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Removing Cross-Border Capacity Bottlenecks in the European Natural Gas Market
- A Proposed Merchant-Regulatory Mechanism

Anne Neumann[1], Juan Rosellón[2] and Hannes Weigt[3]

Abstract:
We propose a merchant-regulatory framework to promote investment in the European natural gas network infrastructure based on a price cap over two-part tariffs. As suggested by Vogelsang (2001) and Hogan et al. (2010), a profit maximizing network operator facing this regulatory constraint will intertemporally rebalance the variable and fixed part of its two-part tariff so as to expand the congested pipelines, and converge to the Ramsey-Boiteaux equilibrium. We confirm this with actual data from the European natural gas market by comparing the bi-level price-cap model with a base case, a no-regulation case, and a welfare benchmark case, and by performing sensitivity analyses. In all cases, the incentive model is the best decentralized regulatory alternative that efficiently develops the European pipeline system.

Keywords: regulation, transportation network, investment

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1 Introduction

The natural gas pipeline network system in Europe has bottlenecks in several cross-border areas, such as those between Spain and France, United Kingdom (UK) and the European mainland, Norway and the European continent, as well as between Russia and Western Europe.[4] The International Energy Agency (IEA) estimates that natural gas supply capacity in Europe will have to significantly increase by 2015 in order to meet the increasing demand. Most of this new supply will come from import sources in the UK, Norway and Russia as well as from liquefied natural gas (LNG) from the Mediterranean, Middle East and the Atlantic areas. Imports into the European Union (EU) will rise from 63% of total supply in 2010 to 77% in 2020 (IEA, 2009). The increasing need to import natural gas necessitates not only additional supply infrastructure but also greater interconnection between EU countries that enable the large increments of imported natural gas to be absorbed efficiently within Europe, and to provide access to LNG supplies to countries without sea-born terminals.

The current outlook for natural gas transmission investment in Europe is less encouraging. Few internal network interconnections are being built; new suppliers are not able to easily enter into the market; while investment in transmission capacity and storage are an issue, especially in cross-border interconnections. There are some initiated pipeline projects designed to relieve congestion, for example, between Norway and the UK, Russia and Germany, and among Russia, Bulgaria, Central Europe and Italy, as well as among Norway, Sweden, Denmark, and Poland. However, there is not a clear consensus yet on the precise regulatory and investment structures that might bring these projects to reality. Uncertainty regarding the regulatory framework on investment in expanding natural gas pipelines affects the incentives to finance the required transmission expansion projects. Important progress, however, is the 2009 establishment of a European regulatory agency that, in particular, will oversee natural-gas transmission investment structure issues.[5]

This paper proposes a combined merchant-regulatory model to remove existing cross-border bottlenecks in the European long-distance natural gas pipeline system. We develop an incentive regulatory framework to promote investment of natural gas network infrastructure based on a price cap over two-part tariffs as proposed by Vogelsang (2001) and Hogan et al. (2010). The basic idea is that, by facing this framework, a profit maximizing network operator (NO) will rebalance the variable and fixed part of its two-part tariff so as to expand congested pipelines.[6] A first intuitive question is why congestion in transmission networks takes place at all. A basic problem with network providers is that they might find it more profitable not to expand the system because of the high revenues of keeping the pipelines congested. In other words, the marginal cost of new transportation capacity might be greater than the expected congestion cost of not adding an additional unit of capacity. Thus, the primal objective of an incentive method that seeks to reverse this congestion "trap" is to make the marginal cost of expansion lower than the one of congestion, and promote over-time convergence to a steady state optimum (or "expanding" equilibrium) where both variables remain equal and where allocative and productive efficiency are achieved (Crew, Fernando and Kleindorfer, 1995).

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[4] Similar congestion cross border issues are internationally present in electricity networks in North America and Europe (Rosellón and Weigt, 2011, and Myslikova, Rosellón and Zenón, 2011). The need to expand energy networks is also highly motivated by large-scale renewable system projects (Fthenakis, Mason and Zweibel, 2009).

[5] Regulation (EC) No. 713/2009 of the European Parliament and of the Council of 13 July 2009: "Establishing an Agency for the Cooperation of Energy Regulators". As we suggest below, an institutional comprehensive European regulatory approach is particularly relevant for our model.

[6] Expansion in transmission networks can also be approached from the point of view of consumers who are willing to pay for excess (or buffer) capacity if they dislike facing any period of congestion (Brito and Rosellón, 2011).

