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Abstract

In the European Union's (EU) gas transmission system, transporting gas requires the booking of transmission capacities. For this purpose, long-term and short-term capacity products are offered. Short-term capacities are priced by multiplying long-term capacity tariffs with factors called multipliers, making them comparably more expensive. As such, the level of multipliers directly affects how capacity is booked and may significantly impact infrastructure utilisation and welfare—an issue that has not received attention in the literature so far. Using a theoretical approach, we show that multipliers equal to 1 minimise costs and maximise welfare. In contrast, higher multipliers are associated with decreasing welfare. Yet, policymakers may favour higher multipliers, as we find that multipliers greater than 1 but sufficiently low can maximise consumer surplus by leading to reduced hub prices and lower regional price spreads on average. These findings are expected to hold for the large majority of the EU countries. Nevertheless, we also identify situations in which capacity demand can become inelastic depending on the proportion of multipliers with respect to the relative cost of transmission versus storage. In such cases, varying multipliers are found to have no effect on infrastructure utilisation, prices and welfare.

Keywords: gas transmission networks, entry-exit tariffs, multipliers, NC CAM

JEL classification: L51, L95, Q41

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1. Introduction

Efficient operation of gas transmission networks is crucial for the gas supply system and overall welfare. Due to the direct effect on network utilisation and the resulting welfare, the applied pricing policy for financing of networks is particularly important. Principles of microeconomics indicate that economic efficiency is maximised when prices reflect short-run marginal costs (Borenstein, 2016). However, the existence of high fixed costs in gas networks necessitates charging tariffs higher than short-run marginal costs so that revenues cover the total network costs.[1] The networks are dimensioned according to maximum (i.e. peak) capacity demand, which in turn largely determines the fixed costs. An important issue when designing the tariff structures then becomes how to charge the network users for the cost of capacity. A common approach for financing networks is to apply capacity tariffs used to distribute the network costs among users depending on their peak capacity demand. As such, in contrast to a pure commodity tariff[2] regime where only the transported volumes are charged, capacity tariffs[3] incentivise the reduction of yearly peak capacity demand and potentially reduce the need for capacity extensions.

Financing of gas networks in the EU occurs via the entry-exit regime. Operated by transmission system operators (TSOs), the EU gas grid consists of numerous regional gas transmission networks (i.e. market areas) which connect producers and neighbouring networks with storage facilities (henceforth storages) and downstream distribution networks. In this context, the entry-exit system requires network users to book entry and exit capacities in explicit auctions whenever transporting gas into or out of a certain market area, paying the corresponding tariffs.[4] When the entry-exit tariff system was first introduced in the EU with Regulation 2009/715, the offered capacities were limited to yearly capacities. This meant traders were not charged according to the actual transported gas volumes but rather for their expected peak capacity demand, which essentially corresponded to a pure capacity pricing regime. However, in some cases, offering only yearly capacities caused inefficient short-term utilisation of the existing pipelines, where significantly high price spreads between market areas occurred despite the absence of physical congestion (ENTSOG, 2017). This inefficiency was caused by arbitrageurs not being able to exploit short-term regional price spreads without procuring capacity covering a whole year.

[1] This is also observed in other natural monopolies such as telecommunication, electricity and railway networks.
[2] Commodity tariffs are also commonly referred to as energy charges or volumetric charges.
[3] Capacity tariffs are also commonly referred to as capacity charges or demand charges.
[4] The booking of capacities occurs in capacity auctions performed by trading platforms (such as PRISMA, GSA, RBP) in which the reserve prices correspond to the transmission tariffs. In a large share of the EU capacity auctions, demand for capacity remains below the offered capacity (ACER, 2019b). In the remaining cases where demand for capacity exceeds the offered capacity a congestion premium arises.

In order to reduce the inefficiencies resulting from offering only yearly capacities, the EU Commission introduced the Network Code on Capacity Allocation Mechanisms (NC CAM) with Regulation 2013/984, extending the available capacity products to cover sub-annual durations. The regulation thus required TSOs to offer short-term (ST) transmission capacities, i.e. quarterly, monthly, daily and within-day capacities, while the previously introduced yearly capacities were defined as long-term (LT) capacities. Instead of the necessity to cover the yearly peak demand with a yearly product, capacities could now be booked according to the actual transmission demand. This enabled traders to make capacity bookings correspondingly to the actual transported volumes, similarly to what would occur under a commodity pricing regime. LT and ST capacities generally do not cost the same. According to EU regulations, ST capacities should be priced low enough to incentivise short-term trade but sufficiently high to support enough LT bookings to achieve stable TSO revenues and tariffs. In this context, in the EU, ST products are priced by multiplying the LT tariff with factors called multipliers. Those multipliers are individually specified by the respective national regulatory authorities (NRAs).[5]

By making ST products comparatively more expensive, NRAs can influence the emphasis of capacity vs. commodity pricing in the pricing of transmission capacities in the EU entry-exit tariff structure. This can be best illustrated with two extreme cases: If the multipliers were equal to 1, then the ST capacities would cost the same as LT capacity. Assuming no transaction costs exist and enough capacity products are offered, there would exist no capacity booking pattern where booking LT capacities is cheaper than booking solely ST capacities. As a result, traders would only book a combination of ST capacities which exactly satisfies their demand profile for transmission capacity. In such a setting, network users behave as being exposed to commodity pricing since they pay for the exact amount of volumes, i.e. the energy they transport. Whereas, if the multipliers were sufficiently high, so that booking LT capacity would be always cheaper than booking ST capacities, then the traders would book only LT capacity. This would essentially result in network users behaving as being exposed to a pure capacity pricing regime, as traders would be required to book enough transmission capacity to cover their yearly peak demand even if their average capacity demand is lower; hence, resulting in them paying for the capacity rather than the energy.

The reality lies somewhere in between these two extreme cases. In a large majority of EU member countries, multipliers are greater than 1 but are still sufficiently low so that both LT and ST bookings are

[5]When NC CAM came into force, multipliers largely varied among countries spanning a wide range from 1 to as high as 5.5 and mostly increased as the run-time of the capacity product decreased. The EU Commission tightened the rules regarding multipliers in their network code on tariff harmonisation (NC TAR) from the EU regulation 2017/460. The regulation limits the range for multipliers for member states to 1–3 from June 2019 onward. Moreover, the EU Agency for the Cooperation of Energy Regulators (ACER) has to decide by April 1st, 2021 whether multipliers are to be further restricted within a range of 1–1.5 starting from April 2023.

observed (ACER, 2019a). Hence, transmission network users in these countries are implicitly charged a combination of capacity and commodity tariffs. The extent to which aspect dominates over the other, and the ensuing effects on infrastructure and welfare, are determined by the multipliers and the underlying tariff structures—the analysis of which constitutes the focus of this paper.

The issue of how to design tariffs within the EU entry-exit framework has been analysed in the literature, where aspects such as cost recovery, cost distribution and efficiency have been considered. Bermúdez et al. (2016), analysing different methodologies of setting LT tariffs, argues that more cost-reflective methodologies ensure more efficient utilisation of the transmission network. Mosácula et al. (2019), however, points out that approaches which charge full costs at EU interconnectors are unlikely to maximise social welfare. This is also mentioned in Hecking (2015), which suggests to reduce inefficiencies by setting entry and exit tariffs equal to short-run marginal costs for interconnectors within the EU while applying sufficiently high tariffs at the EU outer borders to finance the EU transmission grid. In addition to increasing the efficiency of the gas dispatch, the study estimates that such a tariff regime would also allow to redistribute considerable share of network costs towards suppliers at the EU borders, indicating the relevance of tariff design on the distribution of network costs.

The pricing of LT vs. ST capacities and the topic of multipliers have not been analysed in the academic literature so far.[6] To our knowledge, a tariff framework similar to the current tariff structure of the EU gas transmission capacities is also not observed in any other regulated network neither in the EU nor in other regions, hence the lack of comparable literature. Nevertheless, when multipliers are larger than 1, the EU tariff structure has similarities with the concept of peak-load pricing. In peak-load pricing, higher prices are charged in peak periods than in off-peak periods. Similarly, in the EU entry-exit system, when ST capacity is more expensive than LT capacity, traders are incentivised to procure the cheaper LT capacity for meeting base load demand whilst procuring the more expensive ST capacity to meet their peak-load demand. This implicitly results in higher capacity costs for peak periods than for off-peak hours. The founding works of Boiteux (1949) and Steiner (1957) on peak-load pricing have shown that allocating the costs of capacity to peak-load consumers and charging them consequently higher tariffs impacts the networks utilisation and leads to higher long-term efficiency. Further, Gravelle (1976) and Nguyen (1976) indicate that the problem of peak-load pricing remains a valid issue even when storage (with significant costs) is available, which is undeniably the case in the majority of EU gas systems. These findings further underpin the relevance of analysing the effects of the multipliers on network utilisation, efficiency and cost distribution.

[6] The topic is qualitatively addressed only in several consulting studies and technical reports (Strategy& and PwC, 2015; EY and REKK, 2018; ACER and CEER, 2019; ACER, 2019a; Rüster et al., 2012; DNV-GL, 2018).

In order to improve the understanding of the effects of multipliers and fill the research gap in the literature, we develop a stylised theoretical framework with an analytic solution that depicts the gas procurement, storage, and transmission capacity booking in the EU gas market. The model considers two points in time and two nodes under a setting of perfect competition and perfect foresight. We solve the resulting cost minimisation problem analytically using Karush-Kuhn-Tucker (KKT) conditions, providing analyses on the effects of multipliers. The analysed aspects can be grouped into three main categories; the direct impact of multipliers on infrastructure utilisation, effects on hub prices and welfare implications.

Our model results show that high multipliers indeed reinforce the capacity pricing component and cause bookings to shift from ST capacities to LT capacity, resulting in increased storage utilisation. This leads to a more uniform usage of transport capacities, implying decreased volatility of pipeline transportation. The findings above are expected to be valid for the EU gas system in the majority of situations. Nevertheless, we find that these effects are not universal and depend strongly on whether the traders' capacity demand is elastic or not. We define the elasticity as the shift in capacity demand from the peak period to an off-peak period in response to an increase in the relative price of ST capacity (i.e. the multiplier). This elasticity largely results from gas storages, which provide the traders with inter-temporal flexibility, and give them the possibility of meeting their short-term needs with withdrawals from storages instead of booking ST capacities.

We find that certain proportions of multipliers with respect to the ratio of storage tariffs to transmission tariffs can lead to inelastic capacity demand: Multipliers that are sufficiently low (but still larger than 1) compared to the marginal cost of gas storage—or when no storage capacity exists—can result in a domain with inelastic capacity demand, where a change in multipliers does not affect the volume of booked capacities in the respective time periods. Similarly, we show that sufficiently high multipliers can lead to the same behaviour as in a pure capacity pricing regime, with only LT capacity being booked and the volume of booked capacity being independent of the multiplier level.

Regarding the impact of multipliers on temporal hub prices we identify several effects. We find that maximum regional price spreads increase with higher multipliers, an implication also mentioned by ACER (2019a). However, unlike ACER, who argues that ST capacity tariffs would act as reference prices for the regional spreads, we show that ST tariffs rather form the upper bounds for the spreads. As such, our results imply that the volatility in regional price spreads increases with higher multipliers. Further, we find that increases in multipliers can cause increased temporal volatility in hub prices if storage tariffs are comparably high or if storage capacity is unavailable.

The model results indicate that higher multipliers are associated with higher total system costs and consequently lower total welfare in the short-run. However, for the identified multiplier domain which is representative of the majority of the situations in the EU gas system, our results show that there exists a multiplier level potentially larger than 1, which maximises the total consumer surplus.

Therefore, despite the stylised setting, the implications of our model results are highly relevant for policymakers. Maximising total welfare requires the multiplier to be no greater than 1. However, policymakers, who aim to maximise consumer surplus, may favour a multiplier larger than 1, since transmission tariffs can be lowered by the TSOs, which leads to lower average hub prices. Multipliers higher than 1 also foster the redistribution of the network costs from base load towards peak-load consumers, in line with the principle of peak-load pricing.

The contribution of our paper can be summarised as follows: Academic literature on the effects of short-term transmission capacity multipliers is nonexistent. Hence, being the first of its kind, our paper aims to close this research gap. Thanks to the developed theoretical framework, direct effects and implications are identified within the valid tariff domains. Since our analysis shows that multipliers have significant effects on welfare, distinguishing between ranges of validity also helps support tailor-made policymaking.

2. The Model

We develop a theoretical model which depicts the procurement and the subsequent transmission capacity booking in the EU gas market. The model represents the relevant actors in a realistic manner, yet it is simplified enough to have a closed form solution. In this respect, the model considers two points in time (t_1, t_2), and five different groups of players interacting with each other: traders, producers, storage operators, the transmission system operator (TSO), and consumers. The structure of the model and the main assumptions for the considered agents are illustrated in Figure 1.

