* and balancing region *r*.

In **autarky**, the TSO only has access to domestic resources (local flexible gas and domestic pipeline storage) to achieve a safe state of the system. The domestic flexibility has to be equal to the exogenous imbalance ($imb_{r,h}$) between total injections and total withdrawals for each region and for every period as expressed in Eq. (6.8).

$$\sum_i \dot{V}flexup_{r,h,i} - \sum_i \dot{V}flexdown_{r,h,i} - \sum_{a(ij)} \left(Vlp_{r,h,a(ij)} - Vlp_{r,h-1,a(ij)} \right) = -imb_{r,h} \qquad (6.8)$$

Furthermore, each bid for upward or downward flexibility defines a maximum amount ($Qup_{r,h,i}$ and $Qdown_{r,h,i}$) that can be called:

$$0 \le \dot{V}flexup_{r,h,i} \le Qup_{r,h,i} \qquad (6.9)$$

$$0 \le \dot{V}flexdown_{r,h,i} \le Qdown_{r,h,i} \qquad (6.10)$$

Additionally, the system operators have to keep the line-pack level between the safe operation levels $LP\_min_{r,a(ij)}$ and $LP\_max_{r,a(ij)}$ of the respective pipeline systems at all times:

$$LP\_min_{r,a(ij)} \le Vlp_{r,h,a(ij)} \le LP\_max_{r,a(ij)} \qquad (6.11)$$

When **cross-border procurement** is possible, Eq. (6.8) is replaced by Eqs. (6.12) and (6.13), below. Equation (6.12) ensures global system balance in each period, whereas Eq. (6.13) deals with balancing the separate regions taking account of flexibility that is traded ($M_{r,h}$ expressed in Mm^3 and positive for import into region *r*).

$$\begin{pmatrix} \sum_r \sum_i \dot{V}flexup_{r,h,i} - \sum_r \sum_i \dot{V}flexdown_{r,h,i} \\ -\sum_r \sum_{a(ij)} \left(Vlp_{r,h,a(ij)} - Vlp_{r,h-1,a(ij)} \right) \end{pmatrix} = -\sum_r imb_{r,h} \qquad (6.12)$$

$$\begin{pmatrix} \sum_i \dot{V}flexup_{r,h,i} - \sum_i \dot{V}flexdown_{r,h,i} \\ -\sum_{a(ij)} \left(Vlp_{r,h,a(ij)} - Vlp_{r,h-1,a(ij)} \right) + M_{r,h} \end{pmatrix} = -imb_{r,h} \tag{6.13}$$

Evidently, the flexible gas imported in region 1 equals the exports from region 2 in this 2-region model:

$$\forall r \neq rr : M_{r,h} = -M_{rr,h} \tag{6.14}$$

Finally, exchange of flexible gas is constrained by the availability of border capacity in a period (CAP_h):

$$-CAP_h \leq M_{r,h} \leq CAP_h \tag{6.15}$$

Figure 49 shows the hypothetical gas networks of region 1 (nodes 1-4 and border node 9) and region 2 (nodes 5-8 and border node 9). Gas enters the systems through nodes 1 and 5 and demand is located in nodes 3 and 7, respectively. Nodes 4 and 8 offer flexibility, in addition to the production and demand nodes 1, 5, 3 and 7, which can also offer flexible gas. Finally, node 9 represents the border between the two systems. The pipelines have a flow and storage capacity based on geometry and pressure levels (see Appendix C).

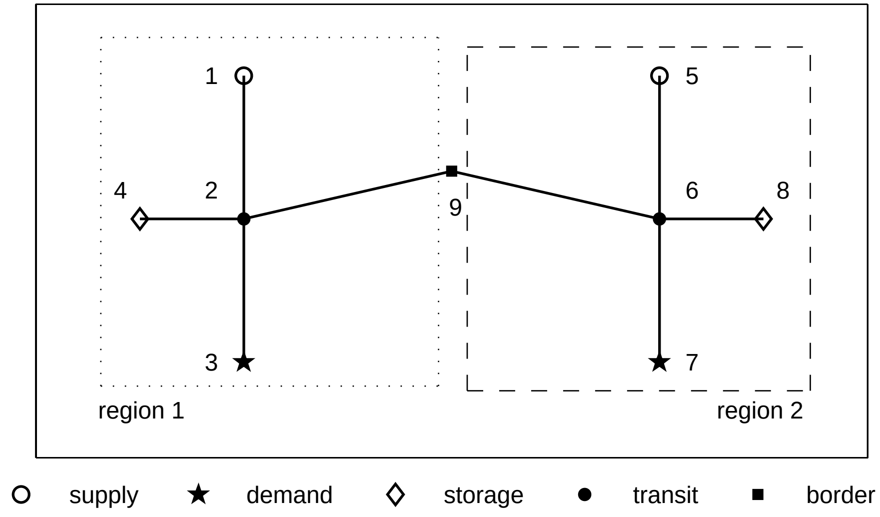

Figure 49. Gas network of region 1 (1-4 and 9) and region 2 (5-8 and 9): gas production/entry (nodes 1 and 5, o), gas demand/exit (nodes 3 and 7, ★), flexible gas (nodes 1, 3, 4, 5, 7 and 8), storage facilities (nodes 4 and 8, ◇) and an interconnecting border point (node 9, ■), further technical details are provided in Appendix C

To examine autarky, border capacity is set to 0, whereas in free trade the capacity is unrestricted. To test the effects of restricted trade, the border capacity is set at a small, but positive number.

The costs of flexible gas have been derived from bid-ladder data that have been published by the Dutch TSO, GTS [50]. Figure 50 shows the mark-up (published bid price – spot price) for different quantities of flexibility.

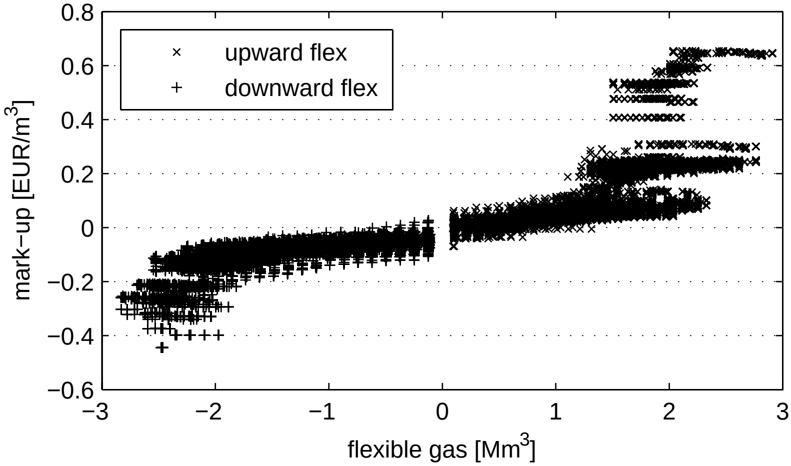

Figure 50. Merit order (hourly) of bids for flexible gas: mark-up/mark-down on wholesale day-ahead price for upward and downward flexible gas (sources: [50; 51]). Mark-downs are represented here as negative mark-ups.

The premium to provide upward flexibility to a short system (positive amount of flexible gas) is approximately 0.05 EUR/m^3 for up to about 1 Mm^3, steadily rising to 0.10 EUR/m^3 and even further to as high as 0.50 EUR/m^3. The mark-down (represented as negative mark-ups in Figure 50) for downward flexibility makes up the cost for the provider of flexibility to accept the gas from the long system. This cost ranges from 0.05 EUR/m^3 to 0.30 EUR/m^3 in order of magnitude. Table 35 lists the location, quantity and cost (mark-up/mark-down) of the assumed flexibility bids in the analysis below.[94] For reference, wholesale gas prices ranging from 0.15 EUR/m^3 to 0.40 EUR/m^3 have been considered, but, as far as system flexibility is concerned, it is the mark-up or mark-down bid by the flexibility provider that is relevant.

[94] The assumption that flexibility-cost structures differ between regions is justified as countries are differently endowed with, e.g., production or storage capabilities (see Appendix A).

Table 35. Offer of flexible gas (hourly bids): quantities of downward and upward flexible gas, and mark-down (to be subtracted from spot price) and mark-up (to be added to spot price), respectively

Node	Qdown [Mm^3]	Mark-down [EUR/m^3]	Qup [Mm^3]	Mark-up [EUR/m^3]
1	0.60	0.08	0.50	0.06
3	0.20	0.16	0.40	0.24
4	0.16	0.05	0.30	0.0025
5	0.30	0.38	0.50	0.21
7	0.40	0.20	0.50	0.30
8	0.18	0.12	0.25	0.15

The cost of line-pack flexibility comes down to the extra compression cost of gas (roughly 0.15 EUR/m^3 for primary fuel gas). Recall that this cost is very hard to separate from the compression that is already required for transmission of gas and that any attempt to disentangle this mixed use is disregarded and the full cost is attributed here to the provision of pipeline flexibility [187]. If there is no local compression, line pack has no operational costs for the TSO in that region. Possible compression, in that case, occurs outside the considered regions and its costs are assumed to be integrated in the shipper's decision making.

Shipper entry and exit nominations are exogenous input for the model, from which the regional system imbalances can be derived. These imbalances, then, have to be covered with line-pack flexibility and flexible gas over the course of a gas day.

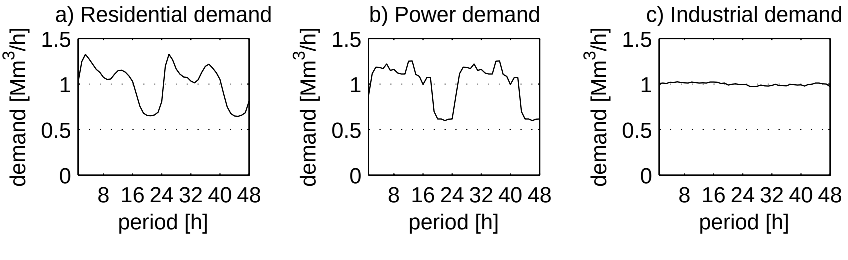

Figure 51. Generic hourly demand [Mm^3] profiles for two gas days (adding up to 48 hours): a) generic residential demand, b) generic electricity-generation demand and c) generic industrial demand; demand has been scaled to average 1 Mm^3/h

Figure 51 shows the used generic profiles that are representative for residential, electricity-generation and industrial consumption.[95] They are all scaled back to an average hourly demand of 1 Mm^3/h. Moreover, perturbations have been superimposed to generate and test random profiles.

For the supply side in nodes 1 and 5, a flat entry profile has been assumed during the day. This entry profile, then, is committed by the shipper based on the forecasted daily demand in nodes 3 and 7. Furthermore, forecast errors (FE) have been introduced, ranging from underestimating demand by 15 percent (negative system imbalance) to overestimating demand by 15 percent (positive system imbalance). As a simplification, it is assumed that regions 1 and 2 are similar with reference to their supply and demand, meaning that mainly cases where the peaks in the two regions are coinciding are looked at, limiting to some extent the pooling effect of hourly imbalances with opposite signs in the two regions.[96]

In the end, it is only the imbalance profile per region and the relative positions of the two regions that is relevant for the analysis. For instance, if region 1 has a surplus of 0.5 Mm^3 and region 2 is short 0.2 Mm^3, pooling ("exchanging" line pack) of imbalances reduces the overall system imbalance to +0.3 Mm^3 to be absorbed by line-pack flexibility or covered by flexible gas. Therefore, demand and supply profiles have been mixed to obtain system-imbalance profiles ranging from extremely short systems (separate systems are both short) to extremely long systems (separate systems are both long) and combinations with pooling effects (one system long when the other is short). This range covers the relevant situations that can occur and that have different requirements regarding flexibility. The chosen demand-profile similarity in the two systems implies that the efficiency gains are to be seen more as a lower limit for these hypothetical case studies because non-coinciding peaks and dips or opposite intra-day imbalances provide more options to improve efficiency by exchanging line-pack flexibility resulting in higher cost reductions.

6.4 Results

Before discussing the main results, a reduced example is presented to clarify the governing principles without the complexity of the gas-system dynamics. Next, the welfare effects of cross-border procurement are discussed taking into account all aspects of the gas system that have been introduced before. This section ends with some reflections on the settlement of individual shipper imbalances.

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[95] The profiles are the same as have been used in Chapter 5 (Figure 36), but are reiterated for convenience of the reader.

[96] This choice is defendable considering that demand profiles do not tend to differ much between regions that are geographically close because, e.g., residential-user behavior will typically see a morning (before working hours) and evening (after working hours) peak.

6.4.1 Small scale example

Suppose a 2-regions and 4-periods balancing problem with line-pack flexibility, flexible-gas bids and border capacity. Furthermore, line pack in region 1 can only cover cumulative deviations ranging between -0.12 and +0.14, whereas region 2 can sustain deviations between -0.15 and +0.15. All units are Mm^3. Finally, it is assumed that using line pack is cheaper than flexible gas and cross-border trade has no transaction costs. In Table 36 and Table 37, "line-pack position" is a *storage variable* that accumulates over the periods. "Flexible gas" and "Trade", on the other hand, have no "memory" over the periods.

Table 36, then, presents the outcome without border capacity: imbalances in a period are absorbed mostly by line-pack buffering, but 0.02 units of upward flexible gas have to be procured in region 1 to keep the line-pack position above the lower limit in the final period, whereas 0.04 units of downward flexible gas have to be procured by the TSO in region 2 to keep the line-pack under the upper deviation limit.

Table 36. Governing dynamics of system balancing without cross-border procurement: imbalance in each period has to be absorbed by line pack or dispatching of flexible gas. Note that, e.g., a surplus is balanced by increasing line pack (>0) or dispatching downward flexibility (<0) in that period. Line pack is a storage variable that accumulates over the periods.

Region	Period	Imbalance over period [Mm^3]	Line-pack position[a] buffering (>0) emptying (<0) [Mm^3]	Flexible gas upward (>0) downward (<0) [Mm^3]	Trade import (>0) export (<0) [Mm^3]
1	1	+0.11	+0.11		/
	2	–0.19	–0.08		/
	3	+0.13	+0.05		/
	4	–0.19	–0.12	+0.02	/
2	1	+0.17	+0.15	–0.02	/
	2	–0.13	+0.02		/
	3	+0.15	+0.15	–0.02	/
	4	–0.11	+0.04		/

[a] Line-pack deviation limits for system 1: up +0.14 / down –0.12 compared to starting level, for system 2: up +0.15 / down –0.15 compared to starting level

Table 37, then, shows the use of line-pack flexibility and the procurement of flexible gas in an integrated market. Because of the trade possibilities, no expensive flexible gas has to be procured. Indeed, the exchange of line-pack gas between the regions enables the TSOs to keep their respective line-pack positions within the safe limits. In the first period, e.g., region 2 exports 0.02 units of excess line-pack gas to region

1, which has unused buffer capacity. Without cross-border trade, region 2 had to procure and dispatch flexible gas to accommodate this excess gas in period 1 (Table 36). Cross-border trade, thus, improves efficiency in the combined region.

Table 37. Governing dynamics of system balancing with unlimited cross-border procurement and pooling: imbalance in each period has to be absorbed by line pack or dispatching of flexible gas in the combined region. Note that, e.g., a surplus is balanced by increasing line pack (>0), dispatching downward flexibility (<0) or exporting gas (<0) to the other region in that period. Line pack is a storage variable that accumulates over the periods.

Region	Period	Imbalance over period [Mm^3]	Line-pack position[a] buffering (>0) emptying (<0) [Mm^3]	Flexible gas upward (>0) downward (<0) [Mm^3]	Trade import (>0) export (<0) [Mm^3]
1	1	+0.11	+0.13		+0.02
	2	–0.19	–0.06		
	3	+0.13	+0.09		+0.02
	4	–0.19	–0.10		
2	1	+0.17	+0.15		–0.02
	2	–0.13	+0.02		
	3	+0.15	+0.15		–0.02
	4	–0.11	+0.04		

[a] Line-pack deviation limits for system 1: up +0.14 / down –0.12 compared to starting level, for system 2: up +0.15 / down –0.15 compared to starting level

6.4.2 Efficiency analysis taking gas network into account

Four cases, summarized in Table 38, that vary according to the system imbalance in each region have been examined: the forecast error is kept constant in one region and the other forecast error varies from -15 percent to +15 percent.

Table 38. Overview of the examined cases, FE = forecast error in a region

Case A	Case B	Case C	Case D
Region 1: FE = –12%	Region 1: FE = +6%	Region 1: FE = –15%=>+15%	Region 1: FE = –15%=>+15%
Region 2: FE = –15%=>+15%	Region 2: FE = –15%=>+15%	Region 2: FE = –12%	Region 2: FE = +6%

The net imbalance profile is obtained by adding the imbalance profiles of the separate regions. This net imbalance profile is then named after the forecast error of the net end-of-day imbalance. A forecast error of, e.g., -12 percent in region 1 and -9 percent in region 2 gives a net forecast error of -21 percent on total demand, or, alternatively, a net supply of 0.79 compared to total demand in the combined region.