In this paper we show how price regulation can be used to solve this duality of incentives for natural gas network so that congestion is removed in the short run, and investment in transmission expansion is achieved in the long run. This is carried out through the means of a bi-level programming model. The lower level of the model represents the welfare-maximizing process (typically managed by a system operator) within the European natural gas pipeline network system where demand, production, LNG supplies, and imports are considered, as well as transportation, liquefaction, regasification and storage capacities. Capacity bottlenecks – and therefore congestion rents – are initially exogenously given. This lower-level model provides the optimal loads and nodal prices that are a further input of an upper-level model representing the incentive regulatory framework that promotes the expansion of the network through price-cap regulation. The complete bi-level programming model works in such a way that the NO will voluntarily expand the pipeline network, choosing the projects and their capacities guided by the nodal-price differences. This process is such that not only considerable expansion of pipeline capacity will be achieved, but also convergence through time to a Pareto optimal (Ramsey-Boiteaux) equilibrium.

We further compare our results of this bi-level price-cap model with a base case without extensions, a no-regulation case, and a welfare benchmark. We are able to confirm, with actual data from the European natural gas market, that the price-cap model over two-part tariffs is the welfare-optimal decentralized regulatory alternative that efficiently develops the entire pipeline system in Europe. Our analysis proceeds as follows. In section 2, we review the literature on incentive regulation for transmission network expansion, and on natural gas transportation models. In section 3, we present the bi-level programming regulatory model (subsection 3.1), both with its lower level (dispatch welfare-maximizing problem) and its upper level (NO's profit maximization subject to a cap on its two-part-tariffs). We also describe, in this subsection, the model representing the welfare-optimal benchmark case. A detailed description of the data used is presented in 3.2. Results for the different considered scenarios are analyzed in section 4, in particular the base case (4.1) and the regulatory approach (4.2). The evaluation of results is provided in 4.3, while a sensitivity robustness analysis is performed in 4.4. Concluding remarks are provided in section 5.

2 State of the Literature

2.1 Incentive regulation, efficiency and network expansion

There are two main concepts in price regulation: regulation of the price level and regulation of the price structure. Price level regulation refers to the long-run distribution of rents and risks between consumers and the firm. Price level regulation can achieve various efficiency goals, such as *allocative efficiency*, *productive efficiency*, and *distributive efficiency*. According to the regulatory economics theory, the price level of firms with increasing returns to scale or natural monopolies (such as natural gas pipelines) needs to be regulated so as to redistribute the monopolistic rent, and achieve a distance from marginal cost that is optimal (Armstrong et al., 1994). Such optimal price cap is derived from the perspective of a regulator that maximizes social welfare (expressed as the weighted sum of consumer and producer surpluses), subject to the individual rationality constraint (or break-even constraint) of the firm with increasing returns. The solution to this problem provides the best Pareto solution under such a market failure. The optimal markup between price and marginal cost ends up being inversely proportional to the elasticity of demand. This is the well-known (non-Bayesian) allocative-efficient Ramsey-Boiteaux equilibrium. Likewise, price-cap regulation might incentivize cost minimization (productive efficiency) by the regulated firm. In practice, it is usually combined with cost-of-service regulation so as to provide a cost-based initial price cap that remains fixed over a regulatory lag, usually only adjusted by inflation and efficiency factors (*RPI-X* regulation).

Regulation of the price structure refers to the short-run allocation of costs and benefits among distinct types of consumers or markets. It can promote convergence to both the "expanding" equilibrium and the Ramsey-Boiteux equilibrium. Under price structure regulation, a cap is set over an index of prices. Such an index is typically calculated as the weighted sum of prices to different consumers. There are two basic ways to establish weights under price structure regulation: one with fixed weights – tariff-basket regulation – and another with variable weights – average revenue regulation. Under the former regime, a maximum limit is established over an index $I(p)=\sum_{i=1}^{n} w_i p_i$, where p_i are the different prices and w_i are the fixed weights. Weights might be output (or throughput) quantities of the previous period (chained *Laspeyres*), quantities of the current period (*Paasche*), intertemporally fixed quantities (fixed *Laspeyres*), or projected quantities that correspond to the steady state equilibrium (ideal *Laffont-Tirole* weights, as in Laffont and Tirole, 1996).[7] Variable weights are usually associated with average-revenue regulation that sets a cap on incomes per unit but does not set fixed weights limiting the relative variation of prices. Compared to tariff-basket regulation, this confers the firm greater flexibility in tariff rebalancing (which is convenient for the firm under risk aversion and uncertain conditions) but lacks convergence to the welfare maximizing equilibrium. The literature has proven that, under non-stochastic (or stable) conditions of costs and demand – and myopic profit maximization (that is, when the firm does not take into account future periods in its current profit maximizing behavior) – the use of the chained Laspeyres index makes the prices of the regulated firm intertemporally converge to Ramsey-Boiteaux pricing (Vogelsang 2001, Vogelsang 1989, Bertoletti and Poletti, 1997, Loeb and Magat 1979, and Sibley, 1989). The chained-Laspeyres structure simultaneously reconciles two opposing objectives: the maximization of social welfare and the individual rationality of the firm (i.e., non-negative profits). Social surplus is redistributed to the monopoly in such a way that long-run fixed costs are recovered but, simultaneously, consumer surplus is maximized over time.[8] Under similar stability conditions, and myopic profit maximization, average revenue regulation causes divergence from Ramsey prices.[9]