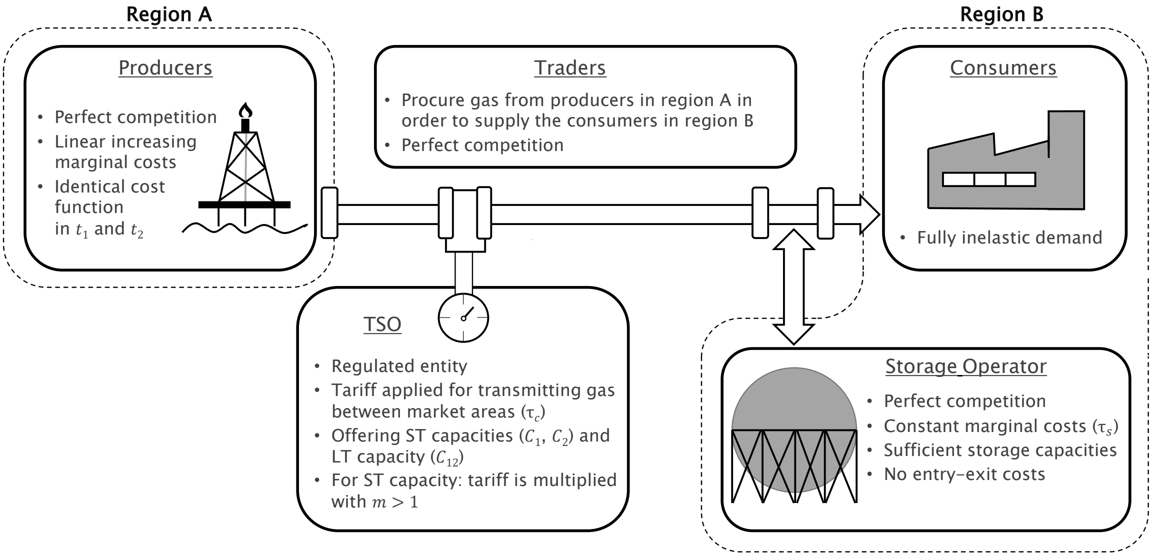


Figure 1: Schematic representation of the model structure and the main assumptions

We assume that the traders are obliged to meet the gas demand of their customers (i.e. consumers) under a perfectly competitive market setting. Accordingly, traders procure gas from the gas producers located at market area A and transport it using the gas transmission network to the consumers which are located at market area B. In order to transport gas over the transmission network, traders need to book sufficient transmission capacities. Furthermore, the traders can store gas in gas storages in t_1 and withdraw it in t_2 to serve the gas demand in t_2. We assume that traders book capacities rationally and efficiently.[7]

We assume producers to face positive and linearly increasing marginal costs[8] and have sufficient capacities. Their aggregated cumulative cost function is linear and remains unchanged in both points in time. The producers are assumed to be under perfect competition and offer their gas at a rate that is equal to their marginal costs. This is in line with the simulations of Schulte and Weiser (2019), which indicate that gas suppliers to Europe behaved competitively in 2016.[9] The aggregated inverse supply function p_t of the producers can be then formulated as follows:

$$p_t(Q_t) = a + b\,Q_t \qquad \forall\, t \in (t_1, t_2) \tag{1}$$

where $Q_t > 0$ represents the aggregated gas procurement volumes of the traders.

[7] This is a realistic assumption also supported by the empirical analysis of Keller et al. (2019).

[8] Having carried out the analysis also by assuming a supply function with quadratic marginal costs, we find that the main findings regarding the effect of multipliers on gas dispatch remain unchanged. Hence, for the sake of clarity, we assume linear increasing marginal costs for producers in this paper.

[9] With increasing LNG supply and lower prices it can be safely assumed that gas markets have become even more competitive in recent years.

The storage capacities of the storage operators are located in market area B where the consumers are located. We assume storage operators to face constant positive marginal costs under perfect competition. We further assume that the storage operators have sufficient capacities to meet the demand at all times and therefore offer their storage capacity at a rate equal to their marginal costs τ_s. This assumption is in line with the situation observed in the EU, where storage operators have been unbundled since the introduction of the third energy package (European Commission, 2010) and have ample storage capacities in the absence of supply disruptions (ACER, 2019a). Furthermore, we assume storage operators to be fully exempt from transmission tariffs when withdrawing or injecting gas in the transmission network.[10]

The consumers have a positive gas demand. The aggregated gas demand of the consumers at t_1 equals d_1. Similarly, the demand in t_2 is equal to d_2. Demand is assumed to be inelastic. This is a common assumption for stylised short-run gas market models and is also supported by the empirical analysis of Burke and Yang (2016), which finds that short-term elasticities for gas demand are generally low, and for the case of households, do not significantly differ from zero. Demand is assumed to be higher in the second period than in the first period, i.e. $d_2 > d_1 > 0$, representing a winter (d_2) and a summer period (d_1). To be able to examine distributional effects among different consumer groups we assume the aggregated consumer demand (i.e. d_1 and d_2) to be split into two demand groups: first, the demand of the base-load consumers (e.g. industry companies) which equals d_1 in both periods, and second, the demand of the peak-load consumers (e.g. households) which only occurs in t_2 and equals $(d_2 - d_1)$.

The TSO operates a transmission grid which connects the producers in market area A with the storages and consumers in market area B. The TSO is a regulated entity which is allowed to apply a tariff for transmitting gas between the two market areas. As in the case of the EU, the TSO offers LT and ST transmission capacity. The LT capacity product (C_{12}) covers both periods and the ST capacity products cover only a single period (i.e. C_1 in t_1 and C_2 in t_2). Traders need to book sufficient transmission capacity rights such that desired gas volumes can be transported to the costumers and the storages in market area B. Similarly to the EU with the regulation NC CAM, traders in our model are permitted to trade booked capacities in secondary capacity markets. As a consequence, in the given setting of perfect foresight, the sum of bookings of many individual traders would be identical to the booking of a single competitive trader

[10] Such an exemption is observed in several EU countries (e.g. Spain, Denmark and Austria) with the goal of inducing positive externalities such as reducing pipeline investment costs and increasing security of supply (ACER, 2019a). In other countries, storages are exempted by at least 50% due to NC TAR regulation; though, most countries apply higher exemptions (ENTSOG, 2019).

who faces the cumulative demand of these many traders.[11] Hence, the supply constraints, where demand in each period is satisfied with corresponding capacity bookings and storage utilisation, can be stated as follows:

$$C_{12} + C_1 \ \geq \ d_1 + S \tag{2}$$

$$C_{12} + C_2 \ \geq \ d_2 - S \tag{3}$$

The regulated tariff for a unit of LT capacity equals τ_c (with $\tau_c > 0$) per time period and is fixed for both periods. The total LT tariff which runs over both periods then becomes $2\,\tau_c$. The tariff for the ST capacity is similarly regulated and is set to $m\,\tau_c$. In reality, as regulated entities, TSOs set the entry-exit tariffs (corresponding to the LT tariff τ_c in our model) such that their expected revenues cover their costs, adjusting the tariffs each year as necessary.

In our main analysis, the effects of multipliers on the players' behaviour and welfare implications are derived analytically in a closed form. For that purpose, we keep τ_c fixed and assume τ_c to be sufficiently high such that the TSO covers its costs in a setting without multipliers ($m = 1$). Therefore, the TSO may generate additional surplus if multipliers are larger than 1 ($m > 1$). After having derived the equations describing the behaviour of the players, we analyse the effects of m when the transmission tariff is adjusted. This allows us to derive the effects of m in the more realistic setting where the TSO surplus is independent of m (see Section 3.4).

The model depicts a setting of perfect competition and consumers' demand is inelastic in the short-run. Hence, the optimal allocation under perfect competition is equivalent to the solution of the planner's problem of maximising welfare by minimising the total costs ($Cost^{Tot}$). Since the total costs are the sum of production costs ($Cost^{Pro}$), transportation costs ($Cost^{Tra}$), and storage costs ($Cost^{Sto}$), the minimisation problem can be expressed as follows:

$$\min Cost^{Tot} = Cost^{Pro} + Cost^{Tra} + Cost^{Sto} \tag{4}$$

[11] Due to the assumptions of perfect competition with perfect foresight, as well as the availability of sufficient transmission capacities and an efficient secondary capacity market, the traders in our model have no incentive to block capacities, as over-booking causes additional costs without additional benefits.

The production costs correspond to the integral of the price function $p_t(Q_t)$ with respect to production quantity Q_t:

$$
\begin{aligned}
Cost^{Pro} &= \int p_t(Q_t)\, dQ_t \\
&= Q_t\,(a + \frac{1}{2}\, b\, Q_t)
\end{aligned}
\tag{5}
$$

Since $d_2 > d_1$ and production costs are represented by a quadratic function of production volumes, it is inherently assumed that injection to storages occurs in t_1 and withdrawal occurs in t_2 to meet the higher demand. Zero storage losses are assumed; injection and withdrawal rates in both periods are the same and equal the stored volumes S. The aggregated gas procurement Q_t is then equal to $Q_1 = d_1 + S$ in t_1 and $Q_2 = d_2 - S$ in t_2. Substituting these into Equation 5, total production costs are obtained.

$$
Cost^{Pro} = a\,(d_1 + d_2) + \frac{1}{2}\left[b\,(d_1 + S)^2 + b\,(d_2 - S)^2\right] \tag{6}
$$

The storage costs correspond to the product of the stored gas volume S and the tariff for storing, τ_s:

$$
Cost^{Sto} = S\,\tau_s \tag{7}
$$

The costs for purchasing the capacity rights for transmission is equal to:

$$
Cost^{Tra} = \left[m\,(C_1 + C_2) + 2\,C_{12}\right]\tau_c \tag{8}
$$

Hence, the minimisation problem can be expressed as in Equation 9, subject to the constraints that demand needs to be satisfied in both periods and the non-negativity constraints discussed previously.

$$
\begin{aligned}
\min_{S,\,C_1,\,C_2,\,C_{12}} \; Cost^{Tot} &= a\,(d_1 + d_2) + \frac{1}{2}\left[b\,(d_1 + S)^2 + b\,(d_2 - S)^2\right] \\
&+ \left[m\,(C_1 + C_2) + 2\,C_{12}\right]\tau_c \\
&+ S\,\tau_s \\
s.t. \qquad C_{12} + C_1 \;&\geq\; d_1 + S \\
C_{12} + C_2 \;&\geq\; d_2 - S \\
C_{12},\; C_1,\; C_2,\; S \;&\geq\; 0
\end{aligned}
\tag{9}
$$

Assigning Lagrange multipliers $(\mu_1, \mu_2 ..., \mu_6)$ to the inequality constraints, the Lagrangian of the optimisation problem and the corresponding KKT conditions are obtained. The Lagrangian formulation and the KKT conditions can be found in Appendix A.

3. Results

3.1. Deriving the Effects on Infrastructure Utilisation

In this section, the solutions of the cost minimisation problem illustrated above are presented. We solve this convex optimisation problem by deriving the KKT conditions and finding the feasible KKT points, which provide us with analytic expressions of the analysed variables. Since the problem fulfils Slater's condition, the analysed KKT points are the optimal solutions of the optimisation problem.[12] As the effects of multipliers largely depend on whether they emphasise the commodity or the capacity pricing aspect, we divide our analysis into two subsections. The cases which, by design, correspond to a pure commodity pricing or conversely to pure capacity regime are considered separately from the cases that occur under a mixed-pricing policy—which are more common in reality and comprise more complex effects.

3.1.1. Pure commodity pricing ($m \leq 1$) or pure capacity pricing ($m \geq 2$)

As multipliers determine the relative price of ST capacities with respect to LT capacity, the outcomes of a pure commodity or capacity pricing regime can arise depending on the level of multipliers. For the case of our two-period model, these instances are shown in Proposition 3.1.

Proposition 3.1. *Multipliers $m \leq 1$ correspond to a pure commodity pricing regime, whereas multipliers $m \geq 2$ correspond to a pure capacity pricing regime.*

Proof. If $m \leq 1$, there exists no demand pattern where booking LT capacity is cheaper than booking ST capacity products. Therefore, the LT product is ignored and only ST capacities are booked. This corresponds to traders being charged for the actual transported volumes. Hence, the behaviour is the same as in a pure commodity pricing regime. If storage tariffs are sufficiently low ($\tau_s < 2b(d_2 - d_1)$), then traders also use storages to meet the demand in the peak period. Else ($\tau_s \geq 2b(d_2 - d_1)$), the demand is met only by booking the ST products at each period, where the transported volumes exactly correspond to the respective demand in each period (d_1 in t_1 and d_2 in t_2). See Appendix B Case 1 (a) for the detailed proof.

If $m \geq 2$, there exists no demand pattern where booking ST capacities is cheaper than booking LT capacity. Hence, only the LT product is booked, inducing the same behaviour seen in a pure capacity pricing regime. Whether gas transmission is aligned between the periods or capacity rights are wasted depends on the ratio of storage tariff to transmission tariff levels: If the relative costs of storage with respect to transmission costs are sufficiently low ($\tau_s \leq 2\tau_c$), storage utilisation aligns transports completely such that the LT capacity is fully utilised. If the storage costs are comparatively high ($\tau_s > 2\tau_c$), the booked LT capacity in off-peak period is underutilised, i.e. some capacity is wasted: Under this condition, if $\tau_s < 2\tau_c + 2b(d_2 - d_1)$, storages align transports partially. In the case that $\tau_s \geq 2\tau_c + 2b(d_2 - d_1)$, storage utilisation is zero. See Appendix B Case 4 (c) for the detailed proof. □

[12] To ensure that no optimal solution is omitted, an extensive analysis of all the possible cases including the non-optimal points are presented in Appendix B.

For $m = 1$, traders' costs are the same as in a pure commodity tariff regime; namely, overall transported volumes determine the traders' transport costs. Further reductions in the multiplier do not change the optimisation rationale of the traders and welfare. For this reason, and since the EU regulation NC TAR 2017 also does not allow for multipliers below 1, the minimum multiplier value considered in the analysis of this paper is $m = 1$.