The total TSO-efficiency surplus ($\Delta S_{TSO,R1+R2}$) is defined as the sum of the differences between the balancing costs with cross-border cooperation and those costs in autarky in region 1 and region 2:

$$\Delta S_{TSO,R1+R2} = \begin{pmatrix} \left(balancingcost_{crossborder,R1} - balancingcost_{autarky,R1}\right) \\ +\left(balancingcost_{crossborder,R2} - balancingcost_{autarky,R2}\right) \end{pmatrix} \quad (6.16)$$

It is positive if cross-border trade improves efficiency in the combined region compared to autarky.

Figure 52 shows the efficiency surplus for cases A (Figure 52.a) and B (Figure 52.b). In both cases, efficiency gains compared to autarky are larger when both regions are unbalanced. Indeed, when a region is more or less balanced, its potential for improvement is limited. The flexible-gas cost structure from Table 35 is such that region 1 has the more efficient resources in its merit order. Therefore, region 2 benefits most when it has an imbalance and can switch domestic resources for more efficient imported flexible gas.

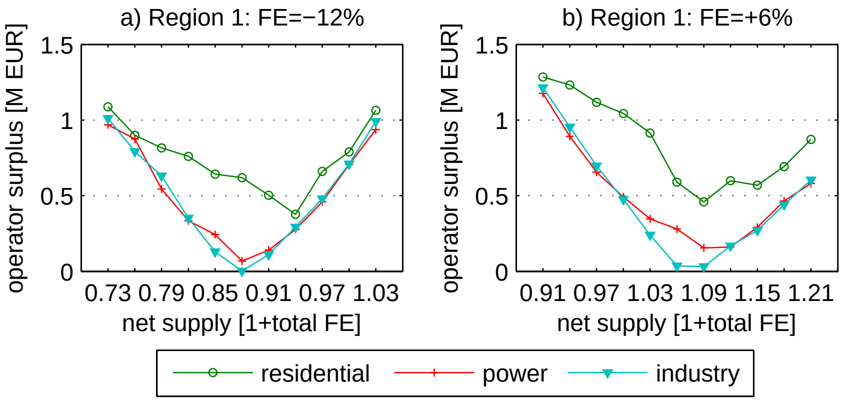

Figure 52. Operator surplus [M EUR]: efficiency gain of cross-border procurement compared to autarky for different net supply levels (1+total FE) in the combined region for different gas demand types – a) region 1 FE -12% and net supply in the combined region ranging from 0.73 to 1.03, b) region 1 FE +6% and net supply in the combined region ranging from 0.91 to 1.21

This is further demonstrated in Figure 53, which shows cases C (Figure 53.c) and D (Figure 53.d). The operator surplus is in these cases much less dependent on the region-1 imbalance than on the region-2 imbalance, which is now kept constant. Indeed, region 1 already has the more efficient resources according to Table 35. Hence, the surpluses are flatter over the considered range of net-supply profiles.

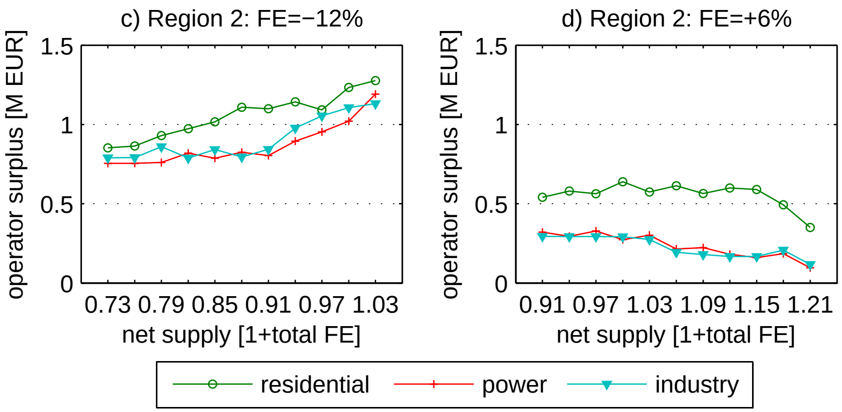

Figure 53. Operator surplus [M EUR]: efficiency gain of cross-border procurement compared to autarky for different net imbalance levels (1+total FE) in the combined region for different gas demand types – c) region 2 FE -12% and net supply in the combined region ranging from 0.73 to 1.03, d) region 2 FE +6% and net supply in the combined region ranging from 0.91 to 1.21

Next, the potential efficiency gains for industrial and power-sector demand are very similar, but the potential for residential demand profiles is higher in all cases A-D. This is due to the swing of the generic profiles that have been used: the residential demand has two peaks a day, whereas industrial demand is almost flat and electricity-sector demand is volatile with small peaks superimposed on a relatively long period of high demand intra-day.

As the absolute numbers for these hypothetical systems do not tell everything, the relative efficiency gain compared to autarky has to be checked as well. In almost all cases the relative gains for the combined region range between 60 and 100 percent and are thus substantial. Evidently, this outcome depends on the relative costs of flexible gas.

A closer examination of case A confirms the theory that the net efficiency change is positive, but, separately, the regions can win or lose as is illustrated in Figure 54. As long as region 2 is short (profiles ranging from 0.73 to 0.85), region 1 loses and region 2 gains because both regions are short. But region 2 can import cheaper flexible gas from region 1, raising the price of flexibility in region 1. As soon as region 2 is long (profile 0.91 and beyond), region 1 benefits from imbalance pooling and can reduce its costs. A proper compensatory mechanism will be required to re-distribute the surplus after all system imbalances have been dealt with.

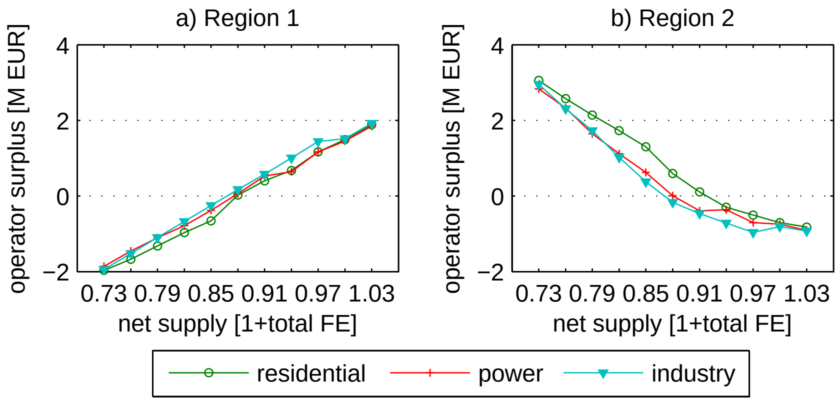

Figure 54. Operator surplus [M EUR] per region for case A for net supply (1+total FE) ranging from 0.73 to 1.03 relative to total demand: efficiency gains are distributed unequally; one TSO can gain as the other loses, but net efficiency increases; the non-linear behavior in panel b is caused by the considered cost structure of flexible gas

Taking a closer look to the use of flexibility in a specific instance of case A (net-supply profile 0.79 for power-sector demand), Figure 55 shows that, when cross-border procurement of flexible gas is possible, region 2 dispatches almost no domestic flexibility, whereas in autarky, flexible gas was extensively dispatched in region 2 as shown in Figure 55.d. Region 1, on the other hand, "produces" more flexible gas to export it to region 2 (Figure 55.b) in the cross-border scenario. Furthermore, Figure 55.c shows a smoother line-pack use in region 2 when cheap flexible gas can be acquired.

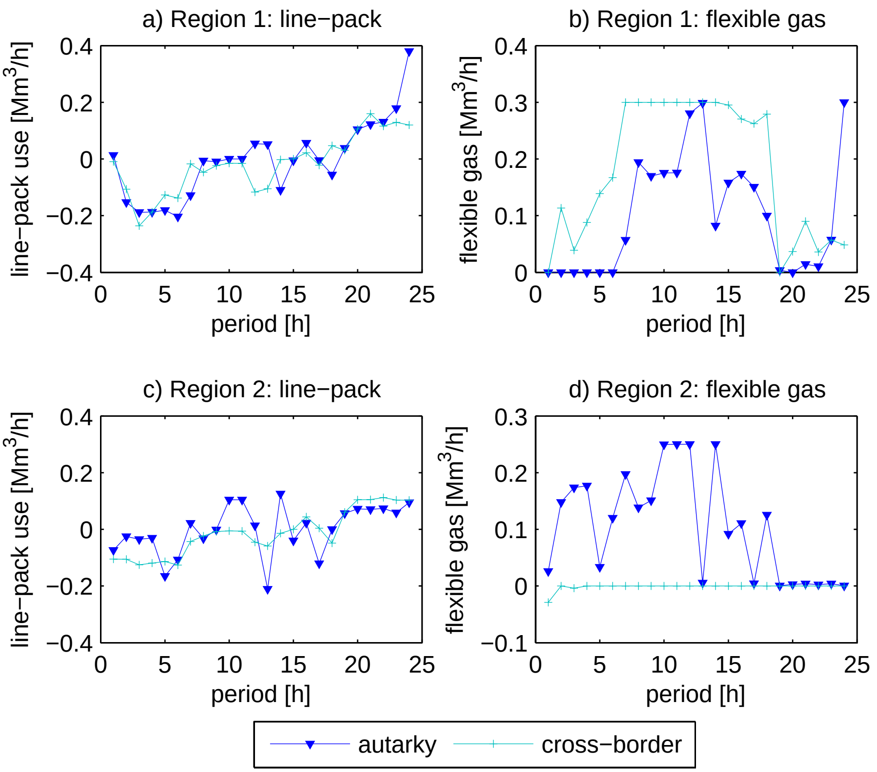

Figure 55. Flexibility dispatching per region: for autarky (▼) and for cross-border cooperation (+) – a) line-pack use in region 1, b) procurement of flexible gas in region 1, c) line-pack use in region 2 and d) procurement of flexible gas in region 2, changes in flexibility use represent trade between the regions

Finally, Figure 56 shows the detailed use of the merit order: the sources of flexibility *flex 1* to *flex 8* refer to the nodes and data from Figure 49 and Table 35, respectively. In this specific instance of case A (net-supply profile of 0.73 and residential demand), bids have been accepted for upward and downward flexibility in region 1 and only upward flexibility in region 2 in the autarkic case. Cross-border procurement allows region 2 to cut back on its more expensive bids from *flex 8* and instead rely on imported flexibility from region 1. In region 1, not only the bid of *flex 4* is accepted, but in some periods also *flex 1* has to be called to satisfy the demand for flexible gas from the international market.

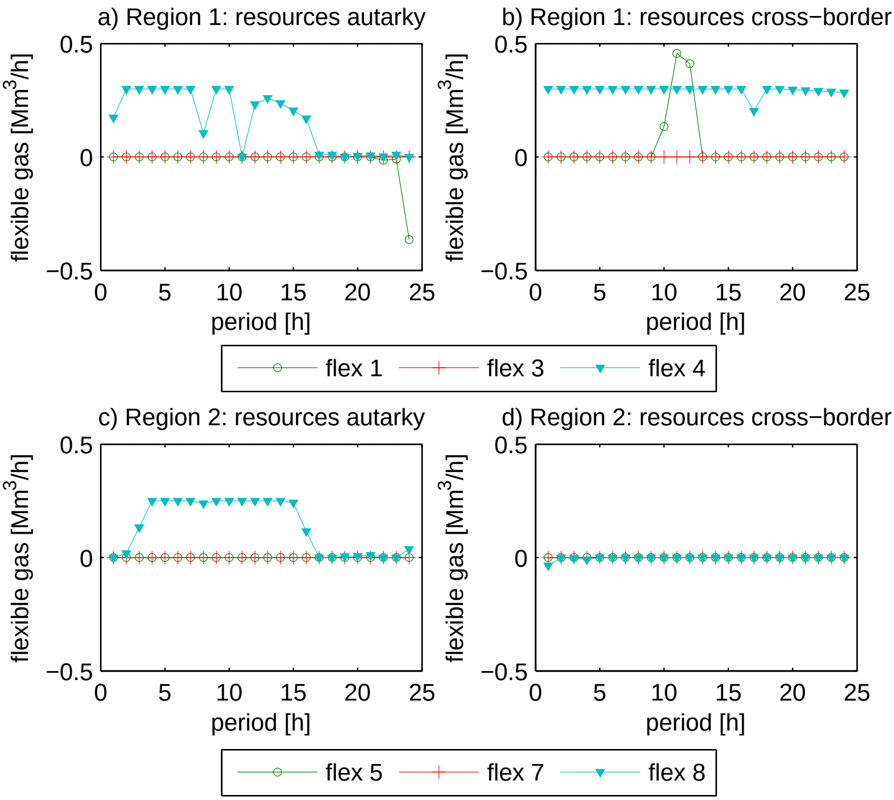

Figure 56. Flexibility dispatching per source (see Figure 49 and Table 35) – a) region 1 in autarky, b) region 1 with cross-border trade, c) region 2 in autarky and d) region 2 with cross-border trade. Region 2 reduces its domestic flexibility production when free trade is possible and it imports from region 1. The dispatching of flex 4 in region 1 is almost continuously at its maximum and the second cheapest flex 1 is also dispatched for local use or export to region 2. Note that in the cross-border scenario the dispatching of downward flexibility at the end of the day in region 1 is avoided.

Overall, the results, which have been based on computations accounting for network effects and technical constraints of the gas system, confirm the outcome predicted by the theory of international trade and the trade-policy framework. In the end, cross-border procurement raises efficiency, but distribution of efficiency between the regions is unequal, with one system gaining at the expense of the other. Therefore, the development of a suitable compensatory mechanism can be identified as an important "transaction cost" for the actual implementation of a TSO-TSO cross-border mechanism.[97]

If border capacity is restricted, the welfare gains become smaller as illustrated in Figure 57 for cases A and B. Four border-capacity levels have been considered and compared to the benchmark surplus if no capacity restrictions apply ("no lim"). Table 39 provides an overview of the border capacities.

Table 39. Considered border capacities [Mm^3/h] for trade between the regions

Capacity 1 [Mm^3/h]	Capacity 2 [Mm^3/h]	Capacity 3 [Mm^3/h]	Capacity 4 [Mm^3/h]	Capacity 5 [Mm^3/h]
no lim	0.025	0.05	0.10	0.15

Any trade restriction reduces the efficiency gains that can be captured compared to the no-lim benchmark. And the more stringent the restriction becomes, the larger the foregone efficiency gains. Furthermore, the missed efficiency gains become bigger if the flexibility needs in region 2 increase (bigger regional forecast error). This can be observed in case A (Figure 57.a), and, to a lesser extent, in case B (Figure 57.b).

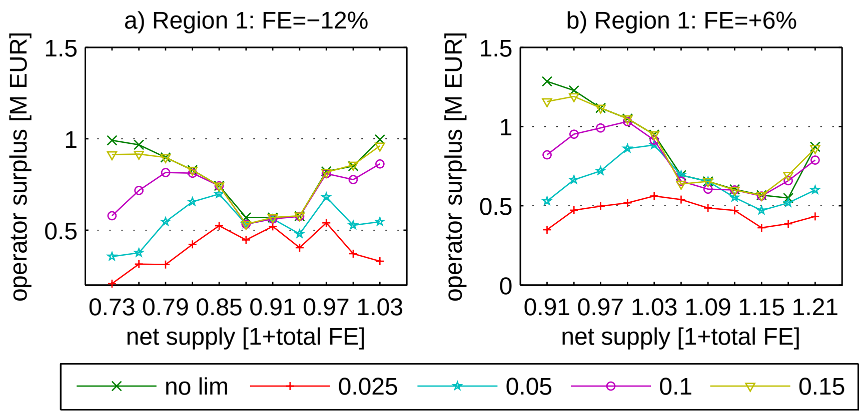

Figure 57. Operator surplus [M EUR] for different border-capacity restrictions [Mm^3/h]: a) region 1 FE fixed at -12% and combined net supply ranging from 0.73 to 1.03, and b) region 1 FE fixed at +6% and net supply ranging from 0.91 to 1.21 – the more trade is restricted by the physically available border capacity the less efficiency gains are captured by cross-border procurement

An explanation for this observation is found in the cost structure and the relative efficiencies of the two regions: region 2 benefits most by importing flexibility from

[97] The design of such a mechanism requires advanced insight into the short-term and long-term costs and benefits of border capacity and is beyond the scope of this work.

region 1. Therefore, trade restrictions have a larger impact if region 2's flexibility-import demand increases. In that case, not all expensive domestic flexibility can be replaced with cheaper imports. Note that the trade restriction of 0.1 Mm^3/h corresponds to 10 percent of the considered average hourly demand that amounts to 1 Mm^3/h.[98]

Similarly, Figure 58 illustrates the TSO surpluses for cases C and D. The considered border-capacity levels are all binding for all net-supply profiles. This is shown in Figure 58.c, which has all surpluses lower than the "no-lim" benchmark. In case D, on the other hand, only the most stringent capacity restrictions are binding. Hence the overlapping results of "no lim" and the capacity limits of 0.1 and 0.15. Indeed, less import is required in case D because the flexibility needs are fairly small and are covered efficiently and predominantly by the domestic line-pack flexibility.

