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Increasing efficiency through market-based cross-border procurement of gas-balancing services in Europe

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Abstract
The gas-balancing mechanism makes up the interface between the users of the network and the transmission-system operator. The latter is responsible for the reliable and efficient operation of the network, whereas the former actually cause imbalances in the system. To deal with these imbalances the operator needs flexibility that can be offered by the network through line-pack flexibility or has to be procured from flexibility providers. Current procurement mechanisms often concern long-term and non-market-based agreements for domestically produced flexibility, likely leading to inefficiencies and raising barriers for entrants in the flexibility market. Market-based procurement of balancing services, on the other hand, relies on bids, specifying amount and price, submitted by all providers of flexibility and these bids, then, form a merit order from which the system operator can call the required amount of flexibility at the most efficient cost. Moreover, cross-border procurement of flexible gas enlarges the pool of flexibility providers and, as is demonstrated for hypothetical gas systems in two geographically adjacent regions, increases overall efficiency of the combined operators. Efficiency gains, however, are not distributed equally among the regions. Furthermore, border capacity should be strengthened when necessary because gas is pipeline-bound and trade cannot exceed available capacity.

Key words: gas balancing, cross-border markets, system efficiency, gas-market regulation

1. Introduction
For network-based industries the quality of the services mainly depends on the adequacy and the reliability of the supporting network, which, in the case of gas, are the pipelines. Gas-system integrity, meaning the day-to-day well functioning of the overall gas system, relies on the control of pressure in the pipelines. And, thus, the load balancing of what enters the pipeline system and what comes out of it, either as local consumption or export to another gas system. It is clear that the final responsibility for the physical gas balancing lies with the transmission-system operator (TSO). Indeed, the TSO imposes balancing rules – through the network code – to transfer responsibility to the network users who actually cause imbalances by virtue of forecast errors (unpredictable) and
differences between supply and demand variability (predictable) throughout a day. Ever since the liberalization of the European gas markets started, and despite the progress in market integration, gas balancing still is a controversial topic in Europe. Indeed, Europe remains a patchwork of balancing rules both regarding procurement of flexibility services by the TSO and regarding financial settlement of individual shipper imbalances. The former is the subject of this paper, in which the efficiency gains are examined that can be made in the procurement of balancing services across system borders. Indeed, the use of a cross-border merit order for flexible gas enables the TSOs to access the most efficient flexibility in the combined “system”. ¹ Thus, balancing can be done cheaper than under an autarkic approach in which both TSOs rely completely on domestic resources. Therefore, the efficiency gains of market-based cross-border procurement of balancing services and of the subsequently derived market-based settlement of imbalances are, first, illustrated using an analytical framework for international-trade policy [1], and second, the efficiency gains are examined using an efficiency-surplus methodology based on the principles of welfare benchmarking.

This paper demonstrates that cross-border procurement of balancing services leads to efficiency gains and thus higher welfare for the combined regions. Indeed, international-trade theory suggests that free trade across the borders of two regions with differing costs in producing services increases overall welfare of the integrated system. 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. Building on this market-based procurement of flexible gas, imbalance-settlement charges could be linked to the real costs of solving the system imbalance. Furthermore, the potential pitfalls and barriers to the implementation of cross-border cooperation are defined. Indeed, overall efficiency increases, but the distribution of efficiency changes as well, raising the need of a compensatory mechanism to overcome this transaction cost.

Gas balancing is not much discussed in the academic literature, even though it has been a very relevant topic to the industry since the start of the gas-market liberalization as demonstrated by the series of principles and guidelines developed by the regulators and transmission-system operators, 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 [2]. The European Regulator’s Group for Electricity and Gas (ERGEG) took over the role of CEER and started developing guidelines on how to design a balancing mechanism [3-6]. 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 gas-balancing issue [7-9]. A clear proposal for a common balancing-mechanism design was never laid down, though.

¹ “System” is defined here as a geographic area that applies a single set of rules. Typically, gas-system borders coincide with national borders, although some countries have multiple balancing zones (e.g., Belgium, France and Germany), which could apply different rules in different zones.
Industrial consultants also contributed to the topic. KEMA [10] advocated a daily balancing period and market-based balancing charges in an extensive report for the German energy regulator. NERA and TPA Solutions [11] 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. Meanwhile, KEMA [12] argued in a report for the European Commission that the lack of market-based balancing mechanisms potentially constitutes a barrier to cross-border trade and thus to market integration. They further identify a number of design parameters such as balancing charges and the balancing period that can distort gas-market development. ERGEG [13] proposed a target model for a common European balancing mechanism that had to re-open the long-lasting discussion. 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 (e.g., actually referring to a “target model”) it uses. The results of that discussion have served as input for the European Agency for the Cooperation of Energy Regulators (ACER), which essentially took over ERGEG’s role in this debate. In 2011, ACER published what appear to be final framework guidelines for gas balancing [14]. In response to ACER’s work, ENTSOG, the organization of the transmission-system operators that grew out of GTE, has been working on the implementation of the guidelines in a European network code that will define balancing rules. Although this implementation is still a work in progress, it seems cross-border integration or harmonization of balancing rules is not a key objective, which is in line with the coverage that is given to this aspect of balancing in ACER’s framework guidelines: while pointing out the need of cross-border cooperation, the actual development of cross-border mechanisms for balancing is left to the discretion of the transmission-system operators. The insertion of soft preconditions regarding technical feasibility and economic reasonableness of cross-border cooperation seems a missed opportunity for ACER. A strong appeal to remove technical and economic barriers for cross-border balancing would be more in line with the efficiency objective of the liberalization process.