The multiplier threshold that corresponds to a pure capacity pricing regime equals to LT product duration expressed in terms of number of ST products. As our model has two time periods, this threshold is found to be equal to 2, as shown in Proposition 3.1. For such multipliers, we find that capacity wasting occurs if gas transports do not align in t_1 and t_2. Thereby, Proposition 3.1 implies that even in a market with perfect foresight, perfect competition, and secondary trading of capacity at no cost, some capacity rights may remain unused with high multipliers if capacity demand is inelastic due to comparatively high storage tariffs or when no storage capacities exist. Increasing multipliers above 2 does not affect the results, as traders do not procure ST capacity, where multipliers are applied. Hence, the highest multiplier considered in this paper is $m = 2$. In the EU, such multipliers, which by design correspond to pure capacity pricing , are ruled out with Regulation NC TAR 2017 as the EU aims to allow for and encourage ST capacity bookings.[13]

3.1.2. Mixed-pricing regime ($1 < m < 2$)

In most EU countries, the range of applied multipliers facilitates traders to consider both long-term and short-term bookings, allowing for an inherent mixed-pricing regime in which capacity and commodity pricing effects are simultaneously present. In our model, this range of multipliers corresponds to $1 < m < 2$.

In the following propositions we present how multipliers influence the capacity booking as well as storage decision and we relate the market outcomes to the regimes of capacity and commodity pricing. We identify specific thresholds for m that affect how changes in m influence the system. We define the lower threshold as $\underline{m}$ and the upper threshold as $\overline{m}$, which then constitute three domains. Despite the inherent mixed-pricing regime, we identify two domains ($m \leq \underline{m}$ and $m \geq \overline{m}$) where the capacity demand is inelastic due to underlying tariff structures. In these domains, the capacity demand in the off-peak and peak periods, and the proportion of LT to ST bookings, are independent of the multiplier. The third domain corresponds to the case with elastic capacity demand ($\underline{m} < m < \overline{m}$) which is representative of the majority of the actual situations observed in the EU gas system.

[13]The multiplier threshold in the actual EU tariff structure would be equal to 12 between the yearly and monthly products, for instance, or equal to 4 between the yearly and quarterly products. As multipliers are required to be below 3, feasible multipliers are sufficiently low to incentivise ST bookings when storage tariffs are low.

Proposition 3.2. *If $m \geq 1$, but sufficiently small ($m \leq \underline{m} = 1 + \frac{\tau_s}{2\,\tau_c} - \frac{b}{\tau_c}\,(d_2 - d_1)$) storages are not utilised, LT capacity is booked to cover the demand in t_1, and the remaining demand in the peak period t_2 is met with the ST product. The proportion of ST to LT bookings is independent of m. The capacity booking and storage volumes are:*

$$\begin{aligned} C_1 &= 0 \\ C_2 &= d_2 - d_1 \\ C_{12} &= d_1 \\ S &= 0 \end{aligned} \tag{10}$$

Proof. See Case 5 (a) i. in Appendix B for the proof. □

Proposition 3.2 indicates that multipliers which are sufficiently low with respect to the ratio of storage to transmission tariffs can result in demand in peak periods to be exclusively met by ST capacities rather than storage withdrawals. The reason for that can be clearly seen by rewriting the $m \leq \underline{m}$ condition as $b\,(d_2 - d_1) + m\,\tau_c \leq \tau_c + \frac{\tau_s}{2}$. In this domain, meeting the additional demand in t_2 by procuring the additional volumes in t_2, and correspondingly booking ST capacity, is cheaper than the combined cost of booking LT capacity and storage utilisation. As a result, storages are not utilised and transported volumes in t_1 and t_2 exactly equal the demand d_1 and d_2. Hence, the capacity demand in the two periods remains independent of the multiplier; i.e. capacity demand is inelastic. Given that ratios of base transmission to storage tariffs allow for $m \leq \underline{m}$, network utilisation is the same as if pure commodity pricing ($m \leq 1$) is applied. This domain can appear in reality in the presence of low multipliers if storage tariffs are comparatively high or if no storage capacities exist.

Proposition 3.3. *If $m \leq 2$, but is sufficiently large ($m \geq \overline{m} = 1 + \frac{\tau_s}{2\tau_c}$), traders book LT capacity only and transport the same volumes in t_1 and t_2. The proportion of ST to LT bookings is independent of m. The capacity booking and storage volumes are:*

$$\begin{aligned} C_1 &= 0 \\ C_2 &= 0 \\ C_{12} &= \frac{d_2 + d_1}{2} \\ S &= \frac{d_2 - d_1}{2} \end{aligned} \tag{11}$$

Proof. See Case 4 (a) in Appendix B for the proof. □

Proposition 3.3 shows that even in situations where m is set to levels, which theoretically allow for ST bookings in the optimum ($m < 2$), ST bookings may not necessarily be part of the optimal solution. This occurs when m is high in comparison to the ratio of storage to transmission tariff such that ST capacities cost more than the combined cost of LT capacity and storage. This can be clearly seen by rewriting the $m \geq \overline{m}$ condition as $m\,\tau_c \geq \tau_c + \frac{\tau_s}{2}$. As a result, the capacity demand is met by booking only LT capacity and using storages. Since transports in both periods align, and consequently there is no potential to shift capacity demand from the peak period to the off-peak period, capacity demand is inelastic. As traders do not procure ST capacity, market outcomes for such multipliers ($m \geq \overline{m}$) are the same as if no ST capacity would be offered; namely, as in a pure capacity pricing regime similar to the one that was in place in the EU before the introduction of NC CAM 2013.

Proposition 3.4. *If $1 \leq m \leq 2$ and $\underline{m} < m < \overline{m}$, the traders book LT capacity to cover the base load and ST capacity C_2 to cover the additional demand in the peak period (t_2). Traders utilise gas storages. The proportion of ST to LT bookings depends on m. The capacity booking and storage volumes are:*

$$\begin{aligned} C_1 &= 0 \\ C_2 &= \frac{\tau_s}{2b} - \frac{\tau_c(m-1)}{b} \\ C_{12} &= \frac{d_2 + d_1}{2} - \frac{\tau_s}{4b} + \frac{\tau_c(m-1)}{2b} \\ S &= \frac{d_2 - d_1}{2} - \frac{\tau_s}{4b} + \frac{\tau_c(m-1)}{2b} \end{aligned} \tag{12}$$

Proof. See Case 5 (a) ii. in Appendix B for the proof.

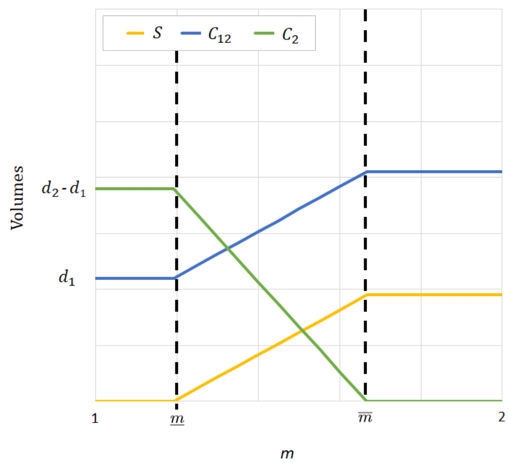
□

Proposition 3.4 shows the results for multipliers, which lie in the domain of moderate multipliers with respect to the ratio of storage to transmission tariffs. The results represent the only solution where the following three aspects occur simultaneously: Both LT and ST capacity are booked, and storages are utilised to satisfy the demand in the peak-period. This corresponds to a situation which can be observed in the EU for most countries. In this domain, the capacity demand is elastic since the capacity demand shifts from peak to off-peak period with increasing multipliers. With increasing m, ST capacity bookings are replaced with LT capacity booking and storage withdrawals. The extent of the effects of an increase in m for the domain $\underline{m} < m < \overline{m}$ can be obtained by taking partial derivatives with respect to m. Thus, an increase in m increases LT bookings by $\frac{\tau_c}{2b}$, decreases ST bookings by $\frac{\tau_c}{b}$, and increases the demand for storage by $\frac{\tau_c}{2b}$.

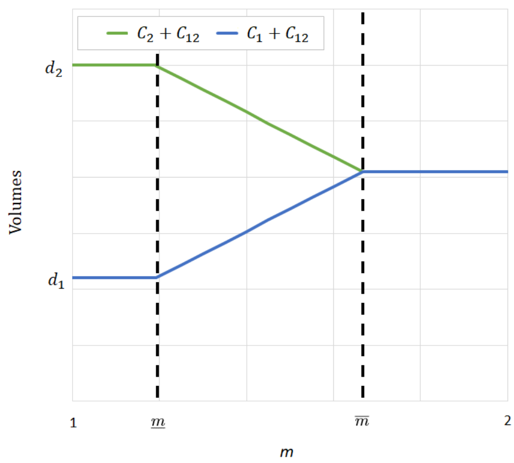
It can be seen that Propositions 3.2 and 3.4 include $m = 1$, the multiplier level that induces the same behaviour as in a pure commodity pricing regime (see Proposition 3.1). This is because for $m = 1$, traders are indifferent between solely procuring ST capacity, or rather booking LT capacity for the base load and ST capacity for the peak load.[14] The same holds for $m = 2$, the multiplier inducing the behaviour seen in a pure capacity pricing regime (see Proposition 3.1). A multiplier of 2 is valid in Propositions 3.3 and 3.4.

[14]A proof can be found in Appendix A Case 3a.

This is because for $m = 2$, traders are indifferent between booking solely LT capacity, or rather procuring LT capacity to meet the base load and ST capacity for the peak load.[15] Therefore, the resulting dispatch and the ensuing welfare are not affected by the choices in these cases. This allows us to analyse the effects of the multipliers that induce a pure commodity and capacity regime behaviour by design (i.e. $m = 1$ and $m = 2$, respectively) in the remainder of the analysis without incorporating separate formulas for such multipliers. Thus, for $1 < m < 2$, the identified KKT points in the Propositions 3.2, 3.3 and 3.4 are unique optimal solutions, which allow for a mixed-pricing regime.



(a) Booking and storage volumes



(b) Transported volumes

Figure 2: Development of the volumes for storage, ST capacity and LT capacity with respect to the multiplier (a); and development of transported volumes at time periods t_1 and t_2 with respect to the multiplier (b)

In Figure 2a we illustrate the findings of Propositions 3.2, 3.3 and 3.4 by plotting the traders' booking and storage decision with respect to m. To be able to illustrate the results for all three identified domains, a setting is chosen in which feasible $\underline{m}$ as well as $\overline{m}$ exist (i.e. $\underline{m} > 1$ and $\overline{m} < 2$). This applies to all the figures in this paper, in which the effects are plotted for the respective multiplier domains. However, it should be noted that, depending on tariff levels, feasible $\underline{m}$ as well as $\overline{m}$ may not exist. In that case, storages would be utilised and transports would differ also for $m = 1$ as well as for $m = 2$.

Figure 2b shows the transported volumes, which are equal to the sum of booked capacities in each period (i.e. $C_{12} + C_1$ in t_1 and $C_{12} + C_2$ in t_2). While the overall transported volume remains unaffected by m, the temporal spread of the transports, which can be interpreted as an indicator for transport volatility, decreases with m. In the multiplier range $m > \overline{m}$, the same amount of volumes are transported

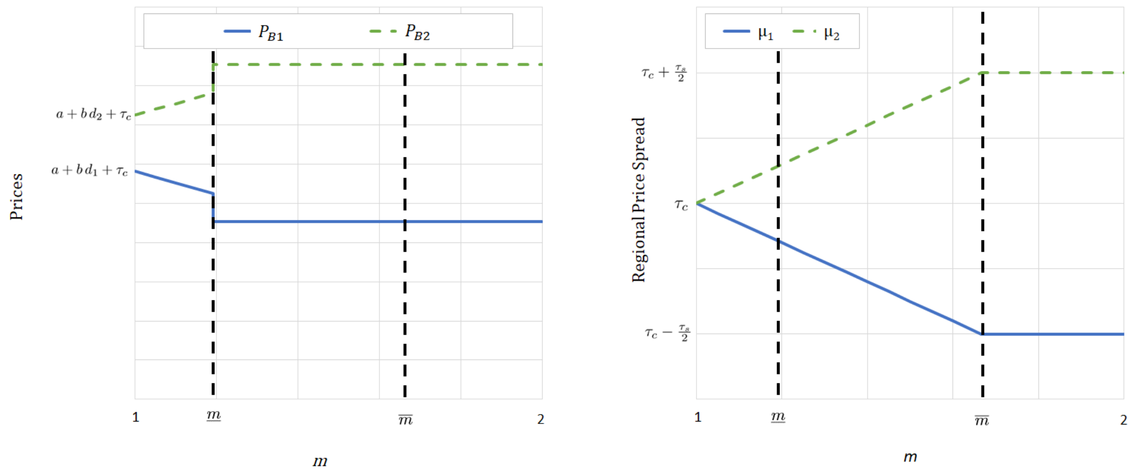
[15] A proof can be found in Appendix A Case 5c.

in both periods.

3.2. Deriving the Effects on Prices and Price Spreads

In a next step we derive the hub prices. In the analysed setting of perfect competition, prices correspond to the marginal cost of supply with respect to demand. Therefore, to obtain the prices in the demand region[16], we insert the solutions derived in the Propositions 3.2, 3.3, and 3.4 in the total cost function shown in Equation 9, and differentiate with respect to d_1 and d_2.

$$
\begin{aligned}
P_{B1} &= \frac{\partial Cost^{Tot}}{\partial d_1} = \begin{cases} a + b\,d_1 + (2-m)\,\tau_c & \text{for } m \leq \underline{m} \\ a + b\left(\dfrac{d_1+d_2}{2}\right) + \tau_c - \dfrac{\tau_s}{2} & \text{for } m > \underline{m} \end{cases} \\
P_{B2} &= \frac{\partial Cost^{Tot}}{\partial d_2} = \begin{cases} a + b\,d_2 + m\,\tau_c & \text{for } m \leq \underline{m} \\ a + b\left(\dfrac{d_1+d_2}{2}\right) + \tau_c + \dfrac{\tau_s}{2} & \text{for } m > \underline{m} \end{cases}
\end{aligned}
\tag{13}
$$



(a) Prices **(b)** Regional Price Spreads

Figure 3: Development of the hub prices in region B (a) and the regional price spread between regions A and B (b), at time period t_1 and t_2 with respect to the multiplier

The functions describing the consumer prices in the demand region are plotted in Figure 3a. For the domain $m < \overline{m}$, in which the traders do not use storages and their capacity demand is inelastic, the price in peak period (P_{B2}) increases. This occurs as marginal demand is transported using additional ST capacity whose price increases in m. Conversely, the price in off-peak period (P_{B1}) decreases as additional demand

[16] Our analysis does not focus on the prices in production regions. For the sake of completeness, we derive the prices in the production region A in Appendix C.

is met by a shift from ST to LT capacity in this period. Such a reallocation of network costs from off-peak users towards peak consumers is in line with the concept of peak-load pricing.