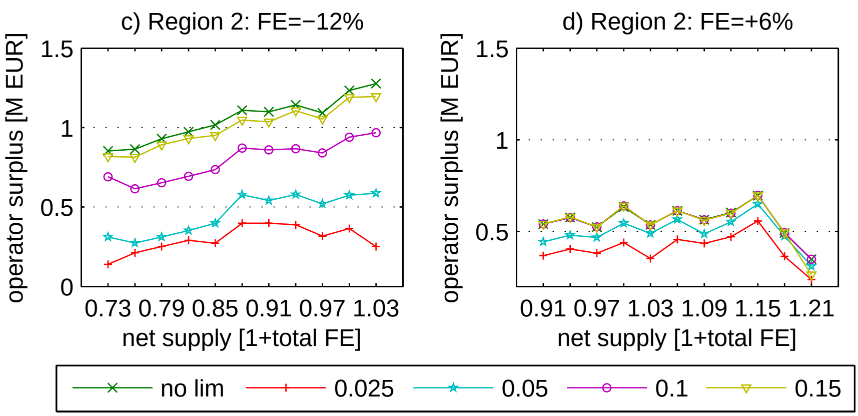

Figure 58. Operator surplus [M EUR] for different border-capacity restrictions [Mm^3/h]: c) region 2 FE fixed at -12% and combined net supply ranging from 0.73 to 1.03, and d) region 2 FE fixed at +6% and net supply ranging from 0.91 to 1.21 – the more trade is restricted by the physically available border capacity the less efficiency gains are captured by cross-border procurement – for case C, all considered border capacities result in a reduced capturing of surplus, whereas for case D, only the limits of 0.025 Mm^3/h and 0.05 Mm^3/h are binding as the other limits are shown to overlap with the "no-lim" benchmark

A study of the dual variable of the border capacity constraint in the optimization can provide clues about the value of increasing this border capacity; at least the part of the value that is related to cross-border procurement of flexibility by TSOs.

[98] Although there are no true transmission-capacity markets in Europe, publicly available data from the Belgian TSO suggests that at some border points about 10% of total marketed capacity is "available" (not contracted) [43]. This is contractual capacity (as both forward and backhaul capacity is marketed), not physical capacity.

6.4.3 Cross-border settlement

Besides procurement of balancing services and physical balancing, a complete balancing mechanism also deals with the settlement of unbalanced shippers. The costs incurred by the transmission-system operator for balancing the gas system have to be recovered from the network users by allocating them to those users who caused the imbalance. Once the true cost of system balancing has been determined taking account of line-pack flexibility and flexible gas on both sides of the border, the settlement of *ex-post* balancing services could also be based on a cross-border mechanism. Such a mechanism should start from the average cost of all flexible gas (including line-pack related costs) or the cost of the marginally accepted bid. The latter provides a good incentive to network users to balance *ex* ante as they have to pay the true cost of flexibility, whereas a profit for the transmission system could be used to invest in the network flexibility or lower the network costs for all users. With such a mechanism, shippers still benefit from cross-border procurement as the overall price of flexible gas will be lower than in autarkic-settlement systems that are also based on the true cost of balancing. The price can, however, rise in the more efficient region as it sees a higher demand for its flexibility.

Next, the lack of an effective "gate closure" actually makes the concept of a formal balancing period redundant. Indeed, shippers can cause balancing costs for the system within the formal balancing period, but they can correct their position before the end of the balancing period. Thus, these shippers cannot be allocated a fair part of those costs. The transmission-system operator, on the other hand, does not care about balancing periods as the reliable operation of the pipeline system requires continuous monitoring with interventions like dispatching flexibility from the merit order. These interventions occur whenever the TSO deems them necessary. A different way of allocating balancing costs should be used: implement a rolling gate closure for shorter intervals, e.g., hourly, in which the shipper cannot change his position anymore. The costs, then, are distributed among those shippers that contributed to the problem with a reward for those users that helped the system at that time. This results in a more efficient cost allocation. At the same time, the line-pack flexibility should be marketed as much as possible as *ex-ante* flexibility so that shippers can use it to help balance their portfolios. Otherwise, a long formal balancing period is just a market-distorting way of subsidizing shippers who have big diurnal swings as has been pointed out in [48].

Note that if both TSOs efficiently procure their balancing services in their respective regions, and if they subsequently settle the unbalanced shippers in an efficient marginal-cost-based way, the outcome of cross-border procurement can be reproduced without having TSO coordination. In that case, the forum-shopping behavior of transnational shippers results in the most efficient allocation of imbalances over the two regions. However, individual BRPs are less informed than

TSOs and they might be unwilling to reveal too much information to their competitors.[99] Furthermore, Chapter 5 has demonstrated the need for correct incentives both regarding the use of end-of-day and intra-day flexibility. Hence, shorter balancing intervals are required to enable the settlement fees to reflect (expected) balancing costs well. Similarly, a well-functioning common intra-day market can provide the necessary incentives for efficient allocation of gas (imbalances) in the different regions. The liquidity of current spot markets for gas remains low, though [36-38; 40].

6.5 Summary and Conclusions on procurement of balancing services in an integrated gas market

This chapter has examined the effects of cross-border procurement of balancing services on the efficiency of system-balancing TSOs in adjacent regions. ACER's framework guidelines, that are to be transposed into a European network code by the European transmission-system operators for gas (ENTSOG), advocate market-based balancing. However, there is no firm requirement to move towards more cross-border harmonization of balancing rules or at least to a compatibility check of the applicable rules.[100]

This lack of a true push towards cross-border cooperation for gas-system balancing is striking because international-trade theory predicts efficiency gains when balancing services are exchanged between geographically adjacent balancing areas. Moreover, using "welfare"-benchmarking for hypothetical gas systems that include technical peculiarities, efficiency gains have been demonstrated to be possible. And in an integrated liberalized gas market, balancing should be done where it is most efficient, but taking technical feasibility into account.

Net efficiency of the combined region certainly increases by exchanging line-pack gas and procuring flexible gas across borders. Nevertheless, resistance against cross-border balancing can exist because not every player or region gains in the same way. The implementation of a compensatory mechanism seems necessary to ensure that no region loses compared to its efficiency in autarky. Furthermore, sufficient short-term cross-border capacity should be available to seize the full efficiency gains. Indeed, border-capacity restrictions limit the amount of efficiency gains that can be captured. The net efficiency gain of cross-border procurement can be used as an

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[99] E.g., the TSO sees the allocations of the previous hours and the intended nominations for the upcoming hours of all shippers.

[100] In the draft network code disclosed by ENTSOG (after this work had been completed), cross-border cooperation is discussed in a separate chapter. Concrete steps are identified to explore integration of adjacent regions. The advocated principles are in line with what is studied and advocated in this thesis.

indication of the value of (adding) border capacity (this is a partial value that refers to balancing costs only).

Although the calculations in this chapter have been based on hypothetical systems using rough estimates for flexibility costs and other parameters, the developed methodology and concepts can be applied for more realistic cases when the numbers are available. E.g., historical data on imbalances from two regions and actual merit-order data can be used.

Finally, the implementation of cross-border balancing with regard to the procurement of flexibility is advisable for policy makers. But also moving towards cross-border based settlement is to be considered by policy makers. The settlement mechanism, then, should be based on the (cross-border) cost of system balancing. Such a change would reduce forum-shopping behavior as a single reference price would be set for flexible gas in the combined region and this price can be used for pricing *ex-post* flexibility.

PART 4

Summary, Conclusions and Recommendations

7. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This final chapter answers the main research questions that have been defined at the start of this thesis, by combining and summarizing the findings that have been presented in the different chapters of this thesis. Furthermore, conclusions with regard to balancing-mechanism design are provided in section 7.2. This thesis fills a gap in the academic literature on gas balancing and can serve as a further advanced starting point for other research, for which recommendations are presented in the third section of this chapter.

7.1 Summary

This thesis starts from the observation that gas balancing in the liberalized European gas market is a controversial topic in the industry, but that academia have had a limited contribution to the debate. In the first part of this thesis, the necessary fundamentals about balancing are introduced. The second part deals with balancing-design issues in a national context. Cross-border aspects of balancing are discussed in the third part. Below, the chapters are consecutively summarized.

Chapter 1 introduces a proper framework and terminology for discussing gas balancing and balancing-mechanism design in liberalized gas markets. First, the roles and responsibilities of the shipper and the transmission-system operator (TSO) in the unbundled gas market are defined. The shipper builds a contract portfolio that matches the different time patterns of supply and demand by contracting *ex-ante* flexibility by himself or by relying on the *ex-post* balancing by the TSO. The TSO, on the other hand, is responsible for the system integrity. Therefore, the system operator manages the pipeline flexibility and procures additional flexible gas to balance the gas network over time. The gas-balancing mechanism, then, serves as the main short-term coordination mechanism between the two actors. However, there is currently no preferred design as illustrated by the various approaches to balancing design in different EU gas markets. Furthermore, Chapter 1 provides a thorough discussion on the lessons that could be drawn from other energy markets that face a balancing problem. The liberalized US gas market relies on tailor-made *ex-ante* flexibility and an effective market for transmission services. However, the different institutional setting impedes the plain copying of this solution. The EU electricity market, on the other hand, has similar institutions as the EU gas market, but is technically different. Gas is compressible and thus efficiently storable, allowing a longer time interval before the gas system integrity is threatened.

The chapters of Part 2 deal with gas balancing in a national context. This means that the discussed problems and challenges arise independent of the cross-border integration of EU gas markets.

In **Chapter 2**, the regulation of the gas-industry-specific line-pack flexibility is thoroughly reviewed. First, the "production" of line-pack flexibility is looked at, followed by a discussion of its use. As the pipeline flexibility is technically bundled with the service of transport by pipeline, its costs cannot be determined directly. Hence, a methodology is proposed based on the opportunity costs of line-pack flexibility. A study of the different trade-offs involving line-pack flexibility reveals the costs and value of the network-based flexibility for the TSO and the shippers.

Furthermore, the major determinants of the line-pack costs are identified. As line-pack costs are not attributed properly to the users of this flexibility, the balancing rules distort the non-competitive infrastructure market and the competitive spot markets and flexibility markets.

Chapter 3 presents a brief overview of the gas-modeling literature and introduces GASFLEX, an operations-research model to study balancing and flexibility from different viewpoints. First, the shipper's contract portfolio is optimized taking contractual constraints into account. Subsequently, the output of this shipper optimization serves as input for optimal network balancing by the TSO. This TSO optimization balances technical accuracy (e.g., non-linear gas dynamics) and economic applicability (e.g., studying a full gas day with an appropriate time step) of the code. Furthermore, the well-known electricity-sector concepts of "unit commitment" and "economic power dispatch" are translated to the gas-market context.

The GASFLEX model is then applied to study the challenge of rising interactions between the gas sector and the electricity-generation sector. The transfer of RES-balancing needs from the electricity-generation system to the gas system results in increasing unpredictability of a "new" type of gas demand. The TSO ultimately has to deal with the rising balancing needs in the gas system, dispatching more and increasingly expensive flexible gas.

Two settlement-mechanism designs, then, are compared with regard to their adequacy in dealing with this unpredictability. Non-market-based settlement design starts from cost neutrality for the TSO. Due to the unpredictable balancing costs, defining a single cost-recovering penalty is impossible. Market-based settlement, on the other hand, starts from the marginal cost of balancing the system. Hence, imbalance settlement can be priced efficiently. However, the daily balancing period prevents intra-day costs to be attributed to those having caused the imbalance. Hence, cost recovery is only attained for end-of-day costs.

In Part 3, that is introduced by **Chapter 4**, the "welfare" effects, to be interpreted in this thesis as efficiency gains, of market integration, and thus cross-border interactions are examined. **Chapter 5** presents the potential market distortions of incompatible balancing-mechanism designs in geographically adjacent gas regions. The patchwork of balancing rules in Europe establishes a profitable playing field for transnational shippers.

Using a self-developed "welfare"-benchmarking methodology in combination with GASFLEX, a case study for the border between the UK and Belgium demonstrates the profitability of a "forum-shopping" strategy. A transnational shipper can reduce his exposure to the more penalizing settlement mechanism by exporting imbalances to the more lenient settlement mechanism at the other side of the border. The profit change of the forum-shopping shipper is certainly positive because he can always revert to an autarkic strategy.

The impact on the residual balancing by the TSO is shown to be positive if the relative settlement mechanisms provide a correct incentive. In that case, imbalances are moved to the region that is most efficient in balancing its gas system. If a wrong incentive is provided, shippers will move imbalances to regions that are actually less efficient in balancing and the TSO efficiency in the combined region decreases. The net impact on efficiency in the combined region, thus, depends on the sum of the TSO surplus and the shipper surplus and can become negative if the relative cost efficiency of the expensive region decreases compared to the efficient region.

In **Chapter 6**, the GASFLEX model and an adaptation of an international-trade-policy framework is applied to studying the potential efficiency gains on the procurement side of the TSO-balancing problem. Starting from the assumptions that gas regions in Europe have different flexibility-cost structures (as their flexibility resources differ) and that market-based procurement of flexibility is used (a move towards market-based methods is advocated in ACER's Framework Guidelines), a "welfare"-benchmarking methodology reveals the impact of cooperating across borders on the TSO efficiency.

Combining the regional merit orders for flexible gas and exchanging line-pack flexibility improves the balancing efficiency in the combined region by using the most efficient balancing service independent from its origin.

The border capacity is identified as a main barrier to achieving efficiency gains. If trading restrictions, e.g., halve border capacity from ten percent of the considered average hourly demand to five percent, fifty percent and more of the efficiency gains can become non-recoverable in some cases. The foregone efficiency gains increase if flexibility-import demand by the less efficient region is large. Furthermore, efficiency gains are not distributed evenly between the regions and actors.

Finally, the possibility of defining a cross-border-settlement mechanism is explored. This corresponds to effectively enlarging the balancing region or removing "gas-region borders".

7.2 Conclusions and Contributions

The conclusions of this thesis relate to the research questions that have been defined at the start of this work.

A **first set of conclusions** relates to the *organization of gas balancing*. System balancing is necessary to ensure continuous gas-system reliability, but the EU gas-market reforms have drastically altered the way that gas balancing is organized. This thesis provides a thorough, yet concise overview of the problems and challenges that have arisen due to the gas-market liberalization and unbundling. The important concepts "*ex-ante* flexibility" *and* "*ex-post* flexibility" are defined and linked to the two stages of balancing: the shipper stage and the TSO stage.

In a gas market with dispersed information and fragmented responsibilities a well-functioning coordination mechanism is a key building block of a truly liberalized and integrated gas market. To define such a balancing mechanism, better insight into the complex interactions of the gas-market players is fundamental. Furthermore, insight is needed in the design parameters:

- Time: definition of the interval over which imbalances are defined and definition of a *gate closure* that separates the wholesale market from the balancing market
- Space: definition of the geographical area within which balance should be achieved
- Price: determination of costs of balancing by means of market-based or non-market based methods for procurement and/or settlement

The variety of approaches in different EU gas markets illustrate the creativity by which national balancing mechanisms have been designed in the past (without satisfactory results if the persisting debate among the industry actors has any meaning).

Could gas-balancing design not learn from other industries that face similar problems? This research shows that while other industries might have developed solutions for balancing, these solutions cannot just be copied to the EU gas market. The US gas market, e.g., relies on competitive markets for transmission services and unbundled flexibility services. This allows shippers to individually negotiate contracts with pipeline companies tailored to their preferences. These pipeline companies, then, can discriminate between network users who value the pipeline services more or less. If the EU policy makers were to implement this solution, the current institutions would have to be reformed, starting with the abolishment of non-discriminatory third-party access that requires all pipeline services to be defined in network codes that confer rights to all network users disregarding any differences between them.

Lessons from the EU electricity market cannot be applied directly to the gas market because the technical parameters are different. Yet, electricity-sector regulation has been leading gas-industry regulation in the past. The just-in-time context of electric-load balancing makes it a technical challenge, whereas the gas dynamics just facilitates gas-system balancing. Therefore, electricity-balancing regulation is missing a vital piece of regulation required for the gas industry: the regulation of the network flexibility.