Further, price structure regulation is used by Vogelsang (2001) and Hogan et al. (2010) to solve (electricity) transmission congestion, in the short run, as well as capital costs and investment issues in the long run. In a two-part tariff regulatory model with a variable (or usage) charge, and a fixed (or capacity) charge, the variable charge is mainly based on nodal prices and relieves congestion. Recuperation of long-term capital costs is achieved through the fixed charge that can be interpreted as

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[7] The steady state equilibrium is characterized by prices whose optimal distance from marginal cost is inversely proportional to the elasticity of demand. These are referred in the literature as the Ramsey-Boiteaux prices (Armstrong et al., 1994).

[8] The social surplus is made up by consumer surplus, the producer surplus**,** and the government surplus (if present).

[9] In a dynamic setting with changing cost and demand functions – and/or non-myopic profit maximization – the chained Laspeyres index (or any other weight index) generates prices that may diverge from the Ramsey structure (Neu, 1993, Fraser, 1995, and Law, 1995a,b, study the effects of the chained Laspeyres restriction under a changing demand function, non-uniform cost changes, and myopic profit maximization, respectively). Ramírez and Rosellón (2002) show that flexible-weight average-revenue regulation might be combined with other regulatory means to achieve a balance in the trade-off between risk management with consumer-surplus maximization by firms under high uncertainty. The use of flexible-weights during the initial stages of greenfield gas distribution projects (characterized by volatile cost and demand conditions) is consistent with investment attraction under uncertain dynamic behavior of demand since it is a laxer constraint for firms than fixed-weight regulation. Tariff-basket regulation is used afterwards, once the cost and demand conditions are stabilized.

the price for the right to use the transmission network. The fixed charge can also provide incentives for productive efficiency and, if it does not affect the number of transmission consumers, allocative efficiency – that is, convergence to the Ramsey price structure – can be intertemporally achieved.

The proper incentives for efficient investment in the expansion of the network in the Vogelsang and Hogan et al models are reached by the rebalancing of fixed and variable charges. Likewise, incentives for investment crucially depend on the type of weights used. For the Laspeyres index the NO will intertemporally invest until its transmission tariffs converge to Ramsey prices. However, this will not occur automatically since the firm faces a tension between short-run gains from congestion, and increases in capacity investment. Thus, when there is congestion in capacity, the NO will expand the network because its profits increase with network expansion when congestion variable charges are marginally larger than the marginal costs of expanding capacity. On the contrary, in times of excess capacity, the variable charge of the two-part tariff will be reduced causing an increase in consumption. The fixed charge, in turn, increases such that total income rises despite the decrease in the variable charge. As a consequence, the NO ceases to invest in capacity expansion and net profits expand since costs do not increase.

For electricity networks, the upgraded merchant-regulatory model by Hogan et al. (2010) emphasizes the need to combine an incentive price-cap Vogelsang type of model (upper level problem) with a power-flow model (lower level problem), where dispatch is carried out by an independent system operator (ISO). The lower level problem provides the inputs (optimal flows and nodal prices) needed in the upper level problem so as to determine the optimal fixed and variable prices. Implementation of the model starts from an existing grid with historic market price information used by the regulator to set up the two-part pricing constraint. Based on the available market information (demand, generation, network topology, etc.) the NO then identifies which lines to expand, and proceeds to auction the available transmission capacity. Meanwhile, the ISO manages actual dispatch, and collects the payoffs from loads and pays the generators according to locational marginal prices (the difference of these latter values represents the congestion rent of the system that is redistributed to the property-right holders). Finally, the NO sets the fixed fee according to the regulatory price cap.[10]

In this paper, we carry out an application of the Hogan et al. (2010) mechanism on the European natural gas network. We analyze how this bi-level programming model can incentivize the NO out from the congestion-trap equilibrium and expand the network systems through the rebalancing of the NO's fixed and variable fees in a process that will eventually intertemporally converge to the Ramsey-Boiteaux welfare-optimal equilibrium.