In the domain $\underline{m} < m < \overline{m}$, the traders were shown to have elastic capacity demand, meaning that they are able to switch from ST to LT capacities with increasing m by using storages. The prices in this case remain constant over m which may seem counter-intuitive since ST transmission tariffs increase in m. However, this is due to additional demand being met by an increase in LT capacity booking and storage usage while ST capacity bookings remain unchanged. This applies to both d_1 and d_2, resulting in consumer prices (P_{B1} and P_{B2}) to be independent of m. In line with the findings of Nguyen (1976), we also show here that the peak price exceeds the off-peak price by the cost of storage (i.e. $P_{B2} - P_{B1} = \tau_s$). In the domain of $m \geq \overline{m}$, despite the inelastic capacity demand, prices are unaffected by changes in m. This is due to the absence of ST bookings and the utilisation of storages. Furthermore, the temporal price spread here is also set by storages.

Interpreting the temporal price spread as price volatility, it can be said that higher multipliers can cause increased volatility in hub prices unless storages are utilised—which requires enough storage capacities to be available and that storage tariffs are sufficiently low compared to transmission tariffs.

In contrast, we find the average hub price to be constant and independent of the multiplier. The average hub price is equal to the gas procurement price that arises when volumes are bought evenly in both periods, plus the base transmission tariff:

$$\frac{P_{B1} + P_{B2}}{2} = a + b\left(\frac{d_1 + d_2}{2}\right) + \tau_c \tag{14}$$

The regional price spreads between the modelled regions A and B correspond to the Lagrange multipliers[17] μ_1 and μ_2, for the time periods t_1 and t_2, respectively. As derived in Case 5 (a) in Appendix B, those spreads are presented in Equation 15 and are plotted in Figure 3b for the corresponding multiplier domains.

$$\begin{aligned} P_{B1} - P_{A1} = \mu_1 &= \begin{cases} \tau_c\,(2 - m) & \text{for } m < \overline{m} \\ \tau_c - \dfrac{\tau_s}{2} & \text{for } m \geq \overline{m} \end{cases} \\ P_{B2} - P_{A2} = \mu_2 &= \begin{cases} m\,\tau_c & \text{for } m < \overline{m} \\ \tau_c + \dfrac{\tau_s}{2} & \text{for } m \geq \overline{m} \end{cases} \end{aligned} \tag{15}$$

[17] Alternatively, regional price spreads can be derived by subtracting the prices in regions A and B.

Results indicate that multipliers cause temporal variation in regional spreads: In the peak period, additional transport demand is met by procuring ST capacity, resulting in a price spread of $m\,\tau_c$. In contrast, additional transport demand in the off-peak period is met by replacing ST capacity with LT capacity, inducing regional spreads of $\tau_c\ (2-m)$. Thus, higher multipliers lead to the widening of the temporal price margin of regional spreads. In sum, the effects in the two periods cancel each other out, such that average regional price spreads remain constant over m.

On the other hand, regional spreads in the domain with pure capacity pricing behaviour ($m \geq \overline{m}$) are found to be independent of the multiplier. As the same volumes are transported in both periods (due to only LT product being booked with storage utilisation), the regional spreads in this case are defined by the storage tariff and are constant. Nevertheless, since the majority of real situations in the EU are expected to correspond to mixed-pricing regimes, our results indicate that higher multipliers are likely to cause increased volatility in regional price spreads.

3.3. Deriving the Effects on Surpluses and Welfare

Having illustrated the impacts of multipliers on prices and price spreads, we now proceed with the analysis of the effects on the surplus of consumers, gas producers, the TSO and the traders as well as on the resulting welfare.

Consumer surplus

To allow for a clear illustration of welfare effects we assume the consumer surplus of base-load and peak-load consumers[18] to be zero for the range of multipliers which result in the highest costs for those consumers. As a result, consumer surplus is obtained as a function of the multiplier, corresponding to the difference between this threshold and the respective consumer costs. The respective consumer surpluses can be expressed as follows:

$$
\begin{aligned}
&Surplus\ of\ base\text{-}load\ consumers = 0 \\
&Surplus\ of\ peak\text{-}load\ consumers = \begin{cases} \frac{1}{2}\,(d_2-d_1)\left(\tau_s - 2\,\tau_c\,(m-1) - b\,(d_2-d_1)\right) & \text{for } m \leq \underline{m} \\ 0 & \text{for } m > \underline{m} \end{cases}
\end{aligned} \tag{16}
$$

In Figure 4, which plots the derived surplus and welfare functions of the respective agents in the model, the development of consumer surplus in the identified multiplier domains can be seen. Base-load consumers

[18] Remember, consumers are assumed to be divided into two groups: Base-load consumers with a flat demand equal to d_1 in both periods and peak-load consumers who consume $d_2 - d_1$ in t_2.

do not earn a surplus with increasing m since their overall costs are not affected by m due to the average prices being constant and their demand being inelastic. For peak-load consumers, in contrast, total costs depend on m as more gas is bought in t_2 than in t_1. Therefore, when prices in t_2 increase and prices in t_1 decrease with the same magnitude, despite the average price remaining constant, overall consumer costs increase. Hence, when P_{B2} is highest (i.e. $m > \underline{m}$) consumers do not earn any surplus. Consumer surplus is greatest, when P_{B2} is lowest (i.e. $m = 1$).

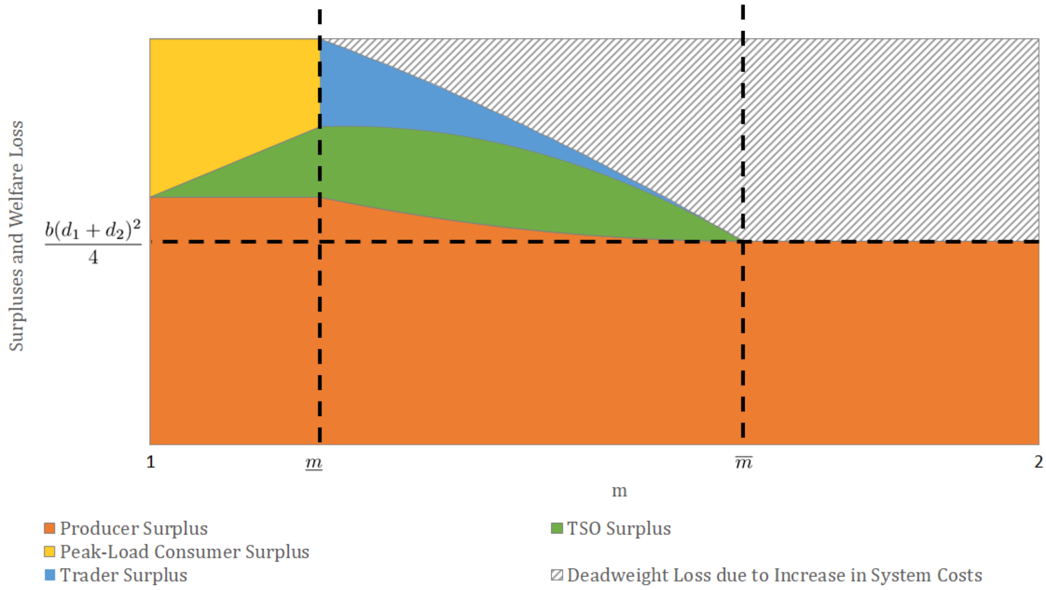


Figure 4: Producer, trader, consumer and TSO surpluses, and deadweight loss with respect to m

Producer Surplus

Producers earn a surplus by selling their gas for a price which is higher than their marginal costs. Producer surplus occurs since marginal costs increase in procured volumes in the model setting, which is representative of the real cost structures for the producers. The resulting surplus thus equals:

$$Producer\ Surplus = \begin{cases} \frac{b\left(d_1^2 + d_2^2\right)}{2} & \text{for } m \leq \underline{m} \\ \frac{b\left(d_1 + d_2\right)^2}{4} + \frac{\left(2\tau_c\left(m-1\right) - \tau_s\right)^2}{16b} & \text{for } \underline{m} < m < \overline{m} \\ \frac{b\left(d_1 + d_2\right)^2}{4} & \text{for } m \geq \overline{m} \end{cases} \tag{17}$$

Producer surplus is highest when $m < \underline{m}$ and lowest for $m \geq \overline{m}$. For multipliers lying in the interval $\underline{m} < m < \overline{m}$, producer surplus decreases with m. This is because profits depend exponentially on sold volumes per period, and as such, producer surplus decreases as sold volumes in t_1 and t_2 converge to the same value.

TSO surplus

The TSO receives revenues from the capacity products booked by the traders. We assume the TSO's revenues to be sufficient to cover costs in a setting without multipliers (i.e. $m = 1$) and any increase in the multiplier level can therefore result in surplus revenues. The resulting surplus can then be expressed as follows:

$$TSO\ surplus = \begin{cases} \tau_c\,(d_2 - d_1)\,(m-1) & \text{for } m \leq \underline{m} \\ \dfrac{\tau_c\,\tau_s\,(m-1)}{2b} - \dfrac{\tau_c^2\,(m-1)^2}{b} & \text{for } \underline{m} < m < \overline{m} \\ 0 & \text{for } m \geq \overline{m} \end{cases} \tag{18}$$

When $m = 1$ or when solely LT capacities are booked, i.e. $m \geq \overline{m}$, the TSO does not earn a surplus. Between those thresholds, the TSO surplus follows a concave form and reaches its maximum at $m = 1 + \frac{\tau_s}{\tau_c}$, as can be seen in Figure 4. The path of the surplus function is based on the combination of two effects: Firstly, the TSO's income increases with increasing m directly due to ST capacity becoming more expensive—an effect that exists for all $m > 1$. Secondly, as traders increasingly shift their bookings from ST to LT capacity with increasing m, the additional revenue generated by the TSO due to more expensive ST capacities is reduced. This effect emerges when m reaches $\underline{m}$, as the storages become utilised and switches from ST to LT booking start to take place. For $m < 1 + \frac{\tau_s}{\tau_c}$, the first effect is more dominant; while for larger values of m, the second effect dominates.

Storage operator surplus

Storage operators do not earn any surplus under perfect competition as they are assumed to have constant marginal costs.

Trader surplus

Surplus of the traders equals the difference of consumer prices and costs of gas provision (i.e. sum of procurement, transport and storage) which is equal to:

$$Trader\ surplus = \begin{cases} \dfrac{\big(\tau_s - 2\,\tau_c\,(m-1)\big)^2}{8\,b} & \text{for } \underline{m} < m < \overline{m} \\ 0 & \text{otherwise} \end{cases} \tag{19}$$

Traders start making surplus when the multipliers cross the $\underline{m}$ threshold. This is because storages become part of the optimal solution. The utilisation of storages creates markups of $\frac{\tau_s}{2}$ in the peak period (t_2) and markdowns of $\frac{\tau_s}{2}$ in the off-peak period (t_1). Since sold volumes in t_2 are higher, a profit is generated. However, as storage utilisation increases with increasing m, this results in higher storage costs and subsequently diminished profits. Traders also bear the additional ST capacity costs arising from increased multipliers, which further reduce the trader surplus.

Welfare

Having derived the individual surplus functions of all the relevant agents of the model, we now derive the total welfare function. Total welfare corresponds to the sum of consumer, producer, TSO, and trader surplus. This equals:

$$Welfare = \begin{cases} \frac{(d_2 - d_1)\,\tau_s}{2} + b\left(d_1\, d_2\right) & \text{for } m \leq \underline{m} \\ \frac{b\,(d_1 + d_2)^2}{4} + \frac{(\tau_s - 2(m-1)\,\tau_c)(3\tau_s + 2(m-1)\,\tau_c)}{16\,b} & \text{for } \underline{m} < m < \overline{m} \\ \frac{b\,(d_1 + d_2)^2}{4} & \text{for } m \geq \underline{m} \end{cases} \tag{20}$$

Welfare is maximal when the gas dispatch is not distorted by transmission tariffs. In our model with inelastic consumer demand, efficient outcomes with maximal welfare are achieved for $m < \underline{m}$ in the case where $\underline{m} \geq 1$ (plotted in Figure 4), or for $m = 1$ if $\underline{m}$ does not exist in the feasible multiplier domain (plotted in Figure D.8 in Appendix D).[19]

As soon as $m > \underline{m}$, higher multipliers reduce welfare by causing additional costs, which occurs as a result of two opposing effects: On the one hand, since the total production cost function is quadratic, total costs of gas production decrease as gas is produced more evenly. On the other hand, total costs of storing gas increase. However, as the increase in storage costs is higher than the decrease in production costs, welfare declines with increasing m. Welfare becomes independent of the multiplier when the multiplier reaches the threshold $\overline{m}$ as gas production in t_1 and t_2 fully converges.