The fairly limited academic literature on gas-balancing design strongly contrasts with the extensive industrial interest in the topic. Codognet [15] has investigated the role of the institutions for European network-access contracts. The gas-balancing rules, according to his findings, is 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 market-distorting effects of ill-designed balancing rules in Europe have been shown by Keyaerts et al. [16]. In that paper, it was argued that the regulation of pipeline flexibility interacts with the regulated activity of offering transmission services and the potentially competitive sector of providing flexibility services. Next, the risk of cross-subsidization was demonstrated between the intensive users of network flexibility and other market players with more

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2 In Europe, services are bundled in standard contracts defined in network codes, leaving no room for heterogeneous network services, whereas in the US, network services are offered in heterogeneous tailored contracts negotiated between the pipeline company and the shipper.
balanced portfolios throughout the day. The compatibility of current balancing designs was further questioned in Keyaerts et al. [17] for the case of massive wind-power introduction in electric-power systems. Balancing designs are not suited to deal with this transfer of electric-power balancing needs to the gas system as the relative position of the shipper imbalance to the system state (aggregate imbalance level) is currently not a design parameter. The settlement side of gas-balancing-mechanism design has been studied by Keyaerts and D'haeseleer [18]. They demonstrated, first, that non-market-based differences between sets of imbalance-settlement rules induce opportunistic cross-border behavior of profit-maximizing shippers arbitrating between more lenient and more stringent balancing mechanisms in geographically adjacent gas systems, increasing shipper efficiency, and, second, that overall efficiency in this non-market-based framework depends on the efficiency change on the side of the system operator. This operator-efficiency change can neutralize the gains in the shipper efficiency, reducing the net efficiency gain or even turning the overall efficiency change negative. Hence, current settlement design might actually reduce overall efficiency, contrary to the objectives of the liberalization. The transmission-system operator – as a regulated monopoly – should act in the interest of society and, thus, the regulator should take overall efficiency as its primary criterion, and then look at operator efficiency in second order. The creation of a cross-border market for procurement of flexibility services, ex ante as well as ex post, can remedy the fallacies of the current non-market based and often incompatible – in the sense that inefficiencies have become internalized – balancing rules.

Cross-border electric-load balancing, on the other hand, has recently received some academic attention. Vandezande [19], for instance, has studied the design parameters for cross-border electric-load balancing. Like gas balancing, electricity balancing has remained predominantly national in scope, save for a solidarity principle to deal with the requirement of instant electric-grid balancing, whereas the gas system has a longer time constant thanks to the line-pack flexibility as described in Keyaerts et al. [16]. Regarding the procurement of real-time balancing energy, Vandezande has proposed a design based on procurement at energy costs, excluding capacity reservation costs. With regard to cross-border electricity balancing, two cooperation mechanisms have been identified: either balancing-services providers offer their services directly to multiple transmission-system operators (TSO-BSP), or operators in geographically adjacent control areas independently trade the balancing services they have contracted or able to acquire (TSO-TSO). The most complete form of such TSO-TSO trading is the use of a single merit order on the border of Belgium and the Netherlands. The cost reductions over a year amounted to about 37% and the calls for actual balancing services lowered by over 20% due to netting of opposite imbalances at the system level.

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 most important 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. 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 using pipelines as short-term storage. This line-pack flexibility is usually the first line of defense against unbalanced shippers [12]. The absence of an explicit “gate closure” in the gas market makes up a second institutional difference with electricity. The “gate closure” marks the end of the wholesale market, 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, removing the clear distinction between shipper activities in the regular wholesale market – that can be intraday – and the actions of the gas-transmission-system operator [20]. Moreover, according to Vandezande [19], 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 and they could, therefore, distort the functioning of the wholesale market.

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 view of ACER on gas balancing as it advocates the active participation of gas-transmission-system operators in the wholesale market to procure balancing services [14]. Technically, electricity is the textbook example of a just-in-time product for which any imbalance between injection of electric power and the offtake thereof is to be covered instantly by adding flexibility (up or down) anywhere in the grid.3 Gas transmission and, thus, gas balancing is a different problem because gas travels at a limited speed [21]. 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. Finally, gas is much easier 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., indirect storage by means of hydro-pump stations.

According to the aforementioned KEMA study [12], 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 1). Examples of these are a regulated or direct contract with a storage operator or an LNG-terminal operator, or the transmission-system operator can have ownership of a source of flexibility. Even market-based procurement is often on a medium-term horizon, e.g., using an annual tender for flexibility. Only a few countries (e.g., Austria, France, the Netherlands and the UK) rely on short-term (day-ahead or intra-day) means and use the wholesale market or a separate balancing market as their main source for procurement of balancing services. The non-market-based or longer-term market-based procurement mechanisms, still according to KEMA, can inhibit competition on the side of flexibility provision in the gas market because new entrants have difficulties in accessing the flexibility market.