2.2 Natural gas transportation models

Figure 1 illustrates the object of our research. The European long-distance natural gas transmission network, including transit routes, seems well developed in terms of geographic coverage. Most of the imported quantities come from North Africa and Russia, while major indigenous production takes place in the North Sea. So far, transporting natural gas mainly follows north-south or east-west routes that separate the market into smaller regions. Therefore, enhancing the development of a competitive

[10] The Hogan et al. mechanism is further tested using simplified grids in Northwestern Europe (Benelux) and in Pennsylvania, New Jersey, Maryland (PJM) with realistic generation structures in Rosellón and Weigt (2011) and Myslíková, Rosellon and Zenón (2011), respectively. This testing results in the NO expanding the network so that prices develop in the direction of marginal costs. The nodal prices that were subject to a high level of congestion converge to a common marginal price level, and consumer and producer surpluses converge to the Ramsey-Boiteaux welfare optimal values.

internal European market needs to focus on interconnections between regions, i.e. the Iberian Peninsula with Central Europe.

Figure 1: European natural gas transmission network

Source: IEA/OECD (http://www.iea.org/gtf/).

The literature on natural gas transportation models principally centers on three approaches. The system dynamic approach is applied by two studies, so far (Stäcker, 2004, Hallouche and Tamvaski, 2005). The Institute of Energy Economics (EWI) in Cologne produced a series of linear optimization models (EUGAS, TIGER, MAGELAN), of which the TIGER model provides the most detailed dispatch model for Europe and is suitable for identifying congestion (Perner and Seeliger, 2004; Lochner and Bothe, 2007). The dynamic model optimizes long-term European natural gas supply by taking into account production and transportation facilities. Model outputs are mainly flows and supply costs. In order to allow for strategic behavior, market power and other market imperfections of the (European) natural gas market, the literature dominantly relies on the complementarity framework. In a first application, Mathiessen et al. (1987) show that the European natural gas market is best described by a Cournot duopoly. The following works by Golombek et al. (1995, 1998) distinguish between upstream and downstream players in the natural gas market and show the positive impact of market restructuring on upstream competition and welfare. Several streams within this literature evolved, which focus on (and study) different issues such as multi-period modeling and supply disruptions, double marginalization, or the cartel creation of exporters settings. The World Gas Model (WGM) provides a high level of granularity in a game-theoretic context while covering 95% of world natural gas production (Egging et al., 2009). Holz (2009) discusses these different model families in more detail. Abrell and Weigt (2011) combine the natural gas and electricity markets in a mixed complementary problem. Their main focus is on the interaction of natural gas as primary input to electricity generation.

In all of these models investment in infrastructure is best described as a net present value calculation optimization. Hence, even as the complementarity framework has attracted the largest share of research and literature so far, it does not include a convincing regulatory investment mechanism. Neumann et al. (2009) design a welfare maximization approach, subject to constraints of natural gas infrastructure facilities. The focus is on optimization of the long-distance transport neglecting influences of strategic company behavior on the exporter side, interaction of traders in Europe, or market power concerns on the intra-European transmission network level. As a result the model provides nodal (here regional) prices for natural gas on a monthly basis and, therefore, represents the lower level problem only. Brito and Rosellón (2011) propose an alternative regulatory approach to the expansion of natural gas transportation pipelines in terms of the welfare-optimal consumers' willingness to pay for excess capacity.

Building on Neumann et al. (2009), Bauer et al. (2011) attempts a basic application of the Hogan et al. (2010) mechanism to natural gas pipelines in Europe. They show an increasing pattern of welfare together with transmission expansion and rising consumer surplus. In this paper, we carry out a more detailed analysis for different economic scenarios, comparing the basic Hogan et al. model with a base case, a case of no regulation, and a welfare Ramsey-type benchmark. This will provide evidence of the advantages (or disadvantages) of the Hogan et al. mechanism compared to other approaches as well as a characterization of its convergence to an efficient equilibrium. We now turn to our representation of the combination of the lower problem in Neumann et al. (2009) with an upper level incentive regulation program. In particular we are interested in efficient investment incentives for a single European grid operator in natural gas whilst leaving out security of supply issues (such as supply disruptions etc.).