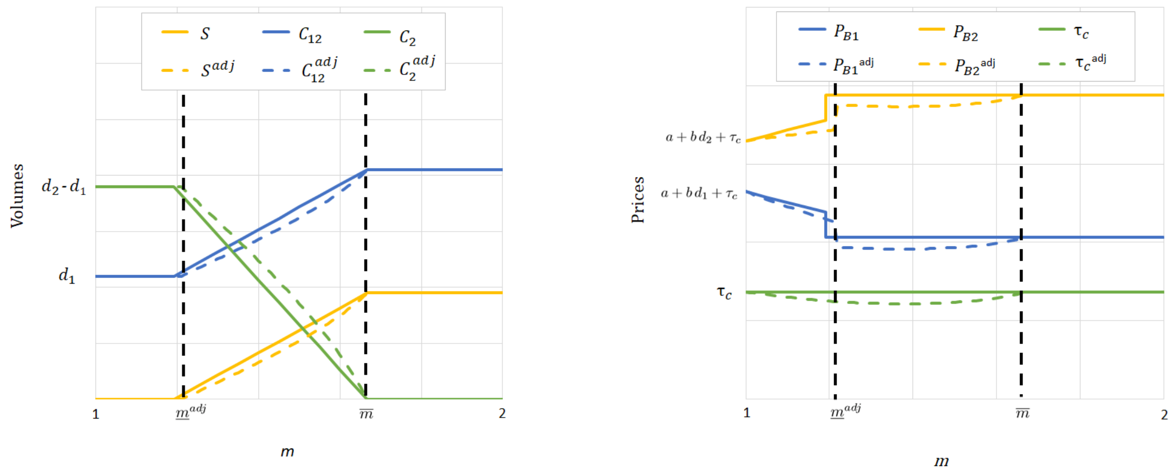
3.4. The regulated TSO: Transmission Tariff Adjustment

We have shown that the TSO makes a surplus as long as $m > 1$ and the traders book ST capacity when $m < \overline{m}$. In reality, being natural monopolies, TSOs are regulated entities and are not allowed to exceed certain revenue caps. Hence, in the case of a potential surplus due to multipliers, the TSO would have to lower its transmission tariffs (i.e. entry/exit tariffs) accordingly for the next year in order to remain at the regulated revenue cap. In this model extension, we consider this aspect by introducing the adjusted

[19] According to economic theory, when consumers' demand is elastic, variable transmission tariffs to cover fixed network costs reduce welfare since they reduce consumers' demand. Such variable costs arise in the entry-exit system independent of the level of multipliers. To achieve more efficient outcomes in the presence of elastic demand, other tariff regimes (e.g. fixed grid fees) may be more appropriate (Borenstein, 2016).

transmission tariff τ_c^{adj} which is set such that the TSO surplus is zero for all m. Since τ_c^{adj} is only a parameter for the agents of our model and does not change the nature of the problem; the optimisation rationale of the agents remains the same as in our main model.

We find that the results with adjusted transmission tariff τ_c^{adj} are similar to the model results with fixed τ_c. All the general findings regarding the effect of m on volumes and prices and price spreads remain intact. The lowered τ_c^{adj} slightly increases $\underline{m}$, the multiplier threshold which is sufficient to incentivise the use of storages. The upper threshold $\overline{m}$ remains unchanged. We define this adjusted threshold as $\underline{m}^{adj}$. Plotting the capacity and storage volumes resulting from adjusted tariffs in Figure 5a, we see that adjusting the transmission tariff also slightly increases ST capacity bookings, decreases LT bookings, and as a consequence, results in lower utilisation of storages for $\underline{m}^{adj} < m < \overline{m}$. New hub prices as a result of adjusted tariffs are plotted in Figure 5b. The average regional price spread still equals the transmission tariff. However, since τ_c^{adj} is lower than τ_c for $1 < m < \overline{m}$, tariff adjustment leads to lower average regional price spreads for $m > 1$. The price spreads are lowest for $m = 1 + \frac{\tau_s}{\tau_c^{adj}}$. Similarly, the lowered transmission tariff translates directly to lower gas consumer prices, hence the average prices are also lowest at $m = 1 + \frac{\tau_s}{\tau_c^{adj}}$.



(a) Volumes

(b) Prices and average regional price spread (τ_c^{adj})

Figure 5: Volumes and prices when τ_c is adjusted such that the TSO does not earn a surplus

The surpluses and welfare effects are plotted in Figure 6. When transmission tariffs are adjusted, the TSO does not earn a surplus anymore. The surpluses of traders and gas producer surplus are impacted very slightly. These effects result from the changes in the production pattern and storage volumes and not from a shift of the TSO's surplus. Instead, the tariff adjustment redistributes all of the surplus formerly earned by the TSO to the consumers. Base-load consumers, who did not earn any surplus when the tariff was fixed, earn a surplus with adjusted tariffs. In the domain $m < \underline{m}^{adj}$, the surplus of base-load consumers increases in m. In the domain $\underline{m}^{adj} < m < \overline{m}$, surpluses of both base-load and peak-load consumers increase in m for sufficiently low multiplier levels ($m < m^{CS,max}$) due to lower consumer prices resulting from decreased LT tariffs. This implies that if feasible $\underline{m}^{adj}$ does not exist due to tariff structures, a multiplier level equal to $m^{CS,max} = 1 + \frac{\tau_s}{\tau_c^{adj}}$ maximises the total consumer surplus (such a case is plotted in Appendix D). For $m > m^{CS,max}$, consumer surplus decreases with m due to increasing system costs. In the domain $m > \overline{m}$, consumer surplus is zero, which was also the case with fixed tariffs.

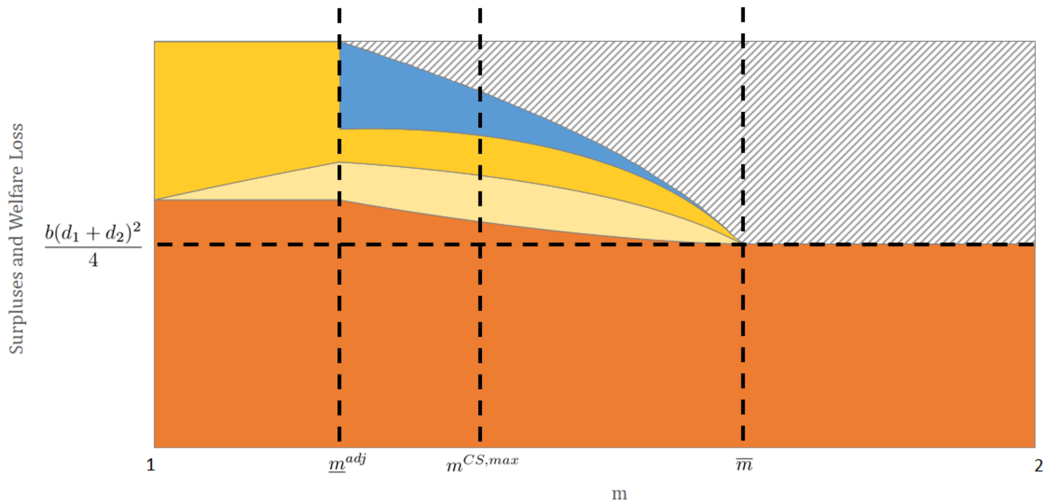


Figure 6: Producer, trader, consumer and TSO surpluses, and deadweight loss with respect to m when τ_c is adjusted such that the TSO does not earn a surplus

4. Discussion

4.1. Effects on Infrastructure Utilisation

Multipliers, by making ST products comparably more expensive, can cause a switch from ST capacities to LT capacities, decrease the volatility of pipeline transports and consequently lead to more uniform capacity utilisation. These aspects associated with higher multipliers have also been mentioned in several studies related to the EU tariff structures (Rüster et al., 2012; Strategy& and PwC, 2015; EY and REKK, 2018; ACER and CEER, 2019; DNV-GL, 2018). We also find that gas storages can have increased utilisation rates with higher multipliers. However, these effects are not universal and strongly depend on the underlying tariff structures, i.e. occurring only when multipliers are neither too high nor too low with respect to the ratio of storage to transmission tariffs such that the capacity demand of the traders is elastic, meaning that the traders can switch between LT and ST products.

The proportions of these tariffs and multipliers constitute the multiplier thresholds (i.e. $\underline{m}$ and $\overline{m}$), which define domains with varying effects of multipliers. We find that multipliers equal to 1 or lower than the threshold $\underline{m}$ result in users to behave as if in a pure commodity pricing regime, while multipliers larger than $\overline{m}$ induce the same behaviour as observed in a pure capacity tariff regime. When multipliers are in between $\underline{m}$ and $\overline{m}$ an inherent mixed regime of capacity and commodity pricing occurs.

The multiplier domains identified by the theoretical model can also be observed in the EU gas markets. Depending on the circumstances, multipliers in the EU can lie in each of the domains identified by the model, their magnitude corresponding to values smaller than $\underline{m}$, higher than $\overline{m}$ or to those that lie in between.

The domain $m < \underline{m}$, for instance, represents a situation where storages are not used. This would occur when marginal storage costs are sufficiently high compared to m. Further, cross-border transports in each period match the corresponding demand. An utmost example, in this regard, would be the case of Finland where there are no gas storages and all of the gas was imported only from a single source until recently[20]; namely, Russia (Jääskeläinen et al., 2018). This implies infinitely large storage tariffs ($\tau_s \to \infty$) for Finland, irrespective of the existing multiplier levels in the country. Hence, any multiplier lies below the lower threshold $\underline{m}$.

Situations corresponding to the domain $m > \overline{m}$, on the other hand, occur when the transported volumes are constant and storages fill the gap between the demand and the imports instead. This would be observed when transmission capacity tariffs are sufficiently high with respect to the multiplier. Such instances can arise for pipelines that are consistently operated at their full capacities as this indirectly corresponds to transmission tariffs being infinitely high for marginal capacity demand ($\tau_c \to \infty$). Hence, any $m > 1$ would already be larger than the upper threshold $\overline{m}$.

In the majority of situations including connections between market areas, both pipelines and storages are utilised and neither of the two operate at their full capacity. These situations correspond to the $\underline{m} < m < \overline{m}$ domain where an inherent mixed regime of capacity and commodity pricing occurs, and as a result, the transmission capacity demand of traders is elastic. This is also valid for countries that apply multipliers equal to 1, where both LT and ST capacities are booked and storages are utilised (this implies feasible $\underline{m}$ does not exist).[21]

[20] As of 1 January 2020, Finland is connected with Estonia via the Balticconnector pipeline (European Commission, 2020).

[21] A corresponding example is the case of Germany during the period 2012–2015 before the introduction of the BEATE regulation. More information can be found in the resolutions BK7-10-001 and BK9-14/608 of the German regulatory agency Bundesnetzagentur.

Even though we have implied here the possibility of directly observing those domains and their effects in the EU gas transmission system for various country pairs and pipelines, it is likely that a mixture of these effects would be prevalent in numerous regions. This is because all the analysed domains arise simultaneously within the EU and on its outer borders, and gas is often transported through several countries. On average, the aggregate effect on volumes, prices and, surpluses would likely be a combination of all of those domains for the EU.

4.2. Effects on Hub Prices

Regarding hub price levels in gas importing regions, model results have several implications: Temporal price spread increases with increasing m if storage utilisation is zero due to comparably high storage tariffs or unavailability of storage capacity (i.e. the domain $m \leq \underline{m}$). In such cases, higher multipliers can cause increased volatility in hub prices. In the case storages are utilised (i.e. the domain $m \geq \underline{m}$), then the storages dampen the effect on temporal price spreads.

Our analysis indicates that increasing multipliers can result in higher regional price spreads, since the upper limit of the spread is shown to be equal to the price of ST capacities ($m\,\tau_c$).[22] ACER refers to such a price spread ($m\,\tau_c$) as the "reference" regional spread (ACER, 2019a), implying that price spreads increase with increasing multipliers on average. In our model, in contrast, increases in spreads are only limited to temporal variations (i.e. increased volatility in spreads), while the average regional price spread remains equal to the transmission tariff (τ_c). This is because the marginal demand is satisfied by LT capacity. In reality, uncertainty as well as frictions in the secondary market for capacity may require the booking of ST capacity to satisfy marginal demand in some situations. As a result, average price spreads are likely to be between LT and ST capacity tariffs.

Whether multipliers increase or decrease regional price spreads also depends on the effect of multipliers on the LT tariff. In our model extension in Section 3.4, which takes into account transmission tariff adjustments by the TSO, we have shown that increases in m allow the TSO to reduce the tariff (τ_c^{adj}) if multipliers are sufficiently low ($m < \frac{\tau_s}{\tau_c^{adj}}$), an aspect also mentioned in several consulting studies (Strategy& and PwC, 2015; Rüster et al., 2012). Therefore, increases in m can both decrease average hub prices and average regional price spreads, which were shown to depend on the transmission tariff. This is an aspect, which studies such as ACER (2019a) and EY and REKK (2018) apparently do not consider when stating that increases in multipliers are likely to increase regional price spreads. By reducing LT tariffs, sufficiently high multipliers may also help support tariff stability by mitigating the tariff increase which is expected to occur

[22] Applies to uncongested pipelines.

when historical LT bookings expire (ACER, 2019a).[23] However, if policymakers set multipliers too high such that they discourage traders from booking ST capacities, we have shown that increasing m elevates the transmission tariff and prices.

4.3. Effects on Surpluses and Welfare

Model results show that the lowest total system costs and correspondingly the highest total welfare are associated with lower multipliers. This is because higher multipliers cause the gas dispatch to deviate from an ideal dispatch based on short-run marginal costs. Nevertheless, the notion that an increase in m always results in higher system costs and lower welfare does not universally apply, but is highly dependent on which domain the system lies in (i.e. the ratio of storage to transmission tariffs with respect to multipliers).