3 The location of electricity balancing services can become relevant when grid congestion is involved.
Table 1: Procurement mechanisms according to contract horizon and reliance on market [source: 12]

<table>
<thead>
<tr>
<th></th>
<th>Non-market based</th>
<th>Market-based</th>
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<tbody>
<tr>
<td>Short term (day-ahead/intra-day)</td>
<td>-wholesale market (5)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-balancing market (4)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>-ownership / regulated (7)</td>
<td>-tender (7)&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>-direct contract (3)&lt;sup&gt;a&lt;/sup&gt;</td>
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(x) number of countries using the mechanism (total sample 22 countries)

<sup>a</sup> update on KEMA report: the Netherlands moved in 2011 to using a balancing market and France moved from a separate balancing market to using the wholesale market since late 2009

<sup>b</sup> tenders can also be short term (e.g., daily) like in Spain and Germany

Although not much is publicly known about gas procurement costs, in line with the main procurement mechanisms applied in Europe, the remuneration of balancing services has two components: an energy cost for actually dispatched balancing energy, on the one hand, and a capacity cost for reservation, often in medium-term and long-term contracts, of an amount of flexibility regardless of its use, on the other hand (Table 2). When balancing services are procured on the market or through a merit-order mechanism, the offers are usually remunerated at a pay-as-bid rate as opposed to a marginal-bid rate.<sup>4</sup>

KEMA advocates short term market-based procurement at just the energy cost, excluding capacity reservation fees, as 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 as mentioned earlier.

Table 2: Procurement costs

<table>
<thead>
<tr>
<th>Capacity fee (EUR/M.m³)</th>
<th>Energy cost (EUR/M.m³)</th>
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<tbody>
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<td></td>
<td></td>
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<tr>
<td>- to ensure availability of an amount of flexibility (MW or M.m³/h) over the contract period</td>
<td>- related to actually dispatched flexible gas (MWh or M.m³) at a certain time</td>
</tr>
<tr>
<td>- typically socialized in network charges or covered through mark-ups or mark-downs (penalties)</td>
<td>- covered by imbalance charges that often refer to a market price</td>
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</table>

Because system balancing should neither be a profitable nor a loss-making business, procurement costs have to be recovered from unbalanced shippers through an imbalance settlement mechanism with any unintended loss or profit to be returned to the society through the general network tariffs [see, e.g., 14, 22]. The main form of energy cost settlement is through charging shippers imbalance charges per unit of imbalance; whereas, reservation costs are often socialized by including them in the overall network tariff. Alternatively, a mark-up (shipper buys gas from TSO) or mark-down (shipper sells

<sup>4</sup> 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.
gas to TSO) can be used to recover some costs. Such penalties are usually just incentives without any relation to procurement costs [12]. The specifics of these settlement mechanisms, however, are not in the scope of this paper. The aforementioned existing literature provides further information on imbalance settlement [see, e.g., 12, 14, 16, 18].

In the next sections, first, the mechanism and drivers behind cross-border trading for balancing services, and second, the methodology applied to study the transmission-system-operator efficiency in autarky (benchmark) and under free-trade conditions are presented. The results of the calculations are dealt with in the fourth section and in the final section the main conclusions and its policy implications are discussed.

2. International-trade policy framework applied to 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. Note that the trade between a TSO and the providers of flexibility is usually not corresponding to perfectly competitive markets as it is typically handled by other bargaining mechanisms. However, the analytical framework for international-trade policy [1] is used here to demonstrate the principles of efficiency gains based on relative cost differences in producing flexibility services. Pipeline-capacity restrictions have a similar effect as non-tariff barriers like import quota.

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. On the one hand, gas consumption is unpredictable, leading to forecast errors that impact the gas “unit commitment” at the supply side. On the other hand, the variability of consumption and production/import differs and requires flexibility for modulating the supply to meet the gas use: a task that also suffers from uncertainty and prediction errors. The aggregation of all individual differences between injections and 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.

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5 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.
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 [22].

Because of the short-term nature of the balancing problem and the inevitability of these system imbalances, the demand for balancing gas is supposed to be inelastic to price and exogenous. It is true that the transmission-system operator 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.7 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.

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 [12] identified a number of tools used to 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 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 gas-fired power plants.

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 a gate closure, but it does suppose a separation between the wholesale market and the 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

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6 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
7 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 [16].

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 3 summarizes the main determinants and defining characteristics of the demand for, and provision of, balancing services.

<table>
<thead>
<tr>
<th>Table 3: Demand for, and supply of, flexible gas</th>
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<tr>
<td><strong>Demand for flexible gas</strong></td>
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<tr>
<td>- residual demand, based on system-imbalance position and priority use of transmission-system operator-controlled line-pack flexibility</td>
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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 gas, until the desired quantities are obtained.

### 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.8 The joining of the separate merit orders into a single merit order that is called in a coordinated way makes up the next step in setting up cross-border market-based procurement of balancing services. Fundamentally, the cross-border procurement of balancing services is not different from any other international trade for services. Therefore, the analytical framework for analyzing the effects of international-trade policy applies to this problem.