Highlights of the first set of conclusions:

- *A clear demarcation of time and space is necessary to define the responsibilities of the TSO and the shippers*
- *Lessons from other energy markets cannot just be copied to the EU gas market*

A **second set of conclusions** is connected to the regulation of the line-pack flexibility. The research in this work demonstrates that current line-pack regulation by means of the balancing rules is ineffective and actually distorts the market. The competitive markets suffer because underpriced intra-day flexibility hampers the spot market and forecloses the flexibility market. Moreover, inefficient determination and allocation of line-pack costs distort the regulated infrastructure market as well. Because line-pack flexibility is technically interdependent with pipeline transport, its cost determination and subsequent pricing are non-trivial. The cost decomposition of the dual-function pipeline is identified as the single most important challenge with regard to balancing design and regulation of network flexibility. Even though this cost decomposition is not part of this thesis, first steps are provided towards valuing and pricing line pack differently than today. Mainly, the capacity cost of line-pack flexibility has to be attributed to the users of this flexibility. To determine this cost, an indirect method is proposed, using the opportunity costs of line-pack flexibility in different trade-offs (e.g., a trade-off between investing in more entry capacity versus relying on the pipeline buffer).

Furthermore, the research in this work establishes a clear relationship between the peak intra-day imbalance position of a shipper and the costs of balancing. So, settlement methods using a daily balancing period fail to correctly allocate costs to users of *ex-post* flexibility. Therefore, if a balancing-mechanism design settles imbalances on a daily basis, it should use the peak cumulative imbalance throughout the day as its charging base and not the end-of-day imbalance. That approach allows a more efficient allocation of costs than the end-of-day imbalance. Ideally, though, the line-pack flexibility should be taken away from the TSO and be marketed as *ex-ante* flexibility (as is the case in the US). Evidently, for security reasons the TSO could and should still hold back some pipeline-flexibility capacity.

Highlights of the second set of conclusions:

- *Gas balancing is not a technical problem, but the economic and regulatory aspects are challenging*
- *Current line-pack regulation distorts the regulated market for transport services*
- *It also distorts the competitive markets for gas and flexibility*
- *Opportunity costs can be used to determine the value and cost of pipeline flexibility*
- *Balancing charges should refer to peak positions, not end-of-day imbalances*

To properly study the technical *and* economic aspects of gas balancing, adequate tools are necessary. In this thesis, an operations-research model, called GASFLEX, has been developed and is introduced, which balances technical accuracy with economic applicability. Gas models are very useful for studying the gas market as proven by the variety of developed gas models. However, these existing models tend to focus either on the economics (e.g., long-term models for analyzing security of supply) or on the operations (the detailed flow development in a pipeline). So, these existing models are not applicable to the problems looked at in this thesis. GASFLEX, then, allows studying the shipper-balancing stage (which concerns the economic optimization of the contract portfolio) and the TSO-balancing stage (focusing on the spatial, temporal and technical constraints of system balancing). So, a **third conclusion** relates to the power of optimization tools and the need for versatile optimization codes that are aligned to the problem that is investigated. Moreover, the public nature of this model allows for a better-informed debate based on quantitative methods; whereas existing industry studies often do not disclose the applied methods – that is if they use a quantitative method.

Third conclusion highlights:

- *Quantitative methodologies should simultaneously take into account technical and economic aspects*
- *Quantitative methods substantiate the gas-balancing debate*

One of the main future challenges of gas balancing, beyond the unbundling and liberalization, is the increasing interaction with the electricity-generation system. Especially the introduction of intermittent renewable energy sources (RES) like wind, transfers flexibility needs from the electricity sector to the gas system. The results of the research on unpredictability in gas demand establish a **fourth set of conclusions**. Other research had demonstrated the operational impact of massive integration of wind power on the gas system, but those works disregarded the economic and regulatory aspects of balancing. This thesis introduces a deterministic methodology for studying both the operational aspects (TSO balancing) and the economic aspects of balancing (shipper balancing) the gas system for varying levels of unpredictability. This unpredictability of gas demand is codified using the electricity-generation concepts of "unit commitment" and "power dispatch".

The results of the analysis suggest that the pricing of *ex-post* flexibility (establishment of proper imbalance tariffs) becomes difficult from a regulatory point of view. First, non-market-based pricing is inefficient in providing incentives to balance *ex ante*. Even cost neutrality (regarding the end-of-day costs) becomes difficult to achieve given that unpredictability makes it hard to determine a unique break-even penalty. Non-market-based settlement, thus, seems inadequate to deal with rising unpredictability. Market-based pricing of *ex-post* flexibility succeeds in providing incentives to the users of the TSO's balancing services by relating the imbalance fees to the marginal cost of balancing. It is thus a more efficient design option. However, market-based settlement in combination with a daily balancing period still fails to allocate the costs to those shippers who have caused the costs. Shippers with large unpredictable portfolios have a large impact on the price and are no longer price takers. Furthermore, the daily balancing period implies that only end-of-day costs can be recovered from the unbalanced shippers, whereas intra-day variability also increases intra-day flexibility costs, which are socialized.

Highlights of the fourth set of conclusions:

- *Non-market-based settlement fails to reflect, and is unsuitable to recover, balancing costs*
- *Market-based settlement is efficient, but still fails to allocate all costs of unpredictability*
- *Risk of shippers becoming imbalance-price setter*

The **fifth set of conclusions** relates to the challenges, threats and opportunities of market integration. The liberalization of the gas market introduces cross-border interactions. Yet, gas balancing remains predominantly nationally organized. On the settlement side, this imbalance between transnational shippers and national TSOs (who procure flexibility domestically) brings forth a potential for market distortions. Current settlement mechanisms are not aligned across borders of adjacent gas regions. Thus, opportunities are created for profit-maximizing shippers to move imbalances to balancing regions with more lenient settlement mechanisms (i.e. cheaper *ex-post* flexibility). If settlement mechanisms do not reflect actual balancing costs and the relative pricing in adjacent regions provides wrong incentives, total welfare can reduce because shippers end up exporting imbalances to regions that are less efficient in balancing their gas system. If the correct incentive is provided, overall efficiency of balancing is improved in the integrated region.

TSOs could also actively exchange line-pack flexibility and procure flexible gas through a cross-border market mechanism, e.g., setting up a shared merit order. This TSO-TSO cooperation, then, increases the balancing efficiency in the combined region, but efficiency gains are not distributed evenly as some regions end up with reduced efficiency. This is the case for the less efficient producers of flexible gas, who can sell less balancing services to their domestic TSO, who now imports cheaper flexibility from abroad.

These opportunities for efficiency gains depend strongly on the availability of physical (and contractual) border capacity. Therefore, policy makers, regulators and TSOs should be encouraged to actively promote cross-border interactions and actively review settlement mechanisms to track incompatibilities. Investments in border capacity have to be undertaken to effectively enlarge balancing areas.

Furthermore, the efficiency gains of cross-border procurement can be reproduced by forum-shopping transnational shippers if each TSO procures domestic flexibility efficiently and prices *ex-post* flexibility correctly. However, the coordinating role of the better-informed TSO is important and difficult to replace.

Highlights of the fifth set of conclusions:

- *Cross-border interactions create opportunities and threats*
- *Shippers always gain from forum shopping*
- *Overall efficiency can decrease if settlement mechanisms are not aligned*
- *Market-based procurement increases efficiency*
- *Border capacity is "bottleneck" for capturing efficiency gains*

To wrap up the findings, the balancing period should shorten to create a better matching between flexibility users and flexibility costs and a (preferably explicit) gate closure should be defined to make a distinction between the upfront market for the shippers and the balancing market for the TSO (the new market-based balancing mechanism in the Netherlands is a practical example that reflects these recommendations), or, as a second best solution, the peak imbalances should be used for allocating costs in a daily balancing mechanism. Balancing regions should be enlarged (or trade should be possible) to capture the efficiency gains that result from comparative advantages between different regions. A supranational approach is thus preferable. Efficient pricing of *ex-post* flexibility has to be based on market-based procurement. Even though spatial constraints might affect the merit order (distance and local congestion might preclude some flexible gas from solving an imbalance at a distant location), adding border capacity to increase trading opportunities for balancing services can improve liquidity of intra-day markets and has a positive effect on overall efficiency of the gas system. Compensatory mechanisms might be necessary, though, to compensate those who lose. Finally, network flexibility should be marketed as *ex-ante* flexibility to avoid market distortions.

Beyond the answers provided regarding the organization and challenges of gas balancing, the regulation of network flexibility, and the welfare effects of cross-border interactions, this thesis presents more general contributions to the literature on gas balancing and gas markets. It has introduced or redefined concepts to properly address balancing issues: e.g., *ex-ante* versus *ex-post* flexibility or gas "unit commitment" and gas "power dispatch". The GASFLEX model is versatile and can be used as a basis to study other short-term gas-market problems that require a combination of technical and economic aspects to be accounted for. Similarly, the "welfare"-benchmarking methodology can be applied to real gas borders if data are available.

7.3 Recommendations for further research

At the start of this work, gas balancing was largely unexplored by academia. This thesis makes a contribution to filling this gap by answering some questions regarding the design of balancing mechanisms in liberalized EU gas markets taking into account technical and economic aspects. However, over the course of the conducted research other questions have arisen that were beyond the scope of this thesis.

A first recommendation for further research concerns the **cost decomposition of the dual-function pipeline**. This cost decomposition can provide valuable insight into the short-term and long-term costs of line-pack flexibility. These insights are vital to correctly and efficiently regulate the pipeline flexibility in the setting of the liberalizing gas market. A starting point can be found in the opportunity-cost methodology presented in Chapter 2. Furthermore, if the capacity costs of flexibility are determined, Ramsey pricing can subsequently be applied to allocating these capacity costs to network users in a welfare-optimal way.

Second, **modeling** could be improved. GASFLEX provides a starting point, but it is insufficient for multi-period optimization of large-scale networks and of longer-term horizons (e.g., simulating a full week or month or…) because of numerical instabilities and scaling problems that are present in non-linear and non-convex optimizations. The development of intelligent algorithms or good heuristics can form interesting research questions, but technical accuracy has to be balanced with economic applicability as both are necessary to study regulatory issues in the short term. Furthermore, GASFLEX could be extended with multiple actors that anticipate or react to each other's actions.

Another recommended line of research is made up of **the interactions between the gas and electricity sectors**. Chapter 3 focuses on the transfer of flexibility needs from the electricity sector to the gas sector, but only elaborates the gas balancing. An extension of this research idea consists of evaluating the trade-offs for an electricity generator between relying on *ex-post* electricity balancing or *ex-post* gas balancing.

Investments have largely been overlooked in this work. The impact of the balancing-mechanism design and flexibility regulation on (long-term) investments forms a complement to the short-term operational issues that have been addressed in this thesis. Furthermore, the design of a suitable compensatory mechanism to distribute the costs of cross-border investments while accounting for the distribution of the benefits could also be part of research with a longer-term focus.

A final recommendation for further research deals with **applying the presented methodologies** to actual gas markets. Over the course of this thesis research, transparency in the gas market was limited. Therefore, much of the conducted work is based on hypothetical examples to develop proper methodologies on a conceptual level. Recently, availability of data is improving and thus the methodologies can be applied with better data. Furthermore, other borders can be examined with regard to the compatibility of balancing mechanisms. And if real data are available the methodologies can be applied to, e.g., assess the impact of strengthening the border capacity or the effects of setting up a shared merit order for procurement of flexible gas.

Appendices

Appendix A
Key gas-market statistics

Data gathered from Eurogas, Eurostat, Energy Information Administration (EIA) and International Energy Agency (IEA) [2; 3; 41; 137; 192-196].

A.1 Global

A.1.1 RESERVES

Table 40. Proven reserves by region [TCM] (estimates 2008) [3; 193-195]

Region	Reserves [TCM]
World	175 - 185
OECD Europe	4.5 - 5
OECD North America	9 - 10
OECD Pacific	1.5 - 2
Eurasia	57 - 60
Middle East	73 - 75
Africa	13 - 14
Asia	12 - 13
Latin America	7 - 8

A.1.2 SUPPLY

Table 41. Production by region: estimates for 2008 [BCM] and expected trend (not including shale-gas revolution) (↑ = 1% annual growth) [3; 193-195]

Region	Estimates 2008 [BCM]	Expected trend
World	3190	↑
OECD Europe	310	↓
OECD North America	800	↑
OECD Pacific	50	↑
Eurasia	890	↑
Middle East	400	↑↑
Africa	210	↑↑
Asia	380	↑↑
Latin America	150	↑↑

A.1.3 DEMAND

Table 42. Demand by region: estimates for 2008 [BCM] and expected trend (↑ = 1% annual growth) [3; 193-195]

Region	Estimates 2008 [BCM]	Expected trend
World	3150	↑
OECD Europe	560	↑
OECD North America	820	↑
OECD Pacific	170	↑
Eurasia	700	↑
Middle East	330	↑↑↑
Africa	100	↑↑
Asia	340	↑↑
Latin America	130	↑↑

A.1.4 OUTLOOK

- [1-3; 41; 132; 194]
- Proven gas reserves are vast and regionally dispersed and can cover 50–70 years of current demand;
- Recoverable resources estimated at about 400 TCM (roughly 50% conventional and 50% unconventional) or 120 years at current demand;
- Domestic production in Europe expected to peak and decrease, increasing import dependency;
- Long-term demand forecasts estimate world gas demand around 4500 TCM by 2035;
- Demand growth comes mainly from non-OECD countries, e.g., China, India and Brazil;
- In OECD countries, gas for power is the main driver for demand growth;
- Interregional LNG trade (Atlantic and Pacific) is expected to grow: liquefaction capacity is expected to grow from about 380 BCM in 2010 to about 540 BCM in 2020; regasification capacity already exceeds 800 BCM.

A.2 Europe

A.2.1 SUPPLY

Table 43. EU-27 (excluding Malta and Cyprus because they have no gas market) supply [BCM] in 2010: total, domestic and main import sources [192; 196]

Country	Total [BCM]	Domestic [BCM]	Norway [BCM]	Russia [BCM]	Algeria [BCM]	Qatar [BCM]
Austria	9.42	1.77	1.39	5.72	0.00	0.00
Belgium	19.87	0.00	6.34	0.47	0.00	5.93
Bulgaria	2.56	0.06	0.00	2.55	0.00	0.00
Czech Republic	8.78	0.14	1.03	5.34	0.00	0.00
Denmark	4.13	7.89	0.00	0.00	0.00	0.00
Estonia	0.61	0.00	0.00	0.61	0.00	0.00
Finland	4.58	0.00	0.00	4.58	0.00	0.00
France	50.76	0.77	16.31	7.12	6.82	2.49
Germany	86.15	11.41	28.82	32.43	0.00	0.00
Greece	3.80	0.00	0.00	2.02	0.75	0.04
Hungary	11.69	2.80	0.00	6.53	0.00	0.00
Ireland	5.61	0.38	0.00	0.00	0.00	0.00
Italy	81.06	8.11	3.63	21.98	27.30	6.92
Latvia	1.75	0.00	0.00	1.75	0.00	0.00
Lithuania	2.95	0.00	0.00	4.30	0.00	0.00
Luxembourg	1.43	0.00	0.74	0.34	0.00	0.18
Netherlands	46.81	75.74	11.02	3.45	0.00	0.00
Poland	15.34	4.40	0.00	9.36	0.00	0.00
Portugal	4.76	0.00	0.00	0.00	2.46	0.00
Romania	13.55	10.78	0.00	2.33	0.00	0.00
Slovakia	5.48	0.10	0.00	6.09	0.00	0.00
Slovenia	0.97	0.00	0.00	0.48	0.33	0.00
Spain	36.94	0.11	3.48	0.00	11.27	6.05
Sweden	1.74	0.00	0.00	0.00	0.00	0.00
United Kingdom	100.94	61.41	26.38	0.00	1.06	14.77
EU-27	521.69	185.86	99.14	117.43	50.00	36.38

A.2.2 DEMAND

Table 44. EU-27 (excluding Malta and Cyprus because they have no gas market) demand [BCM] in 2010: total demand and main sectors [192; 196]