For the identified domain without storage utilisation ($m < \underline{m}$), an increase in m does not cause additional system costs and no consequent welfare losses, as the transported volumes are fixed and independent of m. Similarly, producer surplus remains constant due to fixed volumes. Because storage utilisation is zero in this domain, traders do not make any surplus as they cannot exploit the intertemporal arbitrage potential. Consumer surplus, on the other hand, decreases with increasing m and is passed on to the TSO as a surplus unless the transmission tariffs (τ_c) are adjusted. In the case where the tariffs are adjusted such that the TSO does not make surplus (i.e. no additional TSO revenue than the regulated amount), higher multipliers cause consumer surplus to be redistributed from peak-load consumers (i.e. households) to base-load consumers (i.e. industry). This finding is in line with the implications stated by Strategy& and PwC (2015) and DNV-GL (2018).

We have also shown that sufficiently high multipliers ($m > \overline{m}$) are associated with higher total system costs and lower total welfare. In this setting, the surpluses of the consumers, traders and the TSO are all zero while only the producers make a constant surplus.

In the domain where storages are utilised and both ST and LT products are booked ($\underline{m} < m < \overline{m}$)—a case which is likely to be present in the majority of EU countries—increasing m results in increased system costs and decreased welfare. Trader surplus exists in this domain. However, it decreases exponentially with increasing m as gains by intertemporal arbitrage are reduced due to higher storage utilisation and the respective convergence in gas prices in the production region. The same effect causes the producer surplus to decrease as well. This also offers an explanation why gas traders such as Uniper SE and Gazprom Export

[23] For instance, during the period 2016–2018, about 80% of the total capacity used by traders stemmed from existing LT bookings which were undertaken before ST capacities were introduced (ACER, 2019a), the majority having been booked upfront covering multiple years. As those old bookings start expiring during 2020–2030, the prevalent situation of overbooked capacities and the sunk costs associated with them will start disappearing such that the cost of new bookings will represent the actual opportunity costs (EY and REKK, 2018).

and gas producers such as Shell Energy request low multipliers in their statements during the multiplier consultations (BNetzA, 2019).

TSO makes surplus for $m > 1$ if the transmission tariff is not adjusted. For multipliers that are sufficiently low ($m < 1 + \frac{\tau_s}{\tau_c}$), the TSO surplus increases initially with increasing m due to the additional revenue from ST products. As TSOs may be able to retain at least some of this surplus, they have an incentive to request higher multipliers than traders and producers do. Something which can be observed in the consultation statements of TSOs such as Open Grid Europe, Bayernets, ONTRAS (BNetzA, 2019). When the transmission tariff is adjusted for zero TSO surplus, then the surplus is passed on to the consumers due to lower hub prices.

The results also indicate that for the domain where the capacity demand of traders is elastic and which is representative of the majority of the situations observed in the EU, there exists a multiplier larger than 1 that maximises consumer surplus (i.e. $m = 1 + \frac{\tau_s}{\tau_c^{adj}}$).

This presents us with an interesting trade-off: Minimising total system costs and maximising total welfare in the short-run requires setting the multiplier equal to 1. However, a policymaker willing to maximise consumer surplus would aim for a multiplier greater than 1 but sufficiently low. Furthermore, higher multipliers may enhance security of supply due to increased storage utilisation and potentially resulting in storage investments. Since higher multipliers are more in line with peak-load pricing, and thus help decrease the peak-load capacity demand, the policymaker may also prefer higher multipliers to reduce the need for capacity expansion and to increase long-term efficiency.

We should note that the assumption of perfectly efficient secondary markets is relevant when interpreting our model results regarding welfare. The importance of developed and liquid secondary capacity markets for efficient explicit auction mechanisms is highlighted in the literature (Kristiansen, 2007; Peŕez-Arriaga and Olmos, 2005; Oren et al., 1985). Secondary markets allow traders to exchange booked capacities, enabling them to adjust their commercial positions (Peŕez-Arriaga and Olmos, 2005) and balance their marginal benefits (Oren et al., 1985). Therefore, an imperfect secondary market can hinder the exchange of some booked LT capacities and can lead to instances of contractual congestion[24], even if sufficient technical capacity is available to meet the demand. In such a situation, some traders waste their capacity rights, whereas other traders, whilst having positive capacity demand, are not able to book capacities—a phenomenon that consequently results in underutilised pipelines and inefficient dispatch. As such, Hallack and Vazquez (2013) argues within the context of the EU entry-exit tariff

[24]Contractual congestion means a situation where the level of firm capacity demand exceeds the technical capacity of a pipeline.

system that secondary markets help relieve contractual congestion. We have shown that the ratio of LT bookings increases with increasing multipliers. Therefore, in the case where secondary markets for gas transmission capacities in the EU are not efficient, higher multipliers could cause additional welfare losses due to more frequent instances of contractual congestion, a view shared also in several technical reports (Rüster et al., 2012; Strategy& and PwC, 2015). Hence, in order to minimise those additional welfare losses, policymakers should further promote efficient secondary markets.

5. Conclusion

In this paper, we take a theoretical perspective on the effects of multipliers on gas infrastructure, hub prices and welfare. The model developed for this purpose depicts a setting of perfect competition and is solved analytically by minimising total costs using KKT conditions. The effects of multipliers are then derived from the various solutions to the problem.

Our model results indicate that higher multipliers can cause a switch from short-term (ST) transmission capacity bookings to long-term (LT) bookings, lead to more uniform pipeline transports, and increase gas storage utilisation. In the majority of countries and situations these findings are expected to hold. However, the effects are not universal and are found to depend on the traders' elasticity of capacity demand. Depending on the proportion of multipliers with respect to storage and transmission tariff levels, situations with inelastic capacity demand can arise. It is possible when multipliers are sufficiently low with respect to the tariffs, gas storages are not utilised in the context of capacity bookings. On the other hand, multipliers that are considerably high can cause only LT capacities to be booked.

Regarding the effects of multipliers on hub prices, we find that higher multipliers cause maximum regional price spreads to increase, indicating that they can result in increased volatility in regional price spreads. However, on average, we show that hub prices and regional price spreads can decrease with increasing multipliers, as long as multipliers remain sufficiently low. These effects occur since higher multipliers allow the TSO to lower the transmission tariffs.

Model results show that higher multipliers are associated with higher total system costs and consequently lower total welfare in the short-run. Despite that, for the identified multiplier domain, which is representative of the majority of the situations in the EU gas system, our results indicate that the multiplier maximising total consumer surplus is larger than 1.

Our findings have various policy implications: Setting the multipliers equal to 1 minimises total costs of gas dispatch and thereby maximises total welfare. However, if the aim of the policymakers is to maximise consumer surplus, then opting for multipliers that are greater than 1 but are still sufficiently low can help in achieving the desired outcome. Moreover, a multiplier greater than 1 would lead to redistributing the consumer surplus from peak-load consumers to base-load consumers, if that is desired. In that sense, higher multipliers can also help reduce peak load and therefore result in potential welfare gains in the long-term due to a decreased need for new capacity investments. Since we have shown that higher multipliers cause increased storage utilisation, it could be argued that setting multipliers sufficiently high can also contribute to security of supply by incentivising additional storage investments. Multipliers that are considerably high, however, increase regional price spreads and undermine market integration; and if sufficiently high, can cause only LT capacities to be booked, potentially impeding efficient gas dispatch.

We have shown that optimal level and thresholds for multipliers depend on the level of transmission and storage tariffs. Therefore, it is important to consider the existing tariff structures when setting multipliers. As the current EU tariff landscape has significant variation in tariff structures and levels, this implies a one-size-fits-all approach with a single uniform EU multiplier may not lead to optimal outcomes for individual countries. We therefore find it appropriate that EU regulation specifies the allowed multiplier levels in ranges and not in absolute values. Nevertheless, whether the specified range covers the optimal levels or is too restrictive remains to be researched.

In future work, the model can be applied in a real-world setting by incorporating more time periods and a realistic network structure representative of the EU gas transmission system. The extended model can be used to quantify the effects of multipliers with numerical simulations. This would allow to analyse the effects of regional variations in multiplier levels throughout the EU. An interesting aspect in this case would be to evaluate whether optimal multipliers for individual countries are also optimal for the overall EU system, or whether they cause negative externalities on other countries. Another possibility would be to extend the model by including stochasticity regarding capacity demand in order to represent the realistic situation of imperfect information and uncertainty.

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Appendix A. Formal representation of the theoretical model

The cost minimisation problem can be formulated as the Lagrangian $\mathcal{L}$ with the Lagrange multipliers $\mu_1, \mu_2, \mu_3, \mu_4, \mu_5, \mu_6$:

$$\begin{aligned}
&\mathcal{L}(S, C_1, C_2, C_{12}, \mu_1, \mu_2, ..., \mu_6) = \\
&a\,(d_1 + d_2) + \frac{1}{2}\left[b\,(d_1 + S)^2 + b\,(d_2 - S)^2\right] \\
&+\ \left[m\,(C_1 + C_2) + 2\,C_{12}\right]\tau_c \\
&+\ S\,\tau_s \\
&+ \mu_1\,(d_1 + S - C_{12} - C_1) \\
&+ \mu_2\,(d_2 - S - C_{12} - C_2) \\
&+ \mu_3\,(-S) + \mu_4\,(-C_1) + \mu_5\,(-C_2) + \mu_6\,(-C_{12}))
\end{aligned}$$

The Karush-Kuhn-Tucker (KKT) conditions that need to be fulfilled are as follows:

Stationarity conditions:

$$\frac{\partial \mathcal{L}}{\partial C_1} = m\,\tau_c - \mu_1 - \mu_4 = 0 \tag{A.1}$$

$$\frac{\partial \mathcal{L}}{\partial C_2} = m\,\tau_c - \mu_2 - \mu_5 = 0 \tag{A.2}$$

$$\frac{\partial \mathcal{L}}{\partial C_{12}} = 2\,\tau_c - \mu_1 - \mu_2 - \mu_6 = 0 \tag{A.3}$$

$$\frac{\partial \mathcal{L}}{\partial S} = \tau_s + 2\,b\,(d_1 + 2\,S - d_2) + \mu_1 - \mu_2 - \mu_3 = 0 \tag{A.4}$$

Dual feasibility and complementary slackness:

$$\mu_1\,(d_1 + S - C_{12} - C_1) = 0 \tag{A.5}$$

$$\mu_2\,(d_2 - S - C_{12} - C_2) = 0 \tag{A.6}$$

$$\mu_3\,S = 0 \tag{A.7}$$

$$\mu_4\,C_1 = 0 \tag{A.8}$$

$$\mu_5\,C_2 = 0 \tag{A.9}$$

$$\mu_6\,C_{12} = 0 \tag{A.10}$$

$$\mu_1,\ \mu_2,\ \mu_3,\ \mu_4,\ \mu_5,\ \mu_6\ \geq 0 \tag{A.11}$$

Primal feasibility:

$$C_{12} + C_1 \geq d_1 + S \tag{A.12}$$

$$C_{12} + C_2 \geq d_2 - S \tag{A.13}$$

$$S,\, C_1,\, C_2,\, C_{12} \;\geq 0. \tag{A.14}$$

Appendix B. KKT points

In order to find the optimal KKT points of the optimisation problem and identify the conditions under which they apply, we consider in this section all the realistically possible cases. Those cases correspond to the possible combinations of the Lagrange multipliers of the capacity bookings, C_1, C_2, and C_{12}. The combinations that cannot result in demand being satisfied at both time points, i.e. $(C_1 = C_2 = C_{12} = 0)$, $(C_1 = C_{12} = 0,\ C_2 > 0)$ and $(C_2 = C_{12} = 0,\ C_1 > 0)$, are ruled out. The remaining possible cases are as follows:

1. $C_1,\ C_2 > 0$ and $C_{12} = 0$ (i.e. $\mu_4 = \mu_5 = 0$ and $\mu_6 \geq 0$)
2. $C_1,\ C_{12} > 0$ and $C_2 = 0$ (i.e. $\mu_4 = \mu_6 = 0$ and $\mu_5 \geq 0$)
3. $C_1,\ C_2,\ C_{12} > 0$ (i.e. $\mu_4\,,\mu_5\,,\mu_6 = 0$)
4. $C_{12} > 0$ and $C_1,\ C_2 = 0$ (i.e. $\mu_6 = 0$ and $\mu_4,\ \mu_5 \geq 0$)
5. $C_2,\ C_{12} > 0$ and $C_1 = 0$ (i.e. $\mu_5 = \mu_6 = 0$ and $\mu_4 \geq 0$)

In addition to the main cases listed above, all four sub-cases arising from supply constraints (A.5) and (A.6) and their respective Lagrange multipliers μ_1 and μ_2 are considered. For clarity, the storage constraint (A.7) and its respective Lagrange multiplier, μ_3, if applicable, are considered within the four sub-cases.

1. **Case: $C_1,\ C_2 > 0$ and $C_{12} = 0$**

   This case corresponds to $\mu_4 = \mu_5 = 0$ and $\mu_6 \geq 0$. In order to obtain the conditions under which this case becomes valid, we need to go through the associated sub-cases.

   (a) Supply constraints are binding in t_1 and t_2 (i.e. $\mu_1 \geq 0,\ \mu_2 \geq 0$):

   From Equations A.1 and A.2 $\mu_1 = \mu_2 = m\,\tau_c$ is obtained. Substituting these into Equation A.3 yields:

$$\mu_6 = 2\,\tau_c\,(1 - m)$$

   Since $\mu_6 \geq 0$, the condition for the validity of this case is $m \leq 1$. We now consider two sub-cases where storage S is equal to zero or non-zero, i.e. $\mu_3 \geq 0$ or $\mu_3 = 0$, respectively.

   i. $S = 0$: From Equation A.4 with $\mu_1 = \mu_2 = m\,\tau_c$ and $S = 0$, we obtain:

$$\mu_3 = \tau_s + 2\,b\,(d_1 - d_2)$$

   Since $\mu_3 \geq 0$, the condition for the storage tariff becomes $\tau_s \geq 2\,b\,(d_2 - d_1)$.