Two gas systems that are physically connected in such a way that gas can be traded between the regions have been supposed. Fig. 1 illustrates the welfare effects of free-trade compared to autarky for a single-period and single-node model of the respective gas regions. System 1 (Fig. 1 a) has a demand D for flexibility gas and an offer curve S, whereas system 2 (Fig. 1 c) has a demand D* and a more efficient merit order S*. In autarky, the marginal prices are p(a) and p*(a) for systems 1 and 2, respectively. Now, when free trade (noted by “t” in Fig. 1 and supposing unrestricted border capacity) is

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8 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.
possible, the cross-border price for flexibility reaches \( p(t) = p^*(t) \) and the amount \( m(t) \) is exported from system 2 to system 1. Furthermore, production of flexible gas reduces in system 1 from \( q(a) \) to \( q(t) \) with an amount equal to \( m(t) \) and at the same time production increases with \( m(t) \) from \( q^*(a) \) to \( q^*(t) \) in system 2. Panel b of Fig. 1 shows the international market that combines the production surplus in system 2 (\( S^*-D^* \)) with the demand surplus (D-S) of system 1 for different price levels on the international market. The overall impact of free trade or unrestricted cross-border procurement on welfare will be shown to be positive (\( \Delta W \) in Eq. (3)), but not all stakeholders gain individually. Indeed, welfare in system 1 increases because the system operator gains area \( +a+b \) thanks to the lower equilibrium price \( p(t) \), whereas the providers of flexible gas gains \( -b \) (\( \Delta W_{S1} \) in Eq. (1)). In system 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 \( +a^*+b^* \) (\( \Delta W_{S2} \) in Eq. (2)). The transmission-system operator should pass on any welfare gains to the network users through lowering the network tariffs. Furthermore, the system operator in system 2 loses in this theoretical example because all units of flexible gas are remunerated at the higher marginal price, suggesting cross-border compensation might be required. Such compensation still benefits both system operators if the gain \( +a+b \) exceeds \( -a^* \).

\[
\begin{align*}
\Delta W_{S1} &= +a + b - a > 0 \\
\Delta W_{S2} &= +a^* + b^* - a^* > 0 \\
\Delta W &= +b + b^* > 0
\end{align*}
\]

**Fig. 1:** Free trade: welfare impact of free trade (unrestricted border capacity) compared to autarky for procurement of balancing services: welfare change in system 1 equals \( (+a+b-a) \), and in system 2, \( (+a^*+b^*-a^*) \). Net welfare for the combined systems rises by \( (+b+b^*) \).

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. Fig. 2 shows the welfare effects for restricted cross-border trade (represented by “r” for restricted border capacity in Fig. 2) to, e.g., the amount \( m(r) \) that is smaller than the free-trade exchange of flexible gas \( m(t) \).

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9 D-S is the willingness to pay for imports on the international market, whereas \( S^*-D^* \) represents the marginal costs of exports to the international market

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Fig. 2: Restricted border capacity: welfare impact of restricted procurement compared to unrestricted free trade, system 1 gains \((-a-b-c+a+c+d)\) and system 2 gains \((-a^*-b^*-c^*+a^*+c^*+e^*)\). Net welfare change for the combined regions is \((-b-c-b^*-c^*+c+d)\).

Because of the trade restrictions, system 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 gain \(+a\), whereas the TSO gains \(-a-b-c\). In system 2, the transmission-system operator 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 system 1 and \(p^*(r)\) in system 2. This difference represents the congestion rents for the border capacity \((+c+d=+c^*+d^*)\). Therefore, overall welfare (\(\Delta W_r\) in Eq. (6)) is decreasing compared to free trade, but the welfare change in the separate systems (\(\Delta W_{S1,r}\) in Eq. (4) and \(\Delta W_{S2,r}\) in Eq. (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 \(\Delta W_{S1,r}\) includes the rent \(+c+d\), or \(\Delta W_{S2,r}\) includes the term \(+c^*+e^*\). The congestion rents could, evidently, also be divided among the two transmission-system operators.

\[
\begin{align*}
\Delta W_{S1,r} &= -a - b - c + a + (c + d) & (4) \\
\Delta W_{S2,r} &= -a^* - b^* - c^* + a^* + (c^* + e^*) & (5) \\
\Delta W_r &= -b - c - b^* - c^* + (c + d) & (6)
\end{align*}
\]

Even if border capacity is limited, cross-border procurement still improves welfare compared to autarky (+\(f\) in system 1, +\(f^*\) in system 2 and the congestion rents). However, as argued before, distribution of welfare changes dramatically: the transmission-system operator in system 2 sees a higher marginal price for flexible gas. Therefore, a suitable compensatory mechanism will 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, the system operator takes a higher share of welfare, 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.
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 analytical framework 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. This technical model of the gas-transport dynamics completes the procurement model. The main equations, assumptions, and simplifications of the operations research model are discussed below. Technical details can be found in the Appendix and for more details on the modeling we refer to [23]. 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. This section discusses, first, our 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. 7).

\[
\text{Cost} = \sum_s \sum_t \sum_i (c_{up,s,t} \cdot q_{up,s,t} + c_{down,s,t} \cdot q_{down,s,t} + c_{lp,s,t} \cdot lpflex_{s,t})
\]  

(7)

Where:
- \(lpflex_{s,t}\): amount of line-pack flexibility (M.m \(^3\)) used in system \(s\) during period \(t\),
- \(q_{up,s,t}\): amount of upward flexibility (M.m \(^3\)) of type \(i\) used during period \(t\) in system \(s\),
- \(q_{down,s,t}\): amount of downward flexibility (M.m \(^3\)) of type \(i\) used during period \(t\) in system \(s\),
- \(c_{lp,s,t}\): unit cost of line-pack flexibility (EUR/m \(^3\)) in system \(s\) during period \(t\),
- \(q_{up,s,t}\): unit cost of upward flexibility (EUR/m \(^3\)) of type \(i\) during period \(t\) in system \(s\),
- \(q_{down,s,t}\): unit cost of downward flexibility (EUR/m \(^3\)) of type \(i\) during period \(t\) in system \(s\).