Country	Total [BCM]	Residential & Commercial [BCM]	Power [BCM]	Industry [BCM]
Austria	9.42	2.59	3.31	3.21
Belgium	19.87	9.34	6.20	4.33
Bulgaria	2.56	0.12	0.96	1.39
Czech Republic	8.78	4.18	0.00	4.42
Denmark	4.13	1.10	0.84	0.81
Estonia	0.61	0.09	0.05	0.42
Finland	4.58	0.10	2.47	1.99
France	50.76	28.84	5.10	16.71
Germany	86.15	37.89	16.16	31.86
Greece	3.80	0.47	2.34	0.97
Hungary	11.69	5.69	3.34	1.61
Ireland	5.61	1.23	3.66	0.65
Italy	81.06	33.22	29.60	15.82
Latvia	1.75	0.35	1.12	0.28
Lithuania	2.95	0.30	1.60	1.02
Luxembourg	1.43	0.42	0.63	0.38
Netherlands	46.81	18.80	18.38	8.83
Poland	15.34	6.66	1.16	7.15
Portugal	4.76	0.77	2.08	1.26
Romania	13.55	3.72	3.04	6.25
Slovakia	5.48	2.26	1.09	1.35
Slovenia	0.97	0.32	0.06	0.58
Spain	36.94	5.86	12.52	18.49
Sweden	1.74	0.20	0.97	0.53
United Kingdom	17.84	44.16	36.53	17.67
EU-27	521.69	208.68	153.19	147.98

A.2.3 EU GAS NETWORKS AND SYSTEMS

Table 45. EU-27 (excluding Malta and Cyprus because they have no gas market) national gas-system data (2010): pipeline networks [km], pipeline entry capacity [MCM/d], storage send-out capacity [MCM/d] and LNG capacity [MCM/d] [192; 196]

Country	Pipelines [km]	Entry points capacity [MCM/d]	Storage send-out capacity [MCM/d]	LNG capacity [MCM/d]
Austria	39856	168.9	55.0	
Belgium	71095	196.8	22.8	40.8
Bulgaria	5921	72.6	3.3	
Czech Republic	75939	149.3	51.5	
Denmark	20400		15.7	
Estonia	2306	11.5	0.0	
Finland	2990	/	/	/
France	229700	179.8	270.0	93.8
Germany	443000	586.2	376.0	
Greece	6713	12.4	0.0	18.0
Hungary	86882	67.5	75.0	
Ireland	12923	27.7	2.5	
Italy	283809	278.5	273.6	33.2
Latvia	6035	19.8	24.0	
Lithuania	10000	19.4	0.0	
Luxembourg	2934	6.8	0.0	
Netherlands	150700	139.4	177.0	
Poland	127774	118.1	35.0	
Portugal	15647	16.1	7.2	21.6
Romania	46899	40.4	24.3	
Slovakia	35003	308.3	34.4	
Slovenia	4050	9.2		
Spain	74200	48.6	179.2	164.7
Sweden	3100	/	/	/
United Kingdom	285600	282.6	92.4	127.9
EU-27	2043476			

A.3 Belgium

Table 46. Order of magnitude of different gas demands [Mm^3/h] averaged for a typical winter day and a typical summer day in the Zeebrugge area (aggregated data for multiple offtake points) [43]

Day	Residential and commercial sector [Mm^3/h]	Power sector [Mm^3/h]	Industrial sector [Mm^3/h]	Total [Mm^3/h]
12 July 2011	0.12	0.45	0.16	0.73
2 February 2012	0.80	0.55	0.25	1.6

Appendix B
Gas dynamics

B.1 General-flow-equation and line-pack derivatives

B.1.1 DERIVATIVES

A study of the derivatives of the flow equation and the line-pack equation provides a better understanding of the dynamic interactions between flow and storage. The first derivative of flow rate $\dot{V}_{a(ij)}$ with respect to entry pressure p_i and delivery pressure p_j is given by Eqs. B(1.1) and B(1.2), respectively. To increase flow, either the entry pressure needs to rise or the delivery pressure needs to drop, or both.

$$\frac{\partial \dot{V}_{a(ij)}}{\partial p_i} = k\_flow_{a(ij)} * \frac{p_i}{\sqrt{p_i^2 - p_j^2}} \qquad \text{B(1.1)}$$

$$\frac{\partial \dot{V}_{a(ij)}}{\partial p_j} = -k\_flow_{a(ij)} * \frac{p_j}{\sqrt{p_i^2 - p_j^2}} \qquad \text{B(1.2)}$$

The impact on the pipeline storage, on the other hand, is shown in Eqs. B(1.3) and B(1.4) for entry and exit pressure, respectively. Line pack increases by raising entry or delivery pressure. Consequently, decreasing the delivery pressure p_j allows more gas flow, but reduces the amount of gas that is contained in the pipeline. Changing the lower pressure, therefore, has two countering effects that have to be weighed against each other.

$$\frac{\partial Vlp_{a(ij)}}{\partial p_i} = k\_lp_{a(ij)} * \frac{2}{3} * \left(1 - \frac{p_j^2}{(p_i + p_j)^2}\right) \qquad \text{B(1.3)}$$

$$\frac{\partial V\_lp_{a(ij)}}{\partial p_j} = k\_lp_{a(ij)} * \frac{2}{3} * \left(1 - \frac{p_i^2}{(p_i + p_j)^2}\right) \qquad \text{B(1.4)}$$

Equations B(1.5) and B(1.6) state the partial derivatives of flow rate and line pack with respect to the linear pressure difference (Δp) between the inlet and the outlet of the pipeline. As Δp represents the pressure difference, $2p\text{-}\Delta p$ is the sum of the nodal pressures. Increasing the linear pressure difference has a positive impact on flow rate, whereas the effect on line-pack is always negative for a given pressure p at the pipeline inlet.

$$\frac{\partial \dot{V}}{\partial(\Delta p)} = k\_flow_{a(ij)} * \frac{p - \Delta p}{\sqrt{\Delta p * (2p - \Delta p)}} \quad \text{B(1.5)}$$

$$\frac{\partial Vlp}{\partial(\Delta p)} = k\_lp_{a(ij)} * \frac{2}{3} * \left(\frac{p^2}{(2p - \Delta p)^2} - 1 \right) \quad \text{B(1.6)}$$

B.1.2 TRADE-OFFS BETWEEN FLOW RATE AND LINE-PACK LEVEL

The ratio of the flow rate (Mm^3/h) over the line-pack level (Mm^3) as a function of the entry and exit pressures shows that the higher the entry pressure and the lower the exit pressure, the higher the flow-to-line-pack ratio (1/h), which represents the line-pack depletion rate, or, inverted, the interval over which the line pack can sustain flow (Figure 59). The ratio is clearly related to the pressures in a non-linear way, meaning that giving up a little bit of entry pressure when that pressure is high has a different effect than giving up that same bit of pressure when the entry pressure is already low.

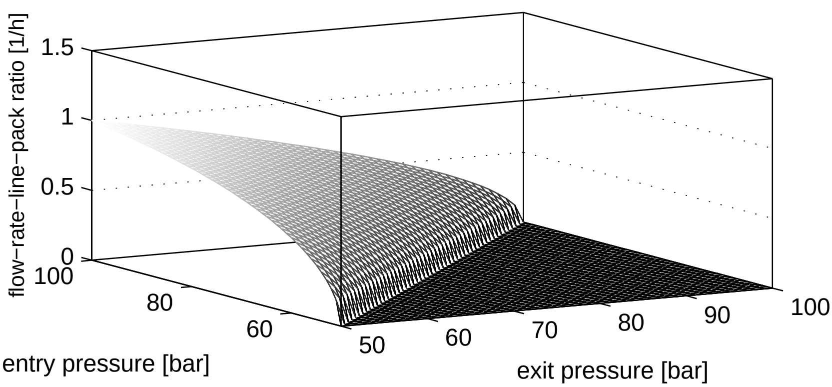

Figure 59. Ratio of flow rate [Mm^3/h] over line-pack level [Mm^3] for entry pressure p_i [bar] and exit pressure p_j [bar], with flow zero for $p_i < p_j$, the ratio serves as an indicator of the depletion interval [1/h]

Figure 60 shows the flow rate and the line-pack level separately, providing a better look at the trade-off between the two. The line-pack is highest when both entry and exit pressure are high, but then the flow-rate drops because the pressure difference is small.

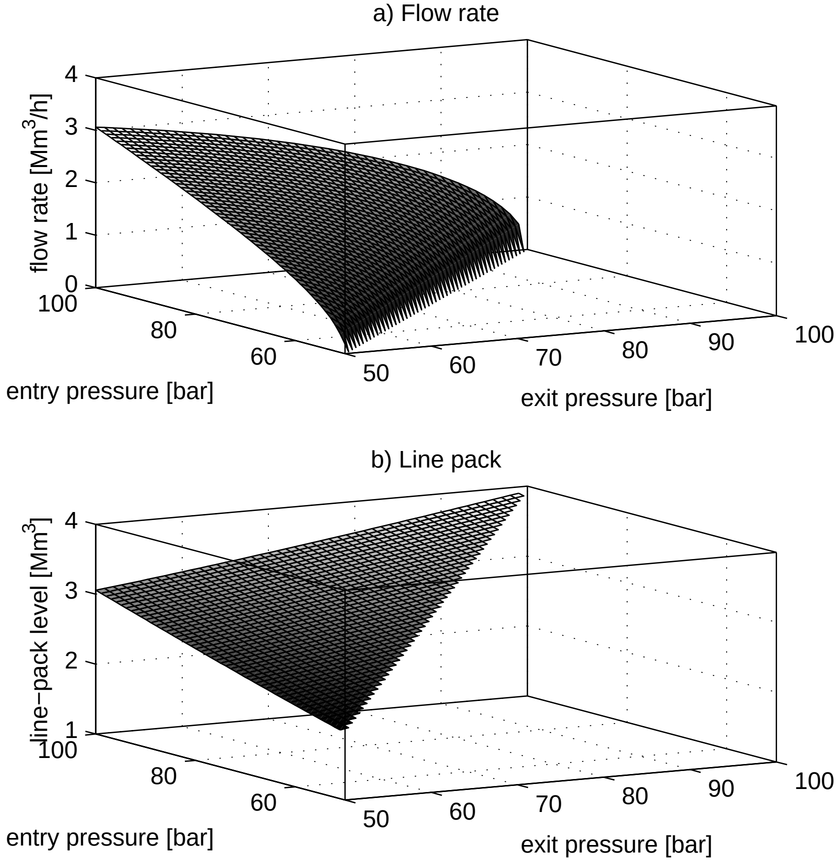

Figure 60. Trade-off between flow rate and line pack: a) flow rate [Mm^3/h] as a function of the pressure drop over the pipeline ($p_i \geq p_j$), b) line pack [Mm^3] as a function of the average pressure over the pipeline

B.2 Pipeline flow direction

Bidirectional flow can be modeled by replacing the square of the flow variable with a multiplication of the flow variable and its absolute value, which would return a negative left-hand side for a negative pressure difference in Eq. (3.15). However, an absolute value is difficult to handle by regular NLP or MINLP solution algorithms because it is non-smooth and non-differentiable. A binary variable $bin_{a(ij)}$ can capture the necessary flow-direction information of the pipeline *a(ij)*, being 1 for a forward directed pipeline and 0 for a backward directed pipeline as has been shown by [159]. The *sign*-variable is then derived from the binary variable by Eq. B(1.7). Note that, as an operational rule, $bin_{h,a(ij)}$ remains fixed intra-day (h = 1..24), but can change between days.

$$sign_{h,a(ij)} = 2 * bin_{h,a(ij)} - 1 \qquad \text{B(1.7)}$$

The variable *bin* is then determined by a number of constraints linking it to both flow and pressure difference: Eqs. B(1.8)-B(1.13). The first four constraints ensure at the same time that flow is bounded by upper limits $\dot{V}i\_max_{a(ij)}$ and $\dot{V}j\_max_{a(ij)}$ for forward flow (*bin* = 1) and lower limits $\dot{V}i\_min_{a(ij)}$ and $\dot{V}j\_min_{a(ij)}$ for backward flow (*bin* = 0).

$$\dot{V}i_{h,a(ij)} \geq \dot{V}i\_min_{a(ij)} * \left(1 - bin_{h,a(ij)}\right). \qquad \text{B(1.8)}$$

$$\dot{V}j_{h,a(ij)} \geq \dot{V}j\_min_{a(ij)} * \left(1 - bin_{h,a(ij)}\right). \qquad \text{B(1.9)}$$

$$\dot{V}i_{h,a(ij)} \leq \dot{V}i\_max_{a(ij)} * bin_{h,a(ij)}. \qquad \text{B(1.10)}$$

$$\dot{V}j_{h,a(ij)} \leq \dot{V}j\_max_{a(ij)} * bin_{h,a(ij)}. \qquad \text{B(1.11)}$$

Equations B(1.12) and B(1.13) ensure in a similar way that the pressure difference remains within the operational limits of the gas network with $dp2\_min_{a(ij)}$ and $dp2\_max_{a(ij)}$, respectively the most negative and most positive difference of the squared nodal pressures.

$$p_{h,i}^2 - p_{h,j}^2 \geq dp2\_min_{a(ij)} * \left(1 - bin_{h,a(ij)}\right). \qquad \text{B(1.12)}$$

$$p_{h,i}^2 - p_{h,j}^2 \leq dp2\_max_{a(ij)} * bin_{h,a(ij)}. \qquad \text{B(1.13)}$$

B.3 Linearization of storage-flow rates

The non-linear storage constraints often cause scaling problems. Therefore, linear approximations can be used instead.

The injection-rate limit is clearly non-convex (Figure 61.b); therefore, an approach with linear cuts is impossible as part of the solution space would be cut. To construct a piecewise-linear approximation, *special ordered sets of type 2* (SOS2) variables can be used. SOS2-variables are related to integer programming, though, and should be solved with MILP or MINLP solvers like *CPLEX* or *BARON*. The withdrawal-rate limit is strictly convex and adding a sufficient amount of linear cuts ensures a good approximation as can be seen in Figure 61.a.

Equation (3.25) is approximated by n linear cuts in Eq. B(1.14) based on m (=$n+1$) well-chosen break points y_m with x_n the working-gas level in the break point and $\theta(x_n)$ the corresponding withdrawal-rate limit based on Eq. (3.25).

$$\dot{V}wd_{h,i} \leq \frac{\vartheta(x_{i,n+1}) - \vartheta(x_{i,n})}{x_{i,n+1} - x_{i,n}} * Vsto_{h,i} - \frac{\vartheta(x_{i,n+1}) - \vartheta(x_{i,n})}{x_{i,n+1} - x_{i,n}} * x_{i,n} + \vartheta(x_{i,n}) \qquad \text{B(1.14)}$$

The piecewise-linear approximation by Eqs. B(1.15)-B(1.17) of the non-convex function in Eq. (3.26) uses *m* SOS2-variables z_m and *m* break points y_m with $\varphi(y_m)$ the function value of break point y_m according to Eq. (3.26) and only two adjacent variables z_m can be different from zero.

$$\dot{V}inj_{h,i} \leq \sum_m z_{h,i,m} * \varphi(y_m) \qquad \text{B(1.15)}$$

$$Vsto_{h,i} = \sum_m z_{h,i,m} * y_m \qquad \text{B(1.16)}$$

$$\sum_m z_m = 1 \qquad \text{B(1.17)}$$

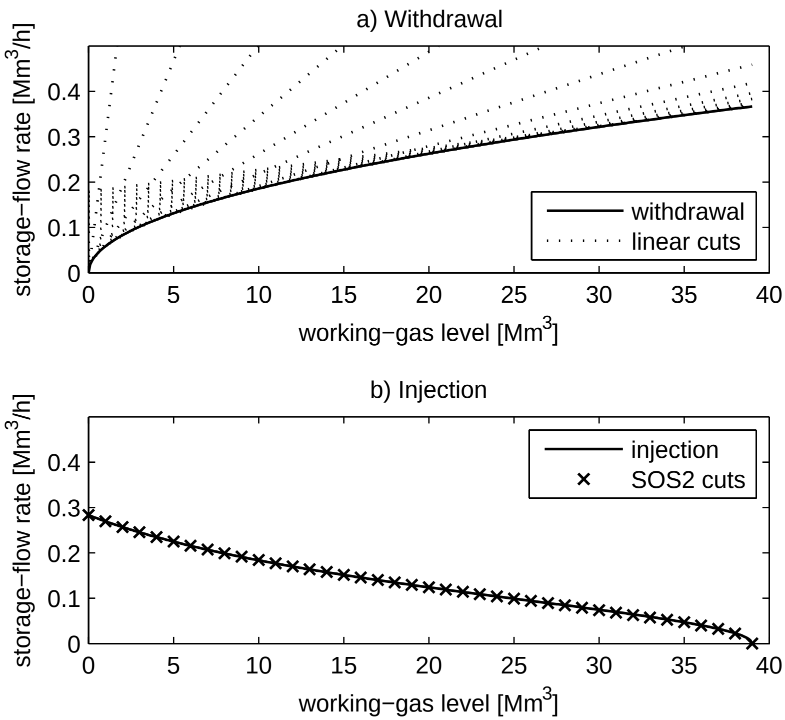

Figure 61. Approximation of a) convex withdrawal rate with linear cuts and b) non-convex injection rate with piecewise-linear approximation using SOS2-variable