3 Model and Data

The analysis is based on a simulation model of the European natural gas market accounting for the underlying network, aggregated at country level. The model is designed to represent the actual market and is adjusted accordingly to account for the proposed regulatory approach and a welfare optimal counter factual setting. Following the underlying basic market model the regulatory and welfare model adjustments are presented. Afterwards the dataset for the analysis is presented.

3.1 Model

3.1.1 Basic market model

The basic (lower level) model setting is taken from the model definition of the InTraGas-Model following Neumann et al. (2009). InTraGas represents the European natural gas market, assuming a perfect competitive market accounting for network restrictions, LNG possibilities and storage facilities. The model is formulated representing a social planer maximizing social welfare in the whole system:

$$\max_{d,g,flow,LNGflow} W = \sum_{n,y,s} \int_0^{d^*_{n,y,s}} p(d_{n,y,s})\,\mathrm{d}d_{n,y,s} - \sum_{n,y,s} c_{n,y} g_{n,y,s} - \sum_{n,m,y,s} tc_{n,m}\, flow_{n,m,y,s} - \sum_{n,m,y,s} LNGtc_{n,m}\, LNGflow_{n,m,y,s} \quad (1)$$

s.t.

$$g_{n,y,s} \leq g^{\max}_{n,y}$$ Production constraint (2)

$$flow_{n,m,y,s} \leq flow^{\max}_{n,m,y}$$ Pipeline constraint (3)

$$LNGflow_{n,m,y,s} \leq LNGflow^{\max}_{n,m,y}$$ LNG route constraint (4)

$$\sum_m \frac{1}{\eta_{liq}} LNGflow_{n,m,y,s} \leq Liquefaction^{\max}_{n,y}$$ Liquefaction constraint (5)

$$\sum_m \eta_{reg} LNGflow_{m,n,y,s} \leq Regasification^{\max}_{n,y}$$ Regasification constraint (6)

$$store_{n,y,s} = store_{n,t,s-1} + \eta_{sto} s^{in}_{n,y,s} - s^{out}_{n,y,s}$$ Storage balance (7)

$$store_{n,y,s} \leq store^{\max}_{n,y}$$
$$s^{in}_{n,y,s} \leq sin^{\max}_{n,y}$$ Storage constraints (8)
$$s^{out}_{n,y,s} \leq sout^{\max}_{n,y}$$

$$g_{n,y,s} + s^{out}_{n,y,s} + \sum_m flow_{m,n,y,s} + \sum_m LNGflow_{m,n,y,s}$$
$$\geq d_{n,y,s} + s^{in}_{n,y,s} - \sum_m flow_{n,m,y,s} - \sum_m LNGflow_{n,m,y,s}$$ Energy balance (9)

The objective of the model (equation 1) is to maximize social welfare, *W*, consisting of the gross consumer surplus (first term, right hand side) reduced by the total production costs (second term), pipeline transport costs (third term), and LNG transport costs (fourth term).

This objective is subject to several constraints representing the technical characteristics of natural gas production, transport, and storage. First, the total production g at any node, $n \in N$, in each year, $y \in Y$, and season, $s \in S$, must be within the upper production limit, g^{max} (equation 2). The same holds true for each pipeline connecting two nodes, n and $m \in N$: the *flow* must remain within the pipeline capacity, $flow^{max}$ (equation 3). For *LNGflow,* the capacity limit, $LNGflow^{max}$, is used to indicate which routes are available (equation 4), as sea-based routes do not have a technical upper capacity limit similar to pipelines. LNG transport is limited by the available liquefaction and regasification facilities. For nodes n, exporting LNG the sum of all *LNGflow*s to other nodes, m, must reflect the available liquefaction capacity, $Liquefaction^{max}$, accounting for the efficiency, η_{liq}, of the process (equation 5). The reverse holds for importing nodes n: the sum of all ingoing *LNGflow*s from other nodes, m, are limited by the regasification capacity, $Regasification^{max}$, accounting for the regasification efficiency, η_{reg} (equation 6).

Storage plays an important role in natural gas markets, providing the capability to balance daily, weekly and seasonally variations, facilitating more stable usage of the transport capacities. Within the model storage is represented by a balance equation and capacity restrictions. The balance (equation 7) intertemporally links the storage level, *store,* of the former season, s-1, to the current season, s, by accounting for storage injections, s^{in}, and withdrawals, s^{out}, in the current period. The actual storage level, the injections and the withdrawals are limited by the respective available capacities: $store^{max}$, sin^{max}, and $sout^{max}$ (equation 8).