This total cost includes the costs of using line-pack flexibility in system \(s\) during period \(t\) (one hour) and the costs of accepted bids \(i\) from the merit order in period \(t\) and balancing region \(s\). Line-pack flexibility is the buffering capacity of the pipeline and represents the change of line-pack levels (M.m \(^3\)) between two periods \((lpflex_{s,t} = lp_{s,t}-lp_{s,t-1})\).

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 \((imb_{st})\) between total injections and withdrawals for each system and for every period as expressed in Eq. (8).

\[(\text{autarky}) \forall s,t: \sum_{i} q_{\text{up}_{sti}} - \sum_{i} q_{\text{down}_{sti}} - (lp_{st} - lp_{st-1}) = -imb_{st} \quad (8)\]

Furthermore, each bid for upward or downward flexibility defines a maximum amount \((Q_{\text{up}_{sti}})\) and \((Q_{\text{down}_{sti}})\) that can be called:

\[\forall s,t,i: \ 0 \leq q_{\text{up}_{sti}} \leq Q_{\text{up}_{sti}} \quad (9)\]
\[\forall s,t,i: \ 0 \leq q_{\text{down}_{sti}} \leq Q_{\text{down}_{sti}} \quad (10)\]

Additionally, the system operators have to keep the line-pack level between the safe operation levels \(LP_{lo}\) and \(LP_{up}\) at all times:

\[\forall s,t: \ LP_{lo} \leq lp_{st} \leq LP_{up} \quad (11)\]

When cross-border procurement is possible, Eq. (8) is replaced by Eqs. (12) and (13), below. Equation (13) ensures global system balance in each period, whereas Eq. (12) deals with balancing the separate systems taking account of flexibility that is imported \((imp_{st}, \text{M.m}^3)\) or exported \((exp_{st}, \text{M.m}^3)\).

\[(\text{free trade}) \forall s,t: \sum_{i} q_{\text{up}_{sti}} - \sum_{i} q_{\text{down}_{sti}} - (lp_{st} - lp_{st-1}) + imp_{st} - exp_{st} = -imb_{st} \quad (12)\]
\[(\text{free trade}) \forall t: \sum_{s} \sum_{i} q_{\text{up}_{sti}} - \sum_{s} \sum_{i} q_{\text{down}_{sti}} - \sum_{s} (lp_{st} - lp_{st-1}) = -\sum_{s} imb_{st} \quad (13)\]

Evidently, the flexible gas imported in system 1 equals the exports from system 2 in this 2-system model (Eq. (14)).

\[\forall s \neq ss,t: \ imp_{st} = exp_{st} \quad (14)\]

Finally, exchange of flexible gas is constrained by the availability of border capacity in a period \((CAP_t)\):

\[\forall s,t: \ 0 \leq imp_{st} \leq CAP_t \quad (15)\]
\[\forall s,t: \ 0 \leq exp_{st} \leq CAP_t \quad (16)\]

Fig. 3 shows the hypothetical gas networks of system 1 (nodes 1-4 and border node 9) and system 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). To examine autarky, border capacity is set to 0, whereas in free trade the capacity is
unlimited. To test the effects of restricted trade, the border capacity is set at a small, but positive number.

![Figure 3: Gas network of systems 1 (1-4 and 9) and 2 (5-8 and 9): Gas production/entry (nodes 1 and 5), gas demand/exit (nodes 3 and 7), flexible gas (nodes 1, 3, 4, 5, 7 and 8) and border (node 9)](image)

The costs of flexible gas have been derived from bid-ladder data that have been published by GTS [24]. Fig. 4 shows the mark-up (published bid price – spot price) for different quantities of flexibility. The premium to provide upward flexibility to a short system (positive amount of flexible gas) is approximately 0.05 EUR/m³ for up to about 1 M.m³ (million cubic meter), steadily rising to 0.10 EUR/m³ and even further to as high as 0.50 EUR/m³. The mark-down (represented as negative mark-ups in Fig. 4) 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/m³ to 0.30 EUR/m³ in order of magnitude. Table 4 lists the location, quantity and cost (mark-up/mark-down) of the assumed flexibility bids in the analysis. For reference, wholesale gas prices ranging from 0.15 EUR/m³ to 0.40 EUR/m³ 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.

![Figure 4: Merit order (hourly) of bids for flexible gas: mark-up/mark-down on wholesale price for upward and downward flexible gas [Sources: 24, 25]. Mark-downs are represented here as negative mark-ups.](image)
Table 4: 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

<table>
<thead>
<tr>
<th>Node</th>
<th>Q_down (M.m³)</th>
<th>Mark-down (EUR/m³)</th>
<th>Q_up (M.m³)</th>
<th>Mark-up (EUR/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.60</td>
<td>0.08</td>
<td>0.50</td>
<td>0.06</td>
</tr>
<tr>
<td>3</td>
<td>0.20</td>
<td>0.16</td>
<td>0.40</td>
<td>0.24</td>
</tr>
<tr>
<td>4</td>
<td>0.16</td>
<td>0.05</td>
<td>0.30</td>
<td>0.0025</td>
</tr>
<tr>
<td>5</td>
<td>0.30</td>
<td>0.38</td>
<td>0.50</td>
<td>0.21</td>
</tr>
<tr>
<td>7</td>
<td>0.40</td>
<td>0.20</td>
<td>0.50</td>
<td>0.30</td>
</tr>
<tr>
<td>8</td>
<td>0.18</td>
<td>0.12</td>
<td>0.25</td>
<td>0.15</td>
</tr>
</tbody>
</table>

The cost of line-pack flexibility comes down to the extra compression cost of gas (roughly 0.15 EUR/m³ for primary fuel gas), but this cost is very hard to separate from the compression that is already required for transmission of gas [18]. When there is no compression, line pack has no variable costs.