Appendix C
Technical information gas networks

C.1 Network to study impact of wind unpredictability (Chapter 3)

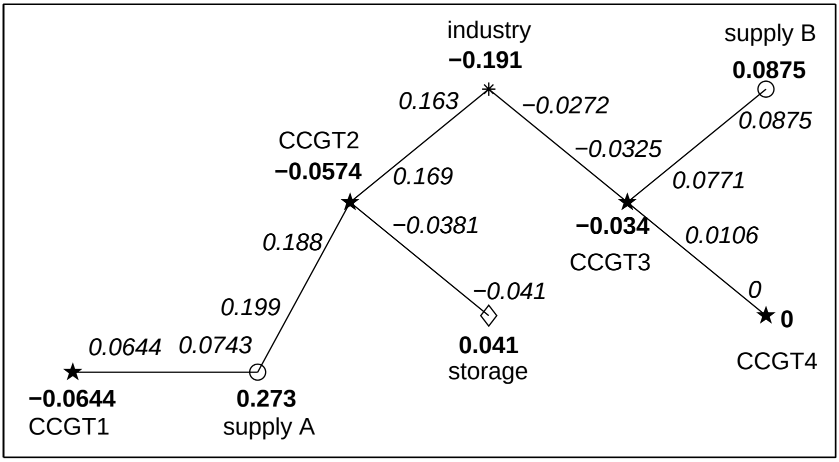

*Figure 62. Hypothetical gas network to study impact of wind unpredictability on gas balancing: five demand nodes (CCGTs, ★ and industry, *), two import nodes (A and B, o), one storage node (◇) and interconnecting pipelines*

Table 47. Nodal information (Figure 62): nodal-pressure limits, presence of compression and the maximal compression ratio and function of node in network

Node	Pressure limits (low/high) [bar]	Compression (y/n)	Function: demand (D), supply (S), transit (T), upward flexibility (F+) or downward flexibility (F-)
Supply A	60 / 80	n	S
Supply B	60 / 80	n	S
CCGT1	60 / 80	n	D
CCGT2	60 / 80	n	D
CCGT3	60 / 80	n	D
CCGT4	60 / 80	n	D
Industry	60 / 80	n	D
Storage	60 / 80	n	F+/F-

Table 48. Pipelines (Figure 62): diameter D, distance L and range of starting average pressures $\bar{p}_{a(ij),start}$ *to determine line pack*

Pipeline	D [m]	L [km]	$\bar{p}_{a(ij),start}$ [bar][a]
Supply A – CCGT1	0.7	30	62 - 70
Supply A – CCGT2	0.7	30	62 - 70
CCGT2 – Storage	0.7	7.5	62 - 70
CCGT2 – Industry	0.7	15	62 - 70
Industry – CCGT3	0.7	15	62 - 70
CCGT3 – CCGT4	0.7	30	62 - 70
Supply B – CCGT3	0.7	30	62 - 70

[a] a range of starting average pressures is tested, the reported cases in Chapter 3 use 62.5 bar (short historic shipper) and 70 bar (long historic) shipper

Table 49. Storage details (Figure 62): base gas that remains in storage, working-gas capacity that can be filled and emptied and injection and withdrawal limits

Node	Base gas [Mm^3]	Working gas [Mm^3]	Injection limit [Mm^3/h]	Withdrawal limit [Mm^3/h]
Storage	39	117	0.85	1.1

C.2 Network to study arbitrage opportunities of cross-border settlement (Chapter 5)

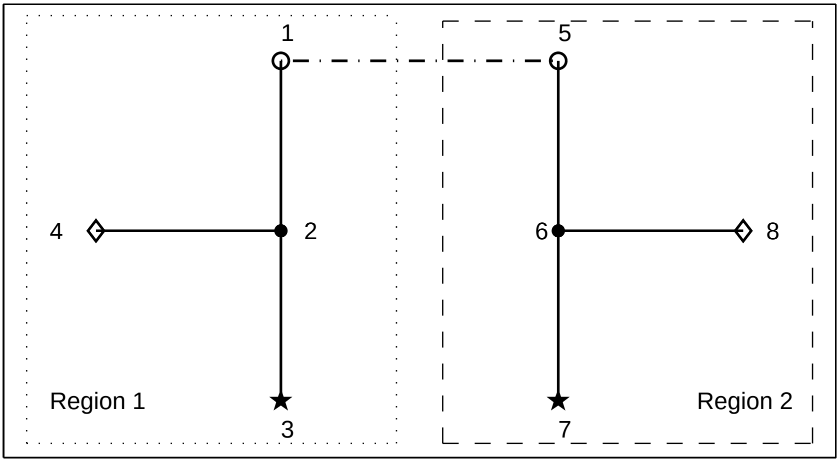

Figure 63. Hypothetical gas networks to study cross-border settlement: region 1 = 1-4, region 2 = 5-8, gas enters in nodes 1 and 5 (o), which are also the locations of the gas compressors, demand is located in nodes 3 and 7 (★) and nodes 4 and 8 are storages (◇), gas-imbalance trade occurs along the trunk pipeline between 1 and 5.

Table 50. Nodal information (Figure 63): nodal-pressure limits, presence of compression and the maximal compression ratio and function of node in network

Node	Pressure limits (low/high) [bar]	Compression (y/n) (ratio)	Function: demand (D), supply (S), transit (T), upward flexibility (F+) or downward flexibility (F-)
1	60 / 80	y (1.33)	S
2	60 / 80	n	D
3	60 / 80	n	D
4	60 / 80	n	F+/F-
5	60 / 80	y (1.33)	S
6	60 / 80	n	D
7	60 / 80	n	D
8	60 / 80	n	F+/F-

Table 51. Pipelines (Figure 63): diameter D, distance L and starting average pressure (to determine starting level of line pack)

Pipeline	D [m]	L [km]	$\bar{p}_{a(ij),start}$ [bar]
1 – 2	1.85	60	70.47
2 – 3	1.85	50	70.47
2 – 4	1.85	5	70.47
5 – 6	1.85	60	70.47
6 – 7	1.85	50	70.47
6 – 8	1.85	5	70.47

Table 52. Storage details (Figure 63): base gas that remains in storage, working-gas capacity that can be filled and emptied and injection and withdrawal limits

Node	Base gas [Mm^3]	Working gas (start) [Mm^3]	Injection limit [Mm^3/h]	Withdrawal limit [Mm^3/h]
Storage 4	26	78 (20)	0.56	0.7
Storage 8	26	78 (20)	0.56	0.7

C.3 Network to study cross-border procurement of balancing services (Chapter 6)

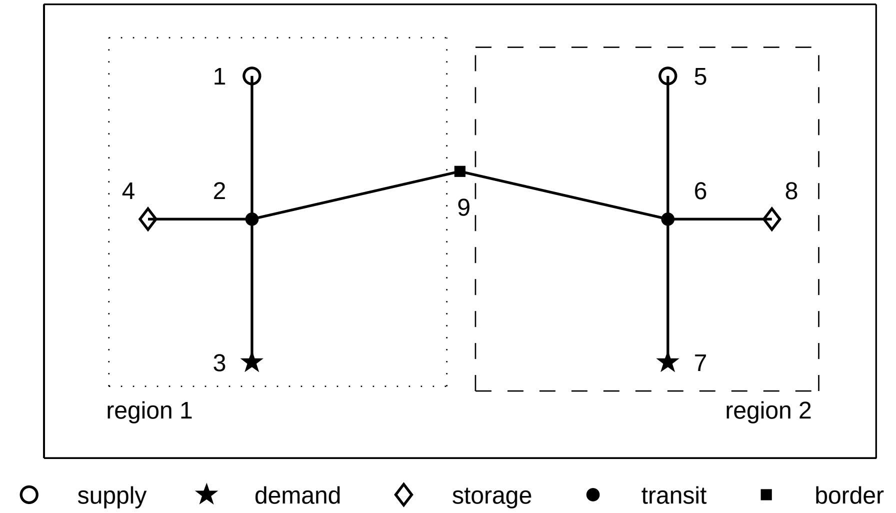

Figure 64. Hypothetical gas network for studying cross-border procurement in region 1 (1-4 and 9) and region 2 (5-8 and 9): gas production/entry (nodes 1 and 5, o), gas demand/exit (nodes 3 and 7, ★), flexible gas (nodes 1, 3, 4, 5, 7 and 8), of which storage (nodes 4 and 8, ◊) and an interconnecting border point (node 9, ■)

Table 53. Nodal information (Figure 64): nodal-pressure limits, presence of compression and the maximal compression ratio and function of node in network

Node	Pressure limits (low/high) [bar]	Compression (y/n) (ratio)	Function: demand (D), supply (S), transit (T), upward flexibility (F+), downward flexibility (F-) or border (B),
1	60 / 80	y (1.33)	S
2	60 / 80	n	T
3	60 / 80	n	D
4	60 / 80	n	F+/F-
5	60 / 80	y (1.33)	S
6	60 / 80	n	T
7	60 / 80	n	D
8	60 / 80	n	F+/F-
9	60 / 80	n	B

Table 54. Pipelines (Figure 64): diameter D, distance L and starting level of average pipeline pressure (to determine starting line-pack level)

Pipeline	D [m]	L [km]	$\bar{p}_{a(ij),start}$ [bar]
1 – 2	1	60	70.47
2 – 3	1	50	70.47
2 – 4	1	5	70.47
5 – 6	1	60	70.47
6 – 7	1	50	70.47
6 – 8	1	5	70.47
2 – 9	1	30	70.47
6 – 9	1	30	70.47

References

[1] Eurogas, IGU, 2010. The role of natural gas in a sustainable energy market. Eurogas, Brussels. www.eurogas.org, last accessed on: 9 July 2012.

[2] IEA, 2009. Natural Gas Market Review 2009. IEA/OECD, Paris.

[3] IEA, 2011. World Energy Outlook 2011 Special Report - Are we Entering a Golden Age of Gas? IEA/OECD, Paris.

[4] Boon von Ochssée, T.A., 2010. The dynamics of natural gas supply coordination in a new world, Doctoral dissertation, Faculty of Economics and Business. University of Groningen, Groningen, the Netherlands.

[5] Hafner, M., Tagliapietra, S., 2012. Rethinking the EU Gas Security of Supply Architecture. Review of Environment, Energy and Economics (RE3), March 2012.

[6] European Union, 2009. Regulation (EC) 715/2009 of the European Parliament and of the Council of 13 July 2009 on conditions for the access to the natural gas transmission networks and repealing Regulation (EC) No 1775/2005.

[7] European Union, 2009. Directive 2009/73/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in natural gas and repealing Directive 2003/55/EC.

[8] Jones, C., 2004. EU Energy Law vol. 1: The Internal Energy Market. Claeys & Casteels, Leuven.

[9] Keyaerts, N., Meeus, L., D'haeseleer, W., 2009. First results of the integrated European gas market: one for all or far from one, World Gas Conference 24. IGU, Buenos Aires, Argentina.

[10] Codognet, M.K., 2004. The shipper as the architect of contractual relations in access to natural gas networks, ISNIE 2004, 8th annual conference, Tucson, Arizona.

[11] Keyaerts, N., Meeus, L., D'haeseleer, W., 2009. Entry in European natural gas retail markets: accessing the right contract portfolio, 6th International Conference on the European Energy Market (EEM), 2009, Leuven, Belgium, pp. 1-7.

[12] European Commission DG Transport and Energy, 2004. 3rd Benchmarking report on the implementation of the internal electricity and gas market. European Commission, Brussels.

[13] CEER, 2003. Principles for balancing rules. 2003. Council of European Energy Regulators. www.energy-regulators.eu, last accessed on: 9 July 2012.

[14] ERGEG, 2006. Guidelines of good practice for gas balancing. E06-GFG-17-04, 6 December 2006. European Regulators Group for Electricity and Gas, Brussels. www.energy-regulators.eu, last accessed on: 9 July 2012.

[15] ERGEG, 2007. Impact assessment for guidelines on good practice for gas balancing. E07-GFG-27-03. European Regulators Group for Electricity and Gas, Brussels. www.energy-regulators.eu, last accessed on: 9 July 2012.

[16] ERGEG, 2005. Gas balancing: an ERGEG discussion paper for public consultation. E05-PC-05-01, 18 July 2005. European Regulators Group for Electricity and Gas, Brussels. www.energy-regulators.eu, last accessed on: 9 July 2012.

[17] ERGEG, 2008. Monitoring report: implementation of the ERGEG guidelines of good practice for gas balancing. E08-GMM-03-03, 10 December 2008. European Regulators Group for Electricity and Gas, Brussels. www.energy-regulators.eu, last accessed on: 9 July 2012.

[18] GTE, 2001. GTE balancing and storage report. Gas Transmission Europe, Brussels. www.gie.eu.com, last accessed on: 9 July 2012.

[19] GTE, 2005. Comments on ERGEG "gas balancing" discussion paper. 05FT137. Gas Transmission Europe, Brussels. www.energy-regulators.eu, last accessed on: 9 July 2012.

[20] GTE, 2009. Report on a benchmark among GTE members to assess difficulties in the application of the current GGP on gas balancing. Gas Transmission Europe, Brussels. www.gie.eu.com, last accessed on: 9 July 2012.

[21] KEMA, 2007. Der deutsche Regel- und Ausgleichsenergiemarkt Gas im Rahmen des neuen Energiewirtschaftsgesetzes und des darauf aufbauenden Gasnetzzugangsmodells. Report commissioned by Bundesnetzagentur. www.bundesnetzagentur.de, last accessed on: 9 July 2012.

[22] NERA, TPA Solutions, 2005. Gas balancing rules in Europe. Report commissioned by CREG. http://www.tpasolutions.co.uk, last accessed on: 9 July 2012.

[23] KEMA, 2009. Study on methodology for gas transmission network tariffs and gas balancing fees in Europe. TREN/C2/240-241-2008. Report for European Commission DG Transport and Energy. http://ec.europa.eu/energy/index_en.htm, last accessed on: 9 July 2012.

[24] ERGEG, 2010. Gas balancing rules on European gas transmission networks: Draft pilot framework guideline. E10-GNM-13-03, 18 August 2010. European Regulators Group for Electricity and Gas, Brussels. www.energy-regulators.eu, last accessed on: 9 July 2012.

[25] ACER, 2011. Framework Guidelines on Gas Balancing in Transmission Systems. FGB-2011-G-002. Agency for the Cooperation of Energy Regulators, Ljubljana. www.acer.europa.eu, last accessed on: 9 July 2012.

[26] Codognet, M.K., 2006. L'analyse économique des contrats d'accès aux réseaux dans les réformes concurrentielles gazières, Doctoral dissertation. Université Paris Sud XI, Paris, France.

[27] Hallack, M., 2011. Economic Regulation of Offer and Demand of Flexibility in Gas Network, Doctoral dissertation, Faculty of economics. University of Paris Sud XI, Paris, France.

[28] Kalashnikov, V.V., Pérez-Valdés, G.A., Tomasgard, A., Kalashnykova, N.I., 2010. Natural gas cash-out problem: Bilevel stochastic optimization approach. European Journal of Operational Research 206, 18-33.

[29] Kalashnikov, V.V., Ríos-Mercado, R.Z., 2006. A natural gas cash-out problem: A bilevel programming framework and a penalty function method. Optimization and engineering 7, 403-420.

[30] Eurelectric, 2006. Security of Electricity Supply - Roles, responsibilities and experiences within the EU. Union of the electricity industry. www.eurelectric.org, last accessed on 30 April 2012.

[31] IEA, 2002. Flexibility in natural gas supply and demand. IEA/OECD, Paris.

[32] ESMAP, 1993. Long term gas contracts: principles and applications. Energy Sector Management Assistance Programme 152/93, ESM 152/93. World Bank. http://documents.worldbank.org/curated/en/1993/01/441399/long-term-gas-contracts-principles-applications, last accessed on: 9 July 2012.

[33] von Hirschhausen, C., Neumann, A., 2008. Long-term contracts and asset specificity revisited: An empirical analysis of producer-importer relations in the natural gas industry. Review of Industrial Organization 32, 131-143.

[34] IEA, 2004. Security of gas supply in open markets. IEA/OECD, Paris.

[35] Neumann, A., von Hirschhausen, C., 2004. Less long term gas to Europe? A quantitative analysis of European long term gas-supply contracts. Zeitschrift für Energiewirtschaft 28, 175-182.

[36] European Commission DG Energy, 2011. Quarterly Report on European Gas Markets: April-June. Market Observatory for Energy 4.

[37] European Commission DG Energy, 2010. Quarterly Report on European Gas Markets: January-March. Market Observatory for Energy 3.