Finally the energy balance (equation 9) secures that, for each node *n* of the network, at any given period, *y,s*, injections consisting of production, *g*, withdrawals from the storage, s^{out}, as well as pipeline, *flow,* and LNG imports, *LNGflow*, from other nodes, *m,* must be greater than or equal to the withdrawals at that node consisting of local demand, *d*, storage injections, s^{in}, as well as pipeline, *flow*, and LNG exports, *LNGflow*, to other nodes, *m*.

This basic model provides the underlying market representation for the different extension scenarios.

3.1.2 Regulatory extension approach

In the proposed regulatory setting we assume that a NO is responsible for collecting transmission revenues, bearing the network costs and deciding about capacity additions. The NO is subject to a profit cap linking inter-temporal revenues in a Laspeyres manner. The market clearing is taking place in a competitive setting, as described in Section 3.1.1. Consequently the NO can only influence the market outcome by deciding about the available capacities, but has no influence on the actual production, demand and LNG decisions.

The NO's profit, π, is given by the revenues due to the price differences, p_m-p_n, on the pipelines and the actual pipeline flow, $flow_{n,m}$, plus a fixed access fee that network users have to pay, *F,*[11] minus the costs consisting of the transport costs, *tc*, and potential extension costs, *extc*, for newly built capacities, $newflow^{max}$:

$$\pi = \sum_{n,m,y,s} (p_m - p_n)\, flow_{n,m,y,s} + \sum_{y} F_y - \sum_{n,m,y,s} tc_{n,m}\, flow_{n,m,y,s} - \sum_{n,m,y,s} extc_{n,m}\, newflow^{\max}_{n,m,y,s} \qquad \text{NO profit function} \qquad (10)$$

The NO is subject to the regulatory constraint allowing an increase in the fixed fee if prices in the market drop and his congestion revenues decrease:

$$\frac{\sum_{n,m} (p_{m,y,s} - p_{n,y,s} - tc_{n,m})\, flow_{n,m,y-1,s} + F_y}{\sum_{n,m} (p_{m,y-1,s} - p_{n,y-1,s} - tc_{n,m})\, flow_{n,m,y-1,s} + F_{y-1}} \le 1 + RPI - X \qquad \text{regulatory cap} \qquad (11)$$

The regulator might adjust the cap for inflation e.g. by the retail price index, *RPI,* and include individual efficiency target factors, *X*. As capacity additions typically reduce the market price differences in the system, the NO's revenue from gas transport would decrease, which dis-incentivizes the NO from carrying out investments. With the regulatory cap he can adjust the fixed fee to compensate the congestion revenue loss and refinance investments.

New capacity, $newflow^{max}$, is added to existing capacity allowing for a greater flow on the transport routes. Equation 3 is adjusted accordingly:

$$flow_{n,m,y,s} \le flow^{\max}_{n,m,y} + newflow^{\max}_{n,m,y} \qquad \text{New pipeline constraint} \qquad (12)$$

The regulatory approach is formulated as Mathematical Program with Equilibrium Constraints (MPEC): the NO maximizes its profit subject to the regulatory cap and the market clearing. The market clearing optimization (equation 1-2, 4-9, 12) is reformulated as equilibrium problem by deriving the corresponding Karush-Kuhn-Tucker conditions.

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[11] The number of network users is normalized to 1.

3.1.3 Welfare optimal extension

In order to evaluate the regulatory approach, a counterfactual benchmark is calculated that leads to a welfare optimal expansion. This is obtained by including the possibility to extend the network (accounting for extension costs, *extc*, and for newly built capacities, $newflow^{max}$) within the welfare objective of equation 1:[12]

$$\begin{aligned}\max_{d,g,flow,LNGflow} \quad W = & \sum_{n,y,s} \int_0^{d^*_{n,y,s}} p(d_{n,y,s})\,\mathrm{d}d_{n,y,s} - \sum_{n,y,s} c_{n,y} g_{n,y,s} \\ & - \sum_{n,m,y,s} tc_{n,m} flow_{n,m,y,s} - \sum_{n,m,y,s} LNGtc_{n,m} LNGflow_{n,m,y,s} \\ & - \sum_{n,m,y,s} extc_{n,m} newflow^{\max}_{n,m,y,s}\end{aligned} \tag{13}$$

The welfare optimal extension model consists of equation 13, 2, 4-9, and 12 and is solved as quadratic constraint program (QCP).