Shipper entry and exit nominations are exogenous inputs for the model, from which the system imbalance can be derived. This imbalance, then, has to be covered with line-pack flexibility and other flexible gas over the course of a gas-day. Generic profiles that are representative for residential, electricity-generation and industrial consumption have been used, all scaled back to an average hourly demand of 1 M.m³/h (Fig. 5). Moreover, perturbations have been superimposed to generate random profiles.

Fig. 5: Generic hourly demand [M.m³] profiles for two gas days (adding up to 48 hours), a) generic residential demand, b) generic electricity-generation demand and c) generic industrial demand. All demand profiles have been scaled to average 1 M.m³/h.

For the supply side in nodes 1 and 5, a flat entry profile has been assumed during the day that 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 system 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.\(^{11}\) In the end, it is only the imbalance profile per region and the relative positions of the two systems that is relevant for the analysis. For instance, if system 1 has a surplus of 0.5 M.m\(^3\) and system 2 is short 0.2 M.m\(^3\), pooling (“exchanging” line-pack gas) of imbalances reduces the global system imbalance to +0.3 M.m\(^3\) to be absorbed by line-pack flexibility or covered by other 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 welfare changes are to be seen more as a lower limit because non-coinciding peaks and dips or opposite periodic imbalances provide more options to improve efficiency by exchanging line-pack flexibility resulting in higher efficiency gains.

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 efficiency 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.

4.1. Small-scale example
Suppose a 2-system and 4-period balancing problem with line pack and border capacity. Furthermore, line pack in system 1 can only cover cumulative deviations ranging between -12 and +0.14, whereas system 2 can sustain deviations between -0.15 and +0.15. All units are M.m\(^3\). Finally, it is assumed that using line pack is cheaper than flexible gas and cross-border trading has no transaction costs. In Table 5 and Table 6, “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 5 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 bought in system 1 to keep the line-pack position above the lower limit, whereas 0.04 units of flexible gas have to be sold by the TSO in system 2 to keep the line pack under the upper deviation limit.

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\(^{11}\) This choice is defendable considering that demand profiling does not tend to differentiate 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

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Table 5: Governing dynamics of system balancing without cross-border procurement, imbalance in each period has to be absorbed by the 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.

<table>
<thead>
<tr>
<th>System</th>
<th>Period</th>
<th>Imbalance over period [M.m³]</th>
<th>Line-pack positiona,b buffering (&gt;0) [M.m³]</th>
<th>Flexible gas upward (&gt;0) [M.m³]</th>
<th>Flexible gas downward (&lt;0) [M.m³]</th>
<th>Trade import (&gt;0) [M.m³]</th>
<th>Trade export (&lt;0) [M.m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>+0.11</td>
<td>+0.11</td>
<td></td>
<td></td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.19</td>
<td>-0.08</td>
<td></td>
<td></td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>+0.13</td>
<td>+0.05</td>
<td></td>
<td></td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.19</td>
<td>-0.12</td>
<td></td>
<td>+0.02</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>+0.17</td>
<td>+0.15</td>
<td>-0.02</td>
<td></td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.13</td>
<td>+0.02</td>
<td></td>
<td></td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>+0.15</td>
<td>+0.15</td>
<td>-0.02</td>
<td></td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.11</td>
<td>+0.04</td>
<td></td>
<td></td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

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
b Line-pack position is a storage variable accumulating over the periods

The availability of border capacity to exchange line pack and flexible gas removes the need for any flexible gas. Indeed, Table 6 shows that the combined system is balanced by exchanging line-pack flexibility (pooling of imbalances) between the system operators. Export from system 2 to system 1 amounts to 0.04 units of imbalance.

Table 6: Governing dynamics of system balancing with unlimited cross-border procurement and pooling, imbalance in each period has to be absorbed by the line-pack or dispatching of flexible gas in the combined region. A surplus is balanced by increasing line pack (>0), dispatching downward flexibility (<0) or exporting gas (<0) to the other region in that period.