[38] Ecorys, 2008. Review and analysis of EU wholesale energy markets: Historical and current data analysis of EU wholesale electricity, gas and CO2 markets Report prepared for European Commission DG Transport and Energy. Ecorys, Rotterdam. http://ec.europa.eu/energy/index_en.htm, last accessed on: 9 July 2012.

[39] Energy Charter Secretariat, 2007. Putting a price on energy: International pricing mechanisms for oil and gas. Energy Charter Secretariat, Brussels. www.encharter.org, last accessed on: 9 July 2012.

[40] The Moffatt Associates Partnership, 2008. Review and analysis of EU wholesale markets: Evaluation of factors impacting on current and future market liquidity and efficiency, Report prepared for the European Commission. London. http://ec.europa.eu/energy/index_en.htm, last accessed on: 9 July 2012.

[41] Eurogas, 2010. Long term outlook for gas demand and supply 2007-2030. Eurogas, Brussels. www.eurogas.org, last accessed on: 9 July 2012.

[42] Clingendael International Energy Programme, 2008. Pricing natural gas: The outlook for the European market. Clingendael Energy Papers, CIEP 01/2008. Clingendael Institute, The Hague.

[43] Belgian gas data. http://data.fluxys.com, last accessed on: 20 April 2012.

[44] Kjärstad, J., Johnsson, F., 2007. Prospects of the European gas market. Energy Policy 35, 869-888.

[45] Lapuerta, C., Moselle, B., 2002. Convergence of non–discriminatory tariff and congestion management systems in the European gas sector. Report to the European Commission. The Brattle Group. www.brattle.com, last accessed on: 9 July 2012.

[46] Ruff, L., 2012. Rethinking Gas Markets - and Capacity. Economics of Energy and Environmental Policy 1(3).

[47] Midthun, K.T., Bjorndal, M., Tomasgard, A., 2009. Modeling optimal economic dispatch and system effects in natural gas networks. Energy Journal 30, 155-180.

[48] Keyaerts, N., Hallack, M., Glachant, J.-M., D'haeseleer, W., 2011. Gas market distorting effects of imbalanced gas balancing rules: Inefficient regulation of pipeline flexibility. Energy Policy 39, 865-876.

[49] Hallack, M., Keyaerts, N., Bonafé, E., 2010. Conclusions of the "specialised training on regulation of gas markets". Florence School of Regulation, Training conclusions, March. EUI-RSCAS, Florence.

[50] GTS. www.gastransportservices.nl, last accessed on: 30 April 2012.

[51] APX ENDEX. www.apxendex.com, last accessed on: 30 April 2012.

[52] ERGEG, 2011. Gas balancing in transmission systems: Framework guideline. E10-GNM-13-03, 10 March 2011. European Regulators Group for Electricity and Gas. www.energy-regulators.eu, last accessed on: 9 July 2012.

[53] Joint Office of Gas Transporters, 2010. Uniform Network Code v3.43. www.gasgovernance.co.uk, last accessed on 9 July 2012.

[54] FERC, 2000. Regulation of short-term natural gas transportation services, and regulation of interstate natural gas transportation services. Order No. 637.

[55] Ramsey, F.P., 1927. A Contribution to the Theory of Taxation. The Economic Journal 37, 47-61.

[56] Boiteux, M., 1956. Sur la gestion des Monopoles Publics astreints a l'equilibre budgetaire. Econometrica 24, 22-40.

[57] Hogan, W.W., 2008. Revenue sufficiency guarantees, cost causation and cost allocation. www.hks.harvard.edu/fs/whogan/Hogan_RSG_100908.pdf, last accessed on: 9 July 2012.

[58] Hogan, W.W., 2006. Revenue sufficiency guarantees and cost allocation. www.hks.harvard.edu/fs/whogan/Hogan_RSG_052506.pdf, last accessed on: 9 July 2012.

[59] Cremer, H., Gasmi, F., Laffont, J.-J., 2003. Access to pipelines in competitive gas markets. Journal of Regulatory Economics 24, 5-33.

[60] Cremer, H., Laffont, J.-J., 2002. Competition in gas markets. European Economic Review 46, 928-935.

[61] Fluxys, 2011. Transmission programme: Service offer description 2012-2015 - non-binding document. www.fluxys.com, last accessed on: 9 July 2012.

[62] Fluxys, 2011. Fluxys natural gas transport services in Belgium: Conditions & Tariffs. www.fluxys.com, last accessed on: 6 June 2011.

[63] Fluxys. www.fluxys.com, last accessed on: 30 April 2012.

[64] Fluxys, 2010. Programme indicatif d'acheminement 2011-2012. Version du 19 novembre 2010. www.fluxys.com, last accessed on: 6 June 2011.

[65] GRTgaz, 2011. Règles d'équilibrage sur le réseau de GRTgaz – Version applicable au 1er mai 2011. www.grtgaz.com, last accessed on: 9 July 2012.

[66] CRE, 2011. Délibération de la Commission de régulation de l'énergie du 17 mars 2011 portant décision sur l'évolution des règles d'équilibrage sur les réseaux de transport de gaz de GRTgaz et de TIGF. CRE Déliberations. www.cre.fr, last accessed on: 9 July 2012.

[67] GRTgaz. www.grtgaz.com, last accessed on: 30 April 2012.

[68] GTS, 2010. Functional Workshop 7 October 2010. Gas Transport Services. http://www.gastransportservices.nl/, last accessed on: 9 July 2012.

[69] WMWG, 2010. DPM Biedladder v2.0. GTS Werkgroep Marktmodel Wholesale Gas. www.gastransportservices.nl, last accessed on: 9 July 2012.

[70] Christoph, P., 2003. Beurteilung der Funktionsfähigkeit des österreichischen Ausgleichsenergiemarktes in der Regelzone Ost. Report commissioned by E-Control. www.e-control.at, last accessed on: 9 July 2012.

[71] AGCS, 2010. Anhang Ausgleichsenergiebe-wirtschaftung in der Regelzone Ost zu den AB-BKO V 4.0. www.agcs.at, last accessed on: 9 July 2012.

[72] AGGM. www.aggm.at, last accessed on: 30 April 2012.

[73] AGCS. www.agcs.at, last accessed on: 30 April 2012.

[74] Snam Rete Gas. www.snamretegas.it, last accessed on: 30 April 2012.

[75] FERC. www.ferc.org, last accessed on: 9 July 2012.

[76] Makholm, J.D., 2007. Seeking competition and supply security in natural gas. The US experience and European challenge, 1st CESSA conference Berlin University of Technology, Berlin, Germany.

[77] Vandezande, L., 2011. Design and integration of balancing markets in Europe, Doctoral dissertation, Faculty of Engineering. K.U. Leuven, Leuven, Belgium.

[78] Vazquez, M., Hallack, M., Glachant, J.-M., 2012. Building gas markets: US versus EU, market versus market model. EUI Working Papers, RSCAS 2012/10. EUI, San Domenico di Fiesole.

[79] EFET, 2010. Answer to ERGEG public consultation paper on Pilot Framework Guideline on Gas Balancing Rules. European Federation of Energy Traders. www.efet.org, last accessed on: 9 July 2012.

[80] EFET, 2011. Common position on gas target model. European Federation of Energy Traders. www.efet.org, last accessed on: 9 July 2012.

[81] Eberhard, R., Hüning, R., 1990. Handbuch der Gasversorgungstechnik, Gastransport und Gasverteilung, 2 ed. Oldenbourg.

[82] Mokhatab, S., Poe, W., Speight, J., 2006. Handbook of Natural Gas Transmission and Processing. Gulf Professional Publishing, Burlington (MA).

[83] Coase, R.H., 1960. The problem of social cost. The Journal of Law and Economics 3, 1-44.

[84] ERGEG, 2009. ERGEG principles: Capacity allocation and congestion management in European gas transmission networks. E09-GNM-10-03, 10 December 2009. European Regulators Group for Electricity and Gas, Brussels. www.energy-regulators.eu, last accessed on: 9 July 2012.

[85] Colomer, M., Hallack, M., Perez, Y., 2009. Why the increase participation of LNG should affect the regulation of the national transport network, World Gas Conference 24, Buenos Aires.

[86] European Commission DG Transport and Energy, 2005. Benchmarking report. European Commission, Brussels.

[87] CRE, 2009. Consultation publique: Principes relatifs à l'acheminement du gaz pour les centrales de production d'électricité raccordées aux réseaux de transport de gaz naturel. www.cre.fr, last accessed on: 9 July 2012.

[88] GRTgaz, 2009. Note d'intention: Offre de transfert pour la flexibilité nécessaire aux cycles combines gaz. www.grtgaz.com, last accessed on: 9 July 2012.

[89] Keyaerts, N., Meeus, L., D'haeseleer, W., 2008. Analysis of balancing-system design and contracting behaviour in the natural gas markets, European Doctoral Seminar on Natural Gas Research - Autumn 2008, Delft, the Netherlands.

[90] Lapuerta, C., 2003. Brattle's assessment of the operation of the NTS. OFGEM, The gas trading arrangements: Reform of the gas balancing regime, April. The Brattle group. www.brattle.com, last accessed on: 9 July 2012.

[91] OFGEM, 2003. The gas trading arrangements: Reform of the gas balancing regime. April. www.brattle.com, last accessed on: 9 July 2012.

[92] Tirole, J., 1988. The theory of industrial organization. The MIT Press - Cambridge.

[93] Baumol, W.J., Bradford, D.F., 1970. Optimal Departures From Marginal Cost Pricing. The American Economic Review 60, 265-283.

[94] Oren, S., Sioshansi, R., 2004. Joint energy and reserves auction with opportunity cost payment for reserves, Proceedings of the Bulk Power System Dynamics and Control VI, Cortina D'Ampezzo, Italy, p. 6.

[95] Pineau, P.-O., Lefebvre, V., 2009. The value of unused transmission: Estimating the opportunity cost for the province of Quebec, Canada, Proceedings of the 32nd IAEE International Conference 2009, San Francisco, USA.

[96] Rious, V., Dessante, P., Glachant, J.-M., 2008. Anticipation for efficient electricity transmission network investments, 1st International scientific conference "Building Networks for a Brighter Future", Rotterdam, the Netherlands.

[97] Rious, V., Glachant, J.-M., Perez, Y., Dessante, P., 2008. The diversity of design of TSOs. Energy Policy 36, 3323 - 3332.

[98] Glachant, J.-M., 2002. Why regulate deregulated network industries? Journal of Network Industries 3, 297-311.

[99] Glachant, J.-M., Perez, Y., 2007. Institutional economics and network industry deregulation policy. Université Paris sud working paper. www.iern.net/portal/page/portal/IERN_HOME/IERN_ARCHIV/Publications/Regulation%20-%20Deregulation/Glachant_2007b.pdf, last accessed on: 9 July 2012.

[100] Menon, E.S., 2005. Gas pipeline hydraulics. CRC Press - Taylor & Francis Group, Boca Raton.

[101] Coelho, P.M., Pinho, C., 2007. Considerations about equations for steady state flow in natural gas pipelines. Journal of the Brazilian Society of Mechanical Sciences and Engineering 29, 262-273.

[102] van der Hoeven, T., 2007. Gas transport pipe, 39th Annual Meeting PSIG (Pipeline Simulation Interest Group). PSIG, Calgary.

[103] Joskow, P., 2007. Supply security in competitive electricity and natural gas markets, in: Robinson, C. (Ed.), Utility regulation in competitive markets. Edward Elgar Publishing, Cheltenham, pp. 82-118.

[104] Kahn, A., 1971. The economics of regulation: Principles and institutions Vol. 2. John Wiley & Sons.

[105] Spulber, D.F., 1989. Regulation and markets. The MIT Press.

[106] Hallack, M., 2010. GFPP changing gas flows: the need of shorter term flexibility on gas market, European Doctoral Seminar on Natural Gas Research, 28 May 2010, Florence.

[107] Roques, F.A., 2008. Technology choices for new entrants in liberalized markets: The value of operating flexibility and contractual arrangements. Utilities Policy 16, 245-253.

[108] ERGEG, 2007. Gas transmission tariffs: An ERGEG benchmarking report. C06-GWG-31-05, 18 July 2007. European Regulators Group for Electricity and Gas, Brussels. www.energy-regulators.eu, last accessed on: 9 July 2012.

[109] CNE, 2008. Normas de gestión técnica del sistema gasista: Protocolos de detalle PD-01 a PD-11, Diciembre 2008. Spanish energy regulator, www.ingenieros.es/files/normativas/anteriores/NGTS-Dic_2008.pdf, last accessed on: 9 July 2012.

[110] Keyaerts, N., Rombauts, Y., Delarue, E., D'haeseleer, W., 2010. Impact of wind power on natural gas markets: inter market flexibility, 7th Conference on the European Energy Market 2010, Madrid, Spain.

[111] Costello, K., 2006. Efforts to harmonize gas pipeline operations with the demands of the electricity sector. The Electricity Journal 19, 7-26.

[112] CRE, 2009. Délibération de la CRE du 3 décembre 2009 portant proposition de modification des tariffs d'utilisation des réseaux de transport de gaz naturel. CRE Déliberations. www.cre.fr, last accessed on: 9 July 2012.

[113] CRE, 2011. Deliberation of the French Energy Regulation Commission of 24 March 2011, deciding on operating conditions of the intraday flexibility service for sites with strong flexibility needs. CRE Déliberations. www.cre.fr, last accessed on: 9 July 2012.

[114] GRTgaz, 2011. Meeting intraday modulation needs: Supply and demand match in intraday flexibility - Outlook study for 2012-2020. GRTgaz. www.grtgaz.com, last accessed on: 9 July 2012.

[115] Codognet, M.K., Glachant, J.-M., 2006. Weak investments incentives in new gas storage in the UK?, 29th IAEE International Conference. IAEE, Potsdam, Germany.

[116] Creti, A. (Ed.), 2009. The economics of natural gas storage: A European perspective. Springer Berlin Heidelberg, Berlin.

[117] Glachant, J.-M., Hallack, M., 2009. Take-or-pay contract robustness: A three step story told by the Brazil-Bolivia gas case? Energy Policy 37, 651 - 657.

[118] Masten, S.E., Crocker, K.J., 1985. Efficient adaptation in long-term contracts: Take-or-pay provisions for natural gas. The American Economic Review 75, 1083-1093.

[119] Mulherin, J.H., 1986. Complexity in long-term contracts: An analysis of natural gas contractual provisions. Journal of Law, Economics and Organization 2, 105-117.

[120] Spanjer, A.R., 2009. Regulatory intervention on the dynamic European gas market - neoclassical economics or transaction cost economics? Energy Policy 37, 3250 - 3258.

[121] European Commission, 2009. Commission staff working document, assessment report of Directive 2004/67/EC on security of gas supply, Commission staff working document accompanying proposal for a Regulation of the European Parliament and of the Council concerning measures to safeguard security of gas supply and repealing Directive 2004/67/EC. European Commission, Brussels.

[122] Stern, J., 2009. Continental European long term gas contracts: Is a shift away from oil-linked pricing inevitable? Oxford Institute for Energy Studies Working Papers, NG34. OIES, Oxford.

[123] European Commission DG Transport and Energy 2008. Draft final report on: study on natural gas storage in the EU. European Commission, Brussels.

[124] Neuhoff, K., von Hirschhausen, C., 2005. Long-term vs. short-term contracts; A European perspective on natural gas. University of Cambridge, Cambridge Working Papers in Economics, September. Electricity Policy Research Group. http://www.dspace.cam.ac.uk/handle/1810/131595, last accessed on: 9 July 2012.

[125] Zhuravleva, P., 2009. The nature of LNG arbitrage: An analysis of the main barriers to the growth of the global LNG arbitrage market. Oxford Institute for Energy Studies Working Papers, NG31. OIES, Oxford.

[126] Clingendael International Energy Programme, 2006. The European market for seasonal storage. Clingendael Discussion Papers. Clingendael Institute, The Hague.

[127] Keyaerts, N., Rombauts, Y., Delarue, E., D'haeseleer, W., 2011. Impact assessment of increasing unpredictability in gas balancing caused by massive wind power integration. TME Working Paper Series, WP-EN2011-05. University of Leuven (KU Leuven) Energy Institute.

[128] Luickx, P., 2009. The backup of wind power: analysis of the parameters influencing the wind power integration in electricity generation systems, Doctoral dissertation, Faculty of Engineering. K.U. Leuven, Leuven, Belgium.

[129] EWEA, 2010. Wind Energy and Electricity Prices: Exploring the 'merit order effect'. Report by the European Wind Energy Association. www.ewea.org, last accessed on: 9 July 2012.