3.2 Data

The underlying dataset follows Neumann et al. (2009) and represents the European natural gas market, including major exporters like Russia and LNG exporters like Nigeria. The time range considered is 2010 to 2020, with yearly steps and two seasons each; summer and winter. The network representation is a simplified description of the existing European gas pipeline system. All demand, production, LNG, and storage facilities of individual countries are aggregated into one node. Connections between those nodes represent the summed up cross-border capacities of the respective connected countries.

Available production capacities are taken from IEA (2006), BP (2006) and Eurostat (2011). Capacities are increased or decreased until 2020 according to IEA (2008); production costs are based on OME (2005). Demand is assumed to be linear with an elasticity of -0.3 and a price of 10 €/MWh at the reference point. The corresponding seasonal reference demand is taken from Eurostat (2011) and is based on the average monthly demand for corresponding seasons in 2008 and 2009. The demand levels are adjusted until 2020 according to IEA (2008).

The network capacities are based on the ENTSOG European Natural Gas Network map (ENTSOG, 2011a). All pipelines connecting two countries are aggregated into a single capacity value. European network extensions are taken from the ENTSOG Ten-Year Network Development Plan (ENTSOG, 2011b). Regarding import lines, only the North-Stream project is considered; coming online with 27.5 bcm in 2015 and with an additional 27.5 bcm in 2018. All other major import projects (South-Stream, Nabucco) are not considered within this model setting. Transport costs are based on OME (2005) and depend on the length of a pipeline. As the geographic representation of the model is stylized we assume that the pipeline length is equal to the distance between the geographical centers of the countries.

Storage data is based on the GSE storage map (GSE, 2010a) and adjustments through 2011 are taken from the GSE investment database (GSE, 2010b), thus accounting only for projects that are already under construction or in the permitting phase. LNG data for the European terminals and major exporters is based on the GLE LNG map (GLE, 2010a) and adjustments through 2020 based on their investment database (GLE, 2010b). LNG transportation costs are approximated with 0.67 € per

[12] The extension plan could typically be carried out by an ISO.

nautical mile and mcm; liquefaction losses (12%) and regasification losses (1%) are based on IEA (1994).

4 Scenarios and Results

We analyze four different scenarios to evaluate the proposed regulatory approach given the European market setting. First the *Base Case* is simulated, representing the expected development in Europe given the ENTSOG network extensions as well as projected demand and production changes through 2020. In the framework of our analysis this case is considered to be the no-extension counterfactual, as all extensions are externally defined and remain so in all other scenarios. This case also allows the evaluation of the underlying market model with respect to real market outcomes. However, the model's purpose is to provide a framework for the evaluation of the regulatory approach and not to provide a comprehensive market forecast for Europe.

Second, the *Regulatory Approach* will be implemented. For this setting we assume a single NO to be in charge of investment decisions within Europe, but not for import connections or connections outside Europe. Following the regulatory NO's logic, a non-regulated setting is also simulated (*Profit Case*--third scenario) in which the NO is maximizing its profits via network extensions, but without any regulatory constraints. In a final scenario, the *Welfare* counterfactual is simulated which facilitates the comparison of the regulatory approach against a theoretic first best solution.

4.1 Base case results

The Base Case represents the underlying European market development in case of scheduled network extension following the ENTSOG Ten-Year Network Development Plan. For the initial conditions in 2010 the model reproduces the general market trends of the European natural gas market: African exports supply large fractions of the Spanish and Italian demand, Norwegian gas supplies Central Europe, and Russian imports are used for supplying East Europe, Germany and are also transported to Italy. African and Middle East LNG is transported to the Mediterranean countries and LNG from South America and Central Africa supplies the East Cost of the Iberian Peninsula. The price level in the European countries is about 8.2 €/ MWh in summer and 12.4 €/MWh in winter.

The assumed demand increase in Europe and the decline of local production leads to a price increase through 2020 (Figure 2). For summer the average price increases to about 11.8 €/MWh, which represents a 40% increase in price level. The winter price level does not increase as drastically with 11% to 13.8 €/MWh until 2020. The price development also shows the impact of the assumed extension of the North-Stream pipeline, leading to a price decrease in the respective years by about 10%, limiting the upward price trend through 2020. The project also leads to shifts in European pipeline flows. The additional Russian gas available directly in Germany is partly transmitted to France and Italy, as the existing connection via Belarus and Poland is still fully utilized. Furthermore the shift leads to reduced exports from Norway to Germany, and has impacts on the LNG situation in Europe. As a share of the French demand is now satisfied with Russian gas, the need for LNG imports is declining while at the same time higher demand in Italy and Spain increases the need for LNG imports in those countries. Storage plays an important role in Central and Western Europe, utilizing the available pipeline and LNG capacities during the summer. Generally storage capacities are fully utilized in the modeled countries.