<table>
<thead>
<tr>
<th>System</th>
<th>Period</th>
<th>Imbalance over period [M.m³]</th>
<th>Line-pack positiona,b buffering (&gt;0) [M.m³]</th>
<th>Flexible gas upward (&gt;0) [M.m³]</th>
<th>Flexible gas downward (&lt;0) [M.m³]</th>
<th>Trade import (&gt;0) [M.m³]</th>
<th>Trade export (&lt;0) [M.m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>+0.11</td>
<td>+0.13</td>
<td></td>
<td>+0.02</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.19</td>
<td>-0.06</td>
<td></td>
<td>+0.02</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>+0.13</td>
<td>+0.09</td>
<td></td>
<td>+0.02</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.19</td>
<td>-0.10</td>
<td></td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>+0.17</td>
<td>+0.15</td>
<td></td>
<td>-0.02</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-0.13</td>
<td>+0.02</td>
<td></td>
<td></td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>+0.15</td>
<td>+0.15</td>
<td></td>
<td>-0.02</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-0.11</td>
<td>+0.04</td>
<td></td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

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
b Line-pack position is a storage variable accumulating over the periods

4.2. Efficiency analysis taking account of gas network

Four cases (Table 7) 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 errors vary from -15% to +15%. 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% in system 1 and -9% in system 2 gives a net forecast error of -21% on total demand, or, alternatively, a net supply of 0.79 compared to total demand in the combined region.

The TSO efficiency surplus ($\Delta S_{TSO,R1+R2}$) is defined here as the summation of the regional differences between the balancing costs with cross-border cooperation and the costs in autarky:

$$\Delta S_{TSO,R1+R2} = \left( \text{cost}_{\text{crossborder},R1} - \text{cost}_{\text{autarky},R1} \right) + \left( \text{cost}_{\text{crossborder},R2} - \text{cost}_{\text{autarky},R2} \right)$$  \hspace{1cm} (17)

It is positive if cross-border trade improves efficiency.

**Table 7: Overview of the examined cases, FE = forecast error in a region**

<table>
<thead>
<tr>
<th>Case</th>
<th>system 1: FE</th>
<th>system 2: FE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-12%</td>
<td>-15%&gt;+15%</td>
</tr>
<tr>
<td>B</td>
<td>+6%</td>
<td>+6%</td>
</tr>
<tr>
<td>C</td>
<td>=</td>
<td>-15%&gt;+15%</td>
</tr>
<tr>
<td>D</td>
<td>=</td>
<td>-15%&gt;+15%</td>
</tr>
</tbody>
</table>

Fig. 6 shows the efficiency gains for cases A (panel a) and B (panel b). In both cases, efficiency gains are bigger when both systems are unbalanced. Indeed, when a region is more or less balanced, its potential for improvement is limited. The flexible-gas-cost structure from Table 4 is such that system 1 has the more efficient resources in its merit order. Therefore, system 2 benefits most when it has an imbalance and can switch domestic resources for more efficient imported flexible gas.

Fig. 6: Operator surplus: 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) system 1 FE -12% and net supply in the combined region ranging from 0.73 to 1.03, b) system 1 FE +6% and net supply in the combined region ranging from 0.91 to 1.21.

This is further demonstrated in Fig. 7, which shows cases C (panel c) and D (panel d). The operator surplus is in these cases much less dependent on the system 1 imbalance than on the system 2 imbalance, which is now kept constant. Hence, the surpluses are flatter.
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. 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 intraday.

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 system amounted between 60 and 100 percent and are, thus, substantial. Evidently, this outcome depends on the relative cost structure 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 Fig. 8. As long as system 2 is short (profiles ranging from 0.73 to 0.85), system 1 loses and system 2 gains because both systems are short, but system 2 can import cheaper flexible gas from region 1, raising the price of flexibility in system 1. As soon as system 2 is long (profile 0.91 and beyond), system 1 benefits from imbalance pooling and can reduce its costs. A proper compensatory mechanism will be required to re-distribute efficiency after all system imbalances have been dealt with.
Taking a closer look to the use of flexibility in a specific instance (profile 0.79) of case A, Fig. 9 shows that, when cross-border procurement of flexible gas is possible, region 2 dispatches almost no domestic flexibility. In autarky, flexible gas was extensively dispatched (Fig. 9 c). Region 1, on the other hand, “produces” more flexible gas to export it to region 2 (Fig. 9 b). Panel c shows a smoother line-pack use in system 2 when cheap flexible gas can be acquired.
Finally, Fig. 10 shows the detailed use of the merit order: the sources of flexibility flex1 to flex8 refer to the nodes and data from Fig. 3 and Table 4, respectively. In this specific case (case A, profile 0.73, 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 flex1 has to be called to satisfy the demand for flexible gas from the international market.
Fig. 10: Flexibility dispatching per source (see Table 4 and Fig. 3) – a) system 1 in autarky, b) system 1 with cross-border trade, c) system 2 in autarky and d) system 2 with cross-border trade. Flexibility trades can be observed as the differences between dispatching in autarky and in the cross-border scenario.

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. In the end, cross-border procurement raises efficiency, but the efficiency distribution changes, with one system gaining at the expense of the other. Therefore, the development of a suitable compensatory mechanism can be identified as the main pitfall for the actual implementation of a cross-border mechanism. When border capacity is restricted, the efficiency gains become smaller because, e.g., not all expensive flexible gas in region 2 could be replaced by cheaper sources from region 1 as was the case in Fig. 10. The achievable efficiency gains for different levels of available border capacity are illustrated in Fig. 11. The considered border capacities range from 0.025 to 0.15 M.m³/h. The levels correspond to a few percent till 15 percent of the average hourly gas demand.
Fig. 11: Operator surplus for different border capacities (cases A and B for a residential demand profile): for larger forecast errors, the demand for import of cheaper flexibility from abroad rises, but the capacity restricts trade to a suboptimal level and thus lower efficiency gains

Fig. 11 illustrates the efficiency gains for cases A and B for a residential demand profile. “no lim” is the benchmark scenario with unlimited capacity. It is clearly shown that the surpluses are smaller when trade becomes more restricted. Foregone benefits can become as high as 50 percent (dropping from about 1 M.EUR to about 0.5 M.EUR) and even more. The foregone benefits also depend on the relative cost structure in the regions and the size of the demand for balancing services. In panel b, e.g., there is a higher desire for import of upward flexibility into system 2 as shown by the bigger spread for the profiles numbered 0.91 to 1.06.