[130] Holttinen, H., Meibom, P., Orths, A., van Hulle, F., Lange, B., O'Malley, M., Pierik, J., Ummels, B., Tande, J.O., Estanqueiro, A., Matos, M., Gomez, E., Söder, L., Strbac, G., Shakoor, A., Ricardo, J., Smith, J.C., Milligan, M., Ela, E., 2009. Design and operation of power systems with large amounts of wind power - Final report, IEA WIND Task 25, Phase one 2006-2008. VTT. www.ieawind.org, last accessed on: 9 July 2012.

[131] EWEA, 2010. Powering Europe: Wind energy and the electricity grid. Report by the European Wind Energy Association. www.ewea.org, last accessed on: 9 July 2012.

[132] Vos, I., 2012. The impact of wind power on European natural gas markets. IEA Working Paper. OECD/IEA, Paris.

[133] McLean, J.R., Garran Gassan and Partners Ltd, 2008. TradeWind WP 2.6 - Equivalent Wind Power Curves. TradeWind, July 2008. www.trade-wind.eu, last consulted on: 9 July 2012.

[134] Delarue, E.D., Luickx, P.J., D'Haeseleer, W.D., 2009. The actual effect of wind power on overall electricity generation costs and CO2 emissions. Energy Conversion and Management 50, 1450-1456.

[135] Parrilla, E., 2009. Power and gas integration: the Spanish experience, 2009 IEEE Power & Energy Society General Meeting (PES). IEEE, Piscataway, NY, USA, p. 5 pp.

[136] Qadrdan, M., Chaudry, M., Wu, J.Z., Jenkins, N., Ekanayake, J., 2010. Impact of a large penetration of wind generation on the GB gas network. Energy Policy 38, 5684-5695.

[137] Eurogas, 2010. Statistical report 2010. Eurogas, Brussels. www.eurogas.org, last accessed on: 9 July 2012.

[138] Eurogas, 2002. Statistics 2002. Eurogas, Brussels. www.eurogas.org, last accessed on: 9 July 2012.

[139] Winskel, M., 2002. When Systems Are Overthrown: The 'Dash for Gas' in the British Electricity Supply Industry. Social Studies of Science 32, 563-598.

[140] Brunetto, C., Tina, G., 2011. Wind generation imbalances penalties in day-ahead energy markets: The Italian case. Electric Power Systems Research 81, 1446-1455.

[141] De Vos, K., Driesen, J., Belmans, R., 2011. Assessment of imbalance settlement exemptions for offshore wind power generation in Belgium. Energy Policy 39, 1486-1494.

[142] Helander, A., Holttinen, H., Paatero, J., 2010. Impact of wind power on the power system imbalances in Finland. IET Renewable Power Generation 4, 75-84.

[143] Vandezande, L., Meeus, L., Belmans, R., Saguan, M., Glachant, J.-M., 2010. Well-functioning balancing markets: A prerequisite for wind power integration. Energy Policy 38, 3146-3154.

[144] Keyaerts, N., 2012. Using operations research to study optimal use of flexibility in liberalizing gas markets: GASFLEX, TME Working paper series. University of Leuven (KU Leuven) Energy Institute.

[145] Avery, W., Brown, G.G., Rosenkranz, J.A., Wood, R.K., 1992. Optimization of purchase, storage and transmission contracts for natural gas utilities. Operations Research 40, 446-462.

[146] Gabriel, S.A., Zhuang, J., Kiet, S., 2005. A large-scale linear complementarity model of the North American natural gas market. Energy Economics 27, 639-665.

[147] Midthun, K.T., 2007. Optimization models for liberalized natural gas markets, Doctoral dissertation, Faculty of Social Science and Technology Management. Norwegian University of Science and Technology, Trondheim, Norway.

[148] Osiadacz, A.J., 1996. Different transient models- limitations, advantages, 28th Annual Meeting PSIG (Pipeline Simulation Interest Group). PSIG, San Francisco.

[149] De Wolf, D., Smeers, Y., 1996. Optimal Dimensioning of Pipe Networks with Application to Gas Transmission Networks. Operations Research 44, 596-608.

[150] Babonneau, F., Nesterov, Y., Vial, J.-P., 2012. Design and Operations of Gas Transmission Networks. Operations Research 60, 34-47.

[151] Kabirian, A., Hemmati, M.R., 2007. A strategic planning model for natural gas transmission networks. Energy Policy 35, 5656-5670.

[152] Selot, A., Kuok, L.K., Robinson, M., Mason, T.L., Barton, P.I., 2008. A short-term operational planning model for natural gas production systems. AIChE Journal 54, 495--515.

[153] Bopp, A.E., Kannan, V.R., Palocsay, S.W., Stevens, S.P., 1996. An optimization model for planning natural gas purchases, transportation, storage and deliverability. Omega 24, 511 - 522.

[154] Egging, R., Gabriel, S.A., Holz, F., Zhuang, J., 2008. A complementarity model for the European natural gas market. Energy Policy 36, 2385-2414.

[155] Lise, W., Hobbs, B.F., 2008. Future evolution of the liberalised European gas market: Simulation results with a dynamic model. Energy 33, 989-1004.

[156] Lise, W., Hobbs, B.F., van Oostvoorn, F., 2008. Natural gas corridors between the EU and its main suppliers: Simulation results with the dynamic GASTALE model. Energy Policy 36, 1890-1906.

[157] Holz, F., von Hirschhausen, C., Kemfert, C., 2008. A strategic model of European gas supply (GASMOD). Energy Economics 30, 766-788.

[158] De Wolf, D., 2004. The simplex algorithm extended to piecewise linearly constrained problems. Discussion paper. Université de Lille. www.rogp.hec.ulg.ac.be/DeWolf/PLPI.pdf, last accessed on: 9 July 2012.

[159] De Wolf, D., Smeers, Y., 2000. The gas transmission problem solved by an extension of the simplex algorithm. Management Science 46, 1454-1465.

[160] Martin, A., Möller, M., Moritz, S., 2006. Mixed integer models for the stationary case of gas network optimization. Mathematical Programming 105, 563 - 582.

[161] Ehrhardt, K., Steinbach, M.C., 2005. Nonlinear optimization in gas networks, in: Bock, H.G., Kostina, E., Phu, H.X., Ranacher, R. (Eds.), Modeling, simulation and optimization of complex processes. Springer, Berlin - Heidelberg - New York, pp. 139-148.

[162] Unsihuay, C., Lima, J.W.M., de Souza, A.C.Z., 2007. Modeling the integrated natural gas and electricity optimal power flow, IEEE Power Engineering Society General Meeting, 2007.

[163] Chaudry, M., Jenkins, N., Strbac, G., 2008. Multi-time period combined gas and electricity network optimisation. Electric Power Systems Research 78, 1265-1279.

[164] Thompson, M., Davison, M., Rasmussen, H., 2009. Natural gas storage valuation and optimization: A real options application. Naval Research Logistics 56, 226-238.

[165] GAMS. www.gams.com, last accessed on: 25 January 2011.

[166] Mathworks. www.mathworks.com/products/matlab, last accessed on: 25 January 2011.

[167] Sahinidis, N.V., Tawarmalani, M., 2010. BARON 9.0.6: Global optimization of mixed-integer nonlinear programs: User's manual.

[168] Tawarmalani, M., Sahinidis, N.V., 2005. A polyhedral branch-and-cut approach to global optimization. Mathematical Programming 103, 225 - 249.

[169] ILOG. www.ibm.com/software/integration/optimization/cplex-optimizer, last accessed on: 29 October 2010.

[170] Drud, A.S., 1985. CONOPT: A GRG code for large sparse dynamic nonlinear optimization problems. Mathematical Programming 31, 153-191.

[171] Drud, A.S., 1994. CONOPT--A Large-Scale GRG Code. INFORMS Journal on Computing 6, 207-216.

[172] Delarue, E., 2009. Modeling electricity generation systems: Development and application of electricity generation optimization and simulation models, with particular focus on CO2 emissions, Doctoral dissertation, Faculty of Engineering. K.U. Leuven, Leuven, Belgium.

[173] Elia data on generated electricity for Belgium. www.elia.be, last accessed on: 30 May 2011.

[174] Brand, A., Kok, J., 2003. Aanbodvoorspeller duurzame energie - Deel 2: Korte-termijn prognose van windvermogen. ECN-C--03-049. www.ecn.nl, last consulted on: 9 July 2012.

[175] KNMI Dutch meteorological data. www.knmi.nl, last accessed on: 5 April 2011.

[176] Fluxys, 2012. Discussion on gas-network operations: personal communication.

[177] European Commission DG Competition, 2007. Report on the energy sector inquiry. European Commission, Brussels.

[178] Ascari, S., 2011. An American model for the EU gas market? EUI Working Papers, RSCAS 2011/39. EUI, San Domenico di Fiesole.

[179] Glachant, J.M., 2011. A vision for the EU gas target model: The MECO-S model. EUI Working Papers, RSCAS 2011/38. EUI, San Domenico di Fiesole.

[180] Moselle, B., White, M., 2011. Market design for natural gas: the Target Model for the Internal Market. March 2011. LECG, London. www.energy-regulators.eu, last accessed on: 30 July 2012.

[181] Clingendael International Energy Programme, 2011. CIEP Vision on the Gas Target Model. Clingendael Energy Paper, 2011/3. Clingendael International Energy Programme, The Hague.

[182] Frontier Economics, Stratorg, Ylios, 2011. Target Model for the European Natural Gas Market. www.frontier-economics.com, last accessed on: 31 July 2012.

[183] Ascari, S., Glachant, J.M., 2011. A Gas Target Model for the European Union: Contrasting MECOS and EURAM Proposal. Hallack, M., Vazquez, M., Policy Brief, 2011/08. EUI Florence School of Regulation, San Domenico di Fiesole. http://fsr.eui.eu, last accessed on: 31 July 2012.

[184] Glachant, J.M., 2012. A 'Target Model' for the Internal Gas Market. FSR Webinars, 13 March 2012. EUI Florence School of Regulation. www.florence-school.eu, last accessed on 13 March 2012.

[185] CEER, 2011. CEER vision for a European Gas Target Model: Conclusions paper. C11-GWG-82-03. Council of European Energy Regulators, Brussels. www.energy-regulators.eu, last accessed on: 27 July 2012.

[186] Just, R.E., Hueth, D.L., Schmitz, A., 2004. The Welfare Economics Of Public Policy. Edward Elgar, Cheltenham, UK.

[187] Keyaerts, N., D'haeseleer, W., 2012. Forum shopping for *ex-post* gas-balancing services. TME Working Paper Series. University of Leuven (KU Leuven) Energy Institute.

[188] Juenger, F.K., 1989. Forum shopping, domestic and international. Tulane Law Review 63, 553-574.

[189] Keyaerts, N., D'haeseleer, W., 2012. Increasing efficiency through market-based cross-border procurement of gas-balancing services in Europe. TME Working Paper Series. University of Leuven (KU Leuven) Energy Institute.

[190] Krugman, P.R., Obstfeld, M., 2005. International Economics: Theory and Policy, 6th ed. Pearson.

[191] Vandezande, L., Saguan, M., Meeus, L., Glachant, J.M., Belmans, R., 2009. Assessment of the implementation of cross-border balancing trade between Belgium and the Netherlands, 6th International Conference on the European Energy Market (EEM), Leuven, pp. 1-6.

[192] Eurogas, 2011. Statistical report 2011. Eurogas, Brussels. www.eurogas.org, last accessed on: 9 July 2012.

[193] EIA Energy Statistics. www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm, last accessed on: 11 May 2012.

[194] IEA, 2010. World Energy Outlook 2010. IEA/OECD, Paris.

[195] IEA, 2007. Natural Gas Information. IEA/OECD, Paris.

[196] Eurostat Energy statistics. http://epp.eurostat.ec.europa.eu, last accessed on: 20 May 2011.

Short curriculum

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Born:

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Leuven (Belgium)

Secondary School:

1996 – 2002: Heilige-Drievuldigheidscollege Leuven

University:

2002 – 2007: Handelsingenieur (Business engineering – option International Business) at KU Leuven, Faculty of Business and Economics, graduated Magna cum Laude

Work:

2007 – 2012: Research assistant at KU Leuven, Department of Mechanical Engineering, Division of Applied Mechanics and Energy Conversion

List of publications

Status on September, 2012

Articles in international journals with review

Published or accepted

- Keyaerts, N., Hallack, M., Glachant, J.-M., D'haeseleer, W., 2011. Gas market distorting effects of imbalanced gas balancing rules: Inefficient regulation of pipeline flexibility. Energy Policy 39, 865-876.

Submitted

- Keyaerts, N., D'haeseleer, W., 2012. Increasing efficiency through market-based cross-border procurement of gas-balancing services in Europe. Submitted for publication.
- Keyaerts, N., D'haeseleer, W., 2012. Forum shopping for *ex-post* gas-balancing services. Submitted for publication.
- Keyaerts, N., Rombauts, Y., Delarue, E., D'haeseleer, W., 2012. Impact of unpredictability on gas-balancing design in Europe. Submitted for publication.

International conferences

- Vandewalle, J.M., Zapata, J., Keyaerts, N., D'haeseleer, W., 2012. The impact of a dynamical gas-pricing mechanism on the gas demand at distribution level. 12th IAEE European Energy Conference. Venice, Italy 9-12 September 2012.
- Vandewalle, J.M., Keyaerts, N., D'haeseleer, W., 2012. The Role of Thermal Storage and Natural Gas in a Smart Energy System. 9th International Conference on the European Energy Market (EEM). Florence, Italy 10-12 May 2012.
- Keyaerts, N., Rombauts, Y., Delarue, E., D'haeseleer, W., 2010. Impact of wind power on natural gas markets: inter market flexibility. 7th International Conference on the European Energy Market (EEM). Madrid, Spain, 23-25 June 2010.
- Keyaerts, N., Hallack, M., Glachant, J., D'haeseleer, W., 2010. The trade-offs between line-pack flexibility and transport capacity in a liberalised gas market. 33rd IAEE International conference. Rio de Janeiro, Brazil, 6-9 June 2010.
- Keyaerts, N., Meeus, L., D'haeseleer, W., 2009. First results of the integrated European gas market: one for all or far from one. 24th World Gas Conference. Buenos Aires, Argentina, 5-9 October 2009.
- Keyaerts, N., Meeus, L., D'haeseleer, W., 2009. Entry in European natural gas retail markets: accessing the right contract "portfolio". 6th International Conference on the European Energy Market (EEM). Leuven, Belgium, 27-29 May 2009.

Other symposia

- Keyaerts, N., Rombauts, Y., Delarue, E., D'haeseleer, W., 2010. Impact of wind power on natural gas markets: inter market flexibility. 11th European Doctoral Seminar on Natural Gas. Florence, Italy, 28 May 2010.

- Keyaerts, N., Hallack, M., D'haeseleer, W., Glachant, J., 2009. The trade-offs between line-pack flexibility and transport capacity in the liberalised gas market. 10th European Doctoral Seminar on Natural Gas. Leuven, Belgium, 11 December 2009.
- Keyaerts, N., Meeus, L., D'haeseleer, W., 2008. Analysis of Balancing-System Design and Contracting Behaviour in the Natural Gas Markets. 8th European Doctoral Seminar on Natural Gas. Delft, The Netherlands, 24 October 2008.
- Keyaerts, N., Meeus, L., D'haeseleer, W., 2008. The Value Of Flexibility Relative To Gas Balancing Design. Young Energy Engineers and Economists Seminar. Madrid, Spain, 19-20 September 2008.
- Keyaerts, N., Meeus, L., D'haeseleer, W., 2008. Natural Gas Balancing: Appropriate Framework and Terminology. *Proceedings of the Young Energy Engineers and Economists Seminar*. Young Energy Engineers and Economists Seminar. Vienna, Austria, 24-25 April 2008.

Other contributions

- Hallack, M., Keyaerts, N., Bonafé, E., 2010. Conclusions of the "specialised training on regulation of gas markets", in: Florence School of Regulation (Ed.), Training conclusions. EUI-RSCAS, Florence, Italy.
- Keyaerts, N., Hallack, M., Glachant, J.-M., D'haeseleer, W., 2010. Gas Balancing Rules Must Take into Account the Trade-off between Offering Pipeline Transport and Pipeline Flexibility in Liberalized Gas Market. Working Paper, EUI RSCAS, 2010/71, Loyola de Palacio Programme on Energy Policy. Available at: http://cadmus.eui.eu/handle/1814/2
- Keyaerts, N., Hallack, M., Glachant, J.-M., D'haeseleer, W., 2010. Gas Balancing Rules Must Take into Account the Trade-off between Offering Pipeline Transport and Pipeline Flexibility in Liberalized Gas Market. Working Paper, MIT CEEPR, 2010/14. Available at: http://web.mit.edu/ceepr/www/publications/workingpapers.html

http://www.mech.kuleuven.be/en/tme/research/energy_environment/Energy_and_environment