From Equations A.5 and A.6 the optimal values for the capacity bookings are obtained:

$$C_1 = d_1$$

$$C_2 = d_2$$

ii. $S > 0$: From Equation A.4 with $\mu_1 = \mu_2 = m\,\tau_c$ and $\mu_3 = 0$, we obtain:

$$S = \frac{d_2 - d_1}{2} - \frac{\tau_s}{4\,b}$$

Since $S > 0$, the condition for the storage tariff becomes $\tau_s < 2\,b\,(d_2 - d_1)$. From Equations A.5 and A.6 the optimal values for the capacity bookings are obtained:

$$C_1 = \frac{d_1 + d_2}{2} - \frac{\tau_s}{4\,b}$$
$$C_2 = \frac{d_1 + d_2}{2} + \frac{\tau_s}{4\,b}$$

The results indicate that when $m \leq 1$ only ST capacity products (C_1 and C_2) are booked and LT product (C_{12}) is not booked. If the storage tariff is sufficiently low ($\tau_s < 2\,b\,(d_2 - d_1)$), then the traders utilise storages by booking and transporting more than the required demand in t_1 period ($C_1 > d_1$) and less than the demand in t_2 period ($C_2 < d_2$). However, if the storage tariff is sufficiently high ($\tau_s \geq 2\,b\,(d_2 - d_1)$), then the traders do not use storages and book in both periods the respective demand ($C_1 = d_1$, $C_2 = d_2$).

(b) Supply constraint is binding in t_1 but not in t_2 (i.e. $\mu_1 \geq 0$, $\mu_2 = 0$):

Substituting $\mu_2 = 0$ into Equation A.2 with $\mu_5 = 0$ yields $m\,\tau_c = 0$. Since by definition $m > 0$ and $\tau_c > 0$, this is not a valid case.

(c) Supply constraint is binding in t_2 but not in t_1 (i.e. $\mu_1 = 0$, $\mu_2 \geq 0$):

Substituting $\mu_1 = 0$ into Equation A.1 with $\mu_4 = 0$ yields $m\,\tau_c = 0$. Since by definition $m > 0$ and $\tau_c > 0$, this is not a valid case.

(d) Supply constraints are neither binding in t_1 nor in t_2 (i.e. $\mu_1 = 0$, $\mu_2 = 0$):

Substituting $\mu_1 = 0$ into Equation A.1 with $\mu_4 = 0$ yields $m\,\tau_c = 0$. Since by definition $m > 0$ and $\tau_c > 0$, this is not a valid case.

2. **Case: $C_1, C_{12} > 0$ and $C_2 = 0$**

This case corresponds to $\mu_4 = \mu_6 = 0$ and $\mu_5 \geq 0$. This case is possible for $m > 1$ only if $d_1 > d_2$. However, since by definition $d_2 > d_1$, this is not a valid case.

3. **Case: C_1, C_2, $C_{12} > 0$**

This case corresponds to $\mu_4 = \mu_5 = \mu_6 = 0$. In order to obtain the conditions under which this case becomes valid, we need to go through the associated sub-cases.

(a) Supply constraints are binding in t_1 and t_2 (i.e. $\mu_1 \geq 0$, $\mu_2 \geq 0$):

From Equations A.1 and A.2 $\mu_1 = \mu_2 = m\,\tau_c$ is obtained. Substituting these into Equation A.3 yields:

$$m = 1$$

We now consider two sub-cases where storage S is equal to zero or non-zero, i.e. $\mu_3 \geq 0$ or $\mu_3 = 0$.

i. $S = 0$: From Equation A.4 with $\mu_1 = \mu_2 = m\,\tau_c$ and $S = 0$, we obtain:

$$\mu_3 = \tau_s + 2\,b\,(d_1 - d_2)$$

Since $\mu_3 \geq 0$, the condition for the storage tariff becomes $\tau_s \geq 2\,b\,(d_2 - d_1)$.

By rearranging the condition for τ_s to obtain $d_2 - d_1 \leq \frac{\tau_s}{2\,b}$ and plugging into Equation A.5 subtracted from Equation A.6, we obtain:

$$C_2 - C_1 \leq \frac{\tau_s}{2\,b}$$

We do not obtain unique results for C_1, C_2, and C_{12}. Instead, all combinations of positive C_1, C_2, and C_{12} that fulfil the condition above in addition to the constraints stated in Equations A.12) and A.13 are KKT points and hence optimal solutions.

ii. $S > 0$: From Equation A.4 with $\mu_1 = \mu_2 = m\,\tau_c$ and $\mu_3 = 0$, we obtain:

$$S = \frac{d_2 - d_1}{2} - \frac{\tau_s}{4\,b}$$

Since $S > 0$, the condition for the storage tariff becomes $\tau_s < 2\,b\,(d_2 - d_1)$. By rearranging the condition for τ_s to obtain $d_2 - d_1 > \frac{\tau_s}{2\,b}$ and plugging into Equation A.5 subtracted from Equation A.6, we obtain:

$$C_2 - C_1 > \frac{\tau_s}{2\,b}$$

Again, we do not obtain unique results for C_1, C_2, and C_{12}. All combinations of positive C_1, C_2, and C_{12} that fulfil the condition above in addition to the constraints stated in Equations A.12 and A.13 are KKT points and hence optimal solutions.

(b) Supply constraint is binding in t_1 but not in t_2 (i.e. $\mu_1 \geq 0$, $\mu_2 = 0$):

Substituting $\mu_2 = 0$ into Equation A.2 with $\mu_5 = 0$ yields $m\,\tau_c = 0$. Since by definition $m > 0$ and $\tau_c > 0$, this is not a valid case.

(c) Supply constraint is binding in t_2 but not in t_1 (i.e. $\mu_1 = 0$, $\mu_2 \geq 0$):

Substituting $\mu_1 = 0$ into Equation A.1 with $\mu_4 = 0$ yields $m\,\tau_c = 0$. Since by definition $m > 0$ and $\tau_c > 0$, this is not a valid case.

(d) Supply constraints are neither binding in t_1 nor in t_2 (i.e. $\mu_1 = 0$, $\mu_2 = 0$):

Substituting $\mu_1 = 0$ into Equation A.1 with $\mu_4 = 0$ yields $m\,\tau_c = 0$. Since by definition $m > 0$ and $\tau_c > 0$, this is not a valid case.

4. **Case: $C_1 = C_2 = 0$ and $C_{12} > 0$**

This case corresponds to μ_4, $\mu_5 \geq 0$ and $\mu_6 = 0$. In order to obtain the conditions under which this case becomes valid, we need to go through the associated sub-cases.

(a) Supply constraints are binding in t_1 and t_2 (i.e. $\mu_1 \geq 0$, $\mu_2 \geq 0$):

From Equations *A.5* and *A.6* it follows that $S = \frac{d_2 - d_1}{2}$ and the corresponding Lagrange multiplier $\mu_3 = 0$. The value for the long-term capacity booking is also obtained as $C_{12} = \frac{d_2 + d_1}{2}$. Stationarity conditions then take the form:

$$m\,\tau_c - \mu_1 - \mu_4 = 0$$

$$m\,\tau_c - \mu_2 - \mu_5 = 0$$

$$2\,\tau_c - \mu_1 - \mu_2 = 0$$

$$\tau_s + \mu_1 - \mu_2 = 0$$

Solving the system of equations above yields the following results:

$$\mu_1 = \tau_c - \frac{\tau_s}{2}$$
$$\mu_2 = \tau_c + \frac{\tau_s}{2}$$
$$\mu_4 = \tau_c\,(m-1) + \frac{\tau_s}{2}$$
$$\mu_5 = \tau_c\,(m-1) - \frac{\tau_s}{2}$$

From the condition $\mu_1,\, \mu_2,\, \mu_4,\, \mu_5 \geq 0$ it follows:

$$2\,\tau_c \geq \tau_s$$
$$m \geq 1 + \frac{\tau_s}{2\,\tau_c}$$

To fulfil both equations simultaneously, $m \leq 2$ is required. This implies when multiplier is sufficiently high, but still below 2, and the storage tariff is sufficiently low, then the transported volumes align and only long-term capacity is booked.

(b) Supply constraint is binding in t_1 but not in t_2 (i.e. $\mu_1 \geq 0$, $\mu_2 = 0$):

In this case, the stationary conditions reduce to:

$$(m-2)\,\tau_c = \mu_4$$
$$m\,\tau_c = \mu_5$$
$$2\,\tau_c = \mu_1$$
$$\tau_s + 2\,b\,(d_1 + 2S - d_2) + 2\,\tau_c = \mu_3$$

So $m \geq 2$ since $\mu_4 \geq 0$.

In addition we get from Equations A.5 and A.9 that:

$$C_{12} = d_1 + S$$
$$S = \frac{d_1 - d_2}{2} - \frac{1}{2b}\,\tau_c - \frac{1}{4b}\,\tau_s$$

Substituting C_{12} into Equation A.13, we obtain:

$$S \geq \frac{d_2 - d_1}{2}$$

Substituting the previously obtained storage value into the inequality above yields:

$$0 \geq 2\tau_c + \tau_s.$$

This is not possible since $\tau_s,\, \tau_c > 0$. Hence, this case is not valid.

(c) Supply constraint is binding in t_2 but not in t_1 (i.e. $\mu_1 = 0$, $\mu_2 \geq 0$):

In this case, the stationary conditions reduce to:

$$m\,\tau_c = \mu_4$$

$$2\,\tau_c = \mu_2$$

$$(m-2)\,\tau_c = \mu_5$$

$$\tau_s + 2\,b\,(d_1 + 2S - d_2) - 2\,\tau_c = \mu_3$$

The case is valid for $m \geq 2$ since $\mu_5 \geq 0$.

We now consider two sub-cases where storage S is equal to zero or non-zero, i.e. $\mu_3 \geq 0$ or $\mu_3 = 0$:

i. $S = 0$: From Equations A.12 and A.13, and the assumption $d_2 > d_1$ we derive:

$$C_{12} = d_2$$

To ensure $\mu_3 \geq 0$ the following condition needs to hold:

$$\tau_s \geq 2\tau_c + 2b\,(d_2 - d_1)$$

It can be seen that in this case a portion of C_{12} equal to $d_2 - d_1$ is not utilised i.e. wasted in t_1.

ii. $S > 0$: In this case $\mu_3 = 0$.

Plugging the given information into Equations A.4 and A.6 allows to solve for S and C_{12}:

$$S = \frac{d_2 - d_1}{2} + \frac{1}{2b}\tau_c - \frac{1}{4b}\tau_s$$
$$C_{12} = \frac{d_2 + d_1}{2} - \frac{1}{2b}\tau_c + \frac{1}{4b}\tau_s$$

To ensure $S > 0$ and that the supply constraint as shown in Equation A.12 is satisfied, τ_s has to lie in the range between:

$$2\tau_c \leq \tau_s < 2\tau_c + 2b\,(d_2 - d_1)$$

If $\tau_s > 2\tau_c$, a portion of C_{12} equal to $\frac{\tau_s}{2\,b} - \frac{\tau_c}{b}$ is wasted in t_1. For $\tau_s = 2\tau_c$, this term becomes zero and thus transmissions in t_1 and t_2 align and no capacity booking is wasted.

The results indicate that under the condition $m \geq 2$ only LT capacity is booked for both periods. When the storage tariff is sufficiently high ($\tau_s > 2\,\tau_c$), storage utilisation is not sufficient to align transports in t_1 and t_2 such that some LT capacity is wasted in t_1. For $\tau_s = 2\,\tau_c$, transported volumes in both periods align, such that no LT capacity is wasted.

(d) Supply constraints are neither binding in t_1 nor in t_2 (i.e. $\mu_1 = 0$, $\mu_2 = 0$):

In this case the stationary conditions reduce to:

$$m\,\tau_c = \mu_4$$

$$m\,\tau_c = \mu_5$$

$$2\,\tau_c = 0$$

$$\tau_s + 2\,b\,(d_1 + 2\,S - d_2) = \mu_3$$

This is not a valid case since it yields $\tau_c = 0$, where by definition $\tau_c > 0$.

5. **Case: $C_1 = 0$ and C_2, $C_{12} > 0$**

This case corresponds to $\mu_4 \geq 0$ and $\mu_5 = \mu_6 = 0$. In order to obtain the conditions under which this case becomes valid, we need to go through the associated sub-cases.