4.3. Cross-border settlement
Besides procurement of balancing services and physical balancing, a full-scale balancing mechanism also deals with the settlement of unbalanced shippers. A full study of settlement designs is beyond the scope of this paper. Nevertheless, some reflections and intuitions based on a market-based procurement design are put forward.

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 other 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 flexible gas, 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 based on the true cost of balancing.

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 and, thus, 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 calling bids from the merit order, occurring whenever deemed 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 are distributed among those shippers that contributed to the problem with a reward for those users that helped the system at that time resulting in better 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 Keyaerts et al. [16].

5. Conclusions
Gas balancing has been a controversial topic in Europe since the liberalization of the gas market has started in the late 90s. Ever since, the different stakeholders have been discussing principles, good practices and framework guidelines for designing an efficient balancing mechanism that enhances gas market functioning. The final result of this process is ACER’s framework guidelines that are to be transposed into network codes by the European transmission-system operators (ENTSOG). Although these guidelines advocate market-based balancing, there is no firm requirement to this end in the text, missing an opportunity to move towards more cross-border harmonization of balancing rules or at least to a compatibility check of the applicable rules.

This lack of a true push towards cross-border cooperation for gas-system balancing is striking because Ricardian trade theory predicts welfare gains when balancing services are exchanged between geographically adjacent balancing areas that have different supply and demand functions. Moreover, using hypothetical gas systems that include the technical peculiarities of gas systems, such as pressure driven gas flow and pipeline flexibility, efficiency gains have been demonstrated to be possible in practice as well. Net efficiency of the combined systems certainly increases by exchanging line pack and procuring flexible gas across borders. Nevertheless, resistance against cross-border balancing can exist because not every player gains in the same way. The implementation of a compensatory mechanism seems necessary to ensure that no system loses compared to its efficiency in autarky. Furthermore, sufficient short-term cross-border capacity should be available to capture the full welfare gains. The net efficiency gain of cross-border procurement can be used as an indication of the value of (adding) border capacity.

Although the calculations in this paper 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., using historical imbalances from two regions and using actual merit order data.
Finally, the implementation of cross-border based balancing with regard to the procurement of flexibility is advisable for policy makers, but also moving towards cross-border based settlement, meaning that settlement mechanisms should be based on the (cross-border) cost of system balancing, is to be considered by policy makers. 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.

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**References**


Annex

Table A 1 lists nodal information about pressure limits, presence of compression and the function of the nodes. Pipeline data about diameter (D) and distance (L) and the starting average pressure in the line are given in Table A 2.

Table A 1: Nodes in network Fig. 3; nodal pressure limits, presence of compression and the maximal compression ratio and function of node in network

<table>
<thead>
<tr>
<th>Node</th>
<th>Pressure limits (low/high) [bar]</th>
<th>Compression (y/n) (ratio)</th>
<th>Function: demand (D), supply (S), transit (T), upward flexibility (F+), downward flexibility (F-) or border (B),</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60 / 80</td>
<td>y (1.33)</td>
<td>S</td>
</tr>
<tr>
<td>2</td>
<td>60 / 80</td>
<td>n</td>
<td>T</td>
</tr>
<tr>
<td>3</td>
<td>60 / 80</td>
<td>n</td>
<td>D</td>
</tr>
<tr>
<td>4</td>
<td>60 / 80</td>
<td>n</td>
<td>F+/F-</td>
</tr>
<tr>
<td>5</td>
<td>60 / 80</td>
<td>y (1.33)</td>
<td>S</td>
</tr>
<tr>
<td>6</td>
<td>60 / 80</td>
<td>n</td>
<td>T</td>
</tr>
<tr>
<td>7</td>
<td>60 / 80</td>
<td>n</td>
<td>D</td>
</tr>
<tr>
<td>8</td>
<td>60 / 80</td>
<td>n</td>
<td>F+/F-</td>
</tr>
<tr>
<td>9</td>
<td>60 / 80</td>
<td>n</td>
<td>B</td>
</tr>
</tbody>
</table>

Table A 2: Pipelines in network of Fig. 3; diameter D, distance L and starting level of average pipeline pressure (to determine line pack level)

<table>
<thead>
<tr>
<th>Pipeline</th>
<th>D [m]</th>
<th>L [km]</th>
<th>(\bar{p}_{a(i),start}) [bar]</th>
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<tbody>
<tr>
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<tr>
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<td>5</td>
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<tr>
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<tr>
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<td>1</td>
<td>50</td>
<td>70.47</td>
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<tr>
<td>6 – 8</td>
<td>1</td>
<td>5</td>
<td>70.47</td>
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<tr>
<td>2 – 9</td>
<td>1</td>
<td>30</td>
<td>70.47</td>
</tr>
<tr>
<td>6 – 9</td>
<td>1</td>
<td>30</td>
<td>70.47</td>
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