(a) Supply constraints are binding in t_1 and t_2 (i.e. $\mu_1 \geq 0$, $\mu_2 \geq 0$):

From Equations A.5 and A.6 it follows:

$$S = \frac{d_2 - d_1}{2} - \frac{C_2}{2} \tag{B.1}$$

Since $\mu_5 = \mu_6 = 0$, from Equations A.1, A.2 and A.3 we obtain:

$$\mu_1 = \tau_c\,(2 - m)$$

$$\mu_2 = m\,\tau_c$$

$$\mu_4 = 2\,\tau_c\,(m - 1)$$

From the condition that μ_1, μ_2, $\mu_4 \geq 0$ it follows that:

$$1 \leq m \leq 2$$

Substituting the previously obtained μ_1 and μ_2 into Equation A.4 yields the following:

$$\tau_s + 2\,b\,(d_1 + 2\,S - d_2) + 2\,\tau_c\,(1 - m) - \mu_3 = 0 \tag{B.2}$$

We now consider two sub-cases where storage, S, is equal to zero or non-zero, i.e. $\mu_3 \geq 0$ or $\mu_3 = 0$:

i. $\underline{S = 0}$: In this case $\mu_3 \geq 0$. Setting Equation B.1 to zero, we obtain:

$$C_2 = d_2 - d_1$$
$$C_{12} = d_1$$

Similarly, substituting $S = 0$ in Equation B.2 yields:

$$\mu_3 = \tau_s + 2\,b\,(d_1 - d_2) + 2\,\tau_c\,(1 - m)$$

Since $\mu_3 \geq 0$, the condition for this case becomes:

$$\tau_s \geq 2\,b\,(d_2 - d_1) + 2\,\tau_c\,(m - 1)$$

which can be rewritten as:

$$m \leq 1 + \frac{\tau_s}{2\,\tau_c} - \frac{b}{\tau_c}\,(d_2 - d_1) \tag{B.3}$$

The implication of this finding is that given the multiplier m and model parameters, when the storage tariff τ_s is sufficiently large no gas will be stored in the storage. Similarly, given the parameters, when the multiplier m is less than or equal to the right-hand side of the condition presented in Equation B.3 no gas will be stored in the storage.

ii. $\underline{S > 0}$: In this case $\mu_3 = 0$. From Equation B.2 the optimal storage value then becomes:

$$S = \frac{d_2 - d_1}{2} - \frac{\tau_s}{4b} + \frac{\tau_c(m-1)}{2b} \tag{B.4}$$

From Equations A.5 and A.6, we similarly obtain the optimal values for the capacities:

$$C_2 = \frac{\tau_s}{2b} - \frac{\tau_c(m-1)}{b} \tag{B.5}$$
$$C_{12} = \frac{d_2 + d_1}{2} - \frac{\tau_s}{4b} + \frac{\tau_c(m-1)}{2b} \tag{B.6}$$

Taking into account that $S, C_{12}, C_2 > 0$, the conditions for the validity of the case are obtained as follows:

$$\tau_s < 2\,b\,(d_2 - d_1) + 2\,\tau_c\,(m - 1)$$

which can be rewritten as:

$$m > 1 + \frac{\tau_s}{2\,\tau_c} - \frac{b}{\tau_c}\,(d_2 - d_1) \tag{B.7}$$

and:

$$m < 1 + \frac{\tau_s}{2\,\tau_c} \tag{B.8}$$

The results indicate that while the conditions stated in Equations B.7 and B.8 are valid, i.e.

$$1 + \frac{\tau_s}{2\,\tau_c} - \frac{b}{\tau_c}\,(d_2 - d_1) < \; m \; < 1 + \frac{\tau_s}{2\,\tau_c} \tag{B.9}$$

long-term capacity C_{12} is booked for both periods, short-term capacity C_2 is booked for t_2, no short-term capacity C_1 is booked for t_1, and the storages are utilised.

(b) Supply constraint is binding in t_1 but not in t_2 (i.e. $\mu_1 \geq 0$, $\mu_2 = 0$):

Substituting $\mu_5 = \mu_2 = 0$ into Equation A.2 yields:

$$m\,\tau_c = 0$$

Since both m and τ_c are by definition non-zero, this case is not valid.

(c) Supply constraint is binding in t_2 but not in t_1 (i.e. $\mu_1 = 0$, $\mu_2 \geq 0$):

Considering that $\mu_5 = \mu_6 = \mu_1 = 0$, we obtain from Equations A.1, A.2 and A.3:

$$2\,\tau_c = m\,\tau_c$$

$$m = 2$$

We now consider two sub-cases where storage S is equal to zero or non-zero, i.e. $\mu_3 \geq 0$ or $\mu_3 = 0$, respectively.

i. $S = 0$: In this case $\mu_3 \geq 0$. From Equation A.4 we obtain:

$$\mu_3 = \tau_s + 2\,b\,(d_1 - d_2) - m\,\tau_c$$

Since $\mu_3 \geq 0$, the condition for this case becomes:

$$\tau_s \geq 2\,b\,(d_2 - d_1) + m\,\tau_c$$

The conditions from the supply constraints are as follows:

$$C_{12} \geq d_1$$
$$C_{12} = d_2 - C_2$$

It can be seen that there exists no unique solution for C_2, and C_{12}. All combinations of positive C_2 and C_{12} that fulfil the conditions above are KKT points and hence optimal solutions.

ii. $\underline{S > 0}$: In this case $\mu_3 = 0$. From Equation A.4 we obtain:

$$S = \frac{d_2 - d_1}{2} + \frac{m\tau_c}{4\,b} - \frac{\tau_s}{4\,b}$$

Since $S > 0$, the condition for this case becomes:

$$\tau_s < 2\,b\,(d_2 - d_1) + m\,\tau_c$$

The conditions from the supply constraints are as follows:

$$C_{12} \geq d_1 + S$$
$$C_{12} = d_2 - C_2 - S$$

Again, there exists no unique solution for C_2, and C_{12}. All combinations of positive C_2 and C_{12} that fulfil the conditions above are KKT points and hence optimal solutions.

(d) Supply constraints are neither binding in t_1 nor in t_2 (i.e. $\mu_1 = 0$, $\mu_2 = 0$):

Again, substituting $\mu_5 = \mu_2 = 0$ in Equation A.2 yields:

$$m\,\tau_c = 0$$

Similarly, substituting $\mu_1 = \mu_2 = \mu_6 = 0$ in Equation A.3 yields:

$$2\,\tau_c = 0$$

Since both m and τ_c are by definition non-zero, this case is not valid.

Appendix C. Prices in region A

Deriving prices in region A is less straightforward, since for the sake of simplicity no demand in region A is integrated. To derive the prices in region A one can add a fictional demand d_{A1} and d_{A2} to the procurement cost equation and differentiate it by d_{A1} and d_{A2}. Alternatively, one can subtract the Lagrange multipliers μ_1 and μ_2 from the prices in region B, since the Lagrange multipliers represent the marginal costs for transporting gas from region A to B.

$$P_{A1} = P_{B1} - \mu_1 = \begin{cases} a + b\, d_1 & \text{for } m < \underline{m} \\ a + b\left(\dfrac{d_1 + d_2}{2}\right) + \tau_c\,(m-1) - \dfrac{\tau_s}{2} & \text{for } \underline{m} < m < \overline{m} \\ a + b\left(\dfrac{d_1 + d_2}{2}\right) & \text{for } \overline{m} < m \end{cases}$$

$$P_{A2} = P_{B2} - \mu_2 = \begin{cases} a + b\, d_2 & \text{for } m < \underline{m} \\ a + b\left(\dfrac{d_1 + d_2}{2}\right) - \tau_c\,(m-1) + \dfrac{\tau_s}{2} & \text{for } \underline{m} < m < \overline{m} \\ a + b\left(\dfrac{d_1 + d_2}{2}\right) & \text{for } \overline{m} < m \end{cases} \quad \text{(C.1)}$$

The functions describing the consumer prices in region A are plotted in Figure C.7. Although individual consumer prices are influenced by m for $m < \overline{m}$, unweighted average prices remain constant.

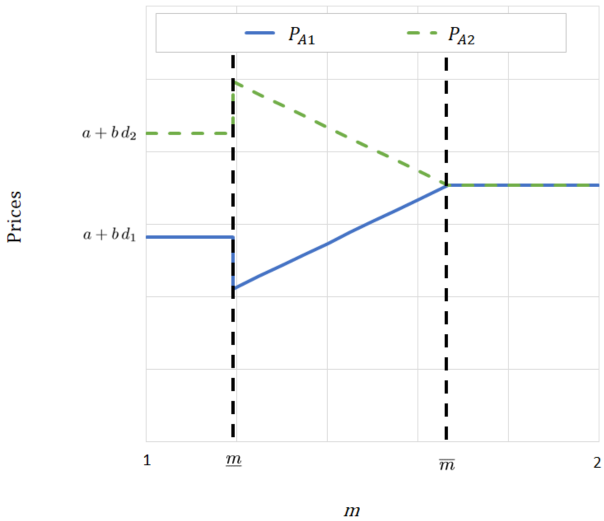

Figure C.7: Development of prices in region A at time periods t_1 and t_2 with respect to the multiplier

The average price in region A is equal to the gas procurement prices which arise when overall demand is split evenly among periods:

$$\frac{P_{A2} + P_{A1}}{2} = a + b\,(\frac{d_2 + d_1}{2})$$

As can be seen in Figure C.7, when $m \leq \underline{m}$, the prices in region A are independent of the multiplier due to storages not being used and prices solely reflecting the costs for gas production. In the domain $\underline{m} < m < \overline{m}$, as storages start being utilised and the marginal costs of storage utilisation is included in the prices, an offset in prices (decrease in t_1, increase in t_2) occurs. With increasing m, prices in region A start converging as production volumes increasingly align. With $m \geq \overline{m}$, production volumes fully converge and the same prices in both periods are observed in region A.

Appendix D. Surpluses and deadweight loss when no feasible $\underline{m}$ and $\overline{m}$ exist

Depending on the tariff structures (i.e. the proportion of τ_s and τ_c), $\underline{m}$ and $\overline{m}$ may not exist in the feasible multiplier range of $1 \leq m \leq 2$. In such a case, the previously identified domains $m < \underline{m}$ and $m > \overline{m}$ do not exist. Hence, Proposition 3.4 holds throughout the feasible multiplier range (i.e. $1 \leq m \leq 2$) and storages are utilised as well as ST and LT capacities are booked for all such multipliers.

The surpluses of the agents in the model and the deadweight loss are plotted in Figure D.8.

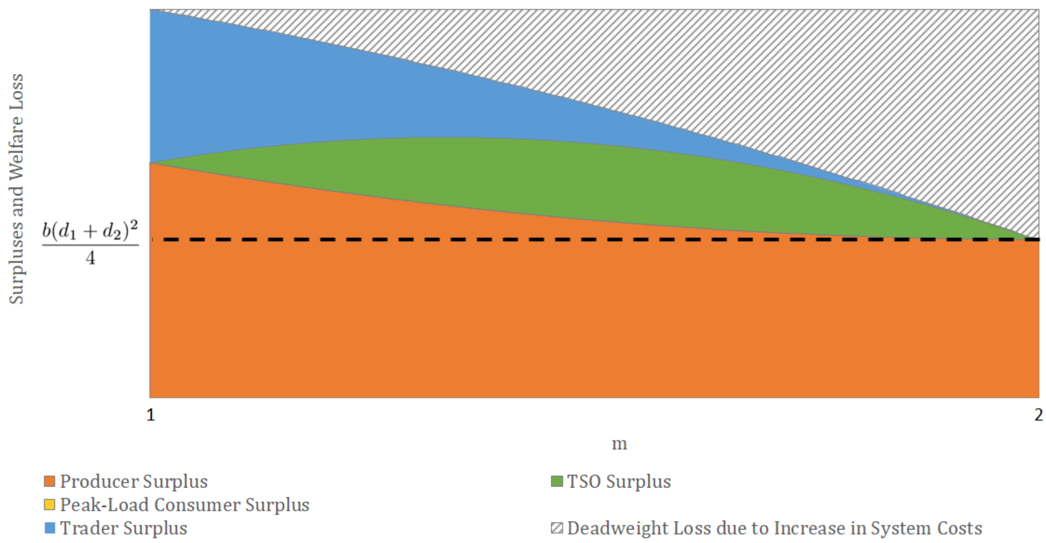

Figure D.8: Surpluses and deadweight loss when no feasible $\underline{m}$ and $\overline{m}$ exist

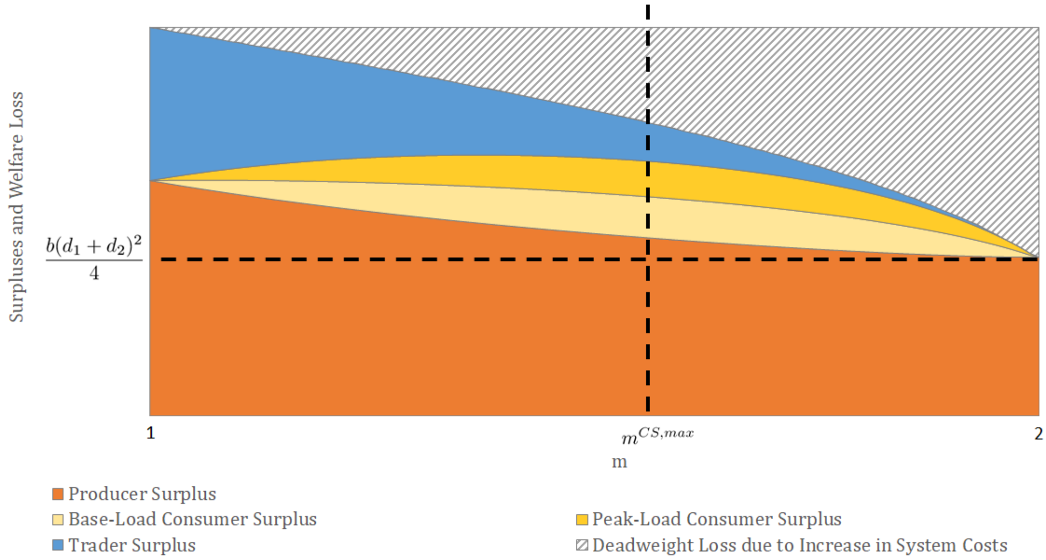

Figure D.9: Surpluses and deadweight loss when no feasible $\underline{m}$ and $\overline{m}$ exist in the case where τ_c is adjusted

For the case when transmission tariffs (τ_c) are adjusted such that the TSO does not earn a surplus, the surpluses of the agents in the model and the deadweight loss are plotted in Figure D.9. The multiplier level that maximises the total consumer surplus is equal to $m^{CS,max} = 1 + \frac{\tau_s}{\tau_c^{adj}}$.