4.2 Regulatory approach

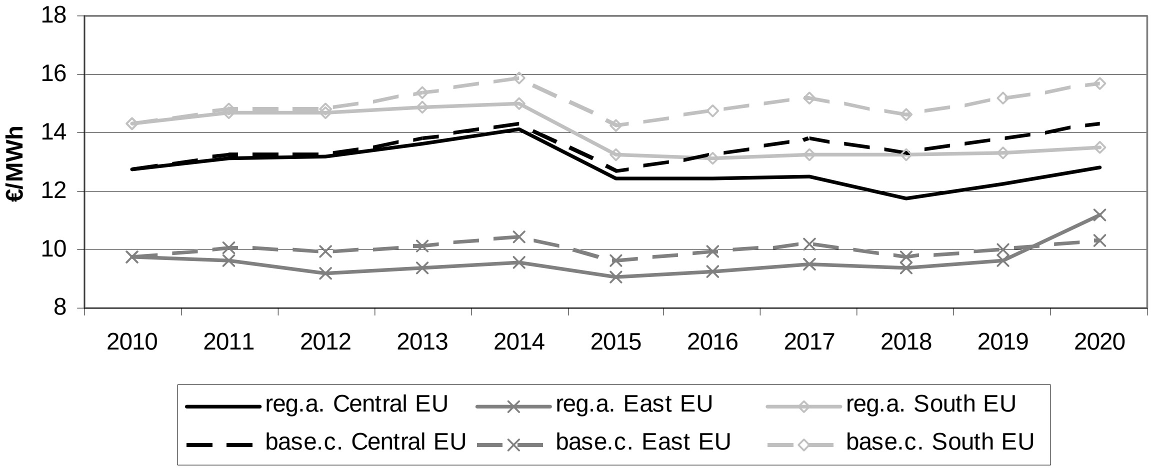
In the regulatory approach, the European network can be extended beyond the ENTSO-G Ten-Year Network Development Plan if the NO can increase its profits by doing so. Extensions are limited to the European pipeline system and do not include import pipelines. Nevertheless, the transmission revenues are collected from all pipelines in the system. Thus congestion revenue outside Europe can be utilized to finance investments in Europe in this setting. This assumption is adjusted in the sensitivity analysis.

Due to the extension possibility, the NO now invests into new pipeline connections. Through 2015 the differences from the base case are limited. Extensions are mostly carried out to better interconnect the East European countries, and establish a larger transport capacity in the direction of Italy, leading to a slight price convergence in this region. Central Europe is mostly unaffected by these extensions. With the introduction of the first, and later on the second, stage of the North-Stream pipeline, the German market has an oversupply of gas import possibilities. The NO therefore reroutes the Russian gas coming via Poland to the South. Austria becomes a new gas hub for Russian gas, transmitting gas onward toward Italy in the South and in the direction of France via Switzerland. This is induced by the NO investments into the region of Austria, Czech Republic, Slovakia and Hungary as well as a major pipeline investment between Austria and France. The results highlight that the regulatory approach leads to an investment pattern that tries to maximize the usage of available pipeline connections and gas imports to regions with high prices.

The price development in the different regions shows the impact of the North-Stream project on the European market with price decreases in 2015 and 2018 (Figure 2). Compared to the base case, the price increase is significantly lower for Central Europe, while South Europe even faces a price decrease through 2020. East Europe faces a slight price increase. The prices in continental Europe slowly converge through 2020 due to the network extensions.

The NO’s fixed tariff component, *F,* is supposed to increase over the periods as the reduced congestion rent is compensated by the increased fixed income. However, in the basic model setting the fixed tariff is negative in most periods and only increases in 2016 and 2019; the years after the North-Stream segments go online. This result is due to the fact that we do not assume any *RPI* or X-Factor for the NO. As the underlying market conditions change (increase in demand with simultaneous decrease in domestic production), the yearly return is also affected and the NO needs to adjust the fixed tariff to keep the regulatory constraint in balance. This highlights the role of the regulator to define proper market forecasts to set appropriate targets.

Figure 2: Price development; base case and regulatory approach



4.3 Evaluation

Although the regulatory approach provides a significant network extension and corresponding price developments, it is not clear whether this extension is a welfare improvement compared to an unregulated market. Therefore two counterfactuals are simulated: a welfare optimal extension pattern following the model described in Section 3.1.3 and a pure profit maximizing NO without regulatory restriction. The latter is an adjustment of the model described in Section 3.1.2 obtained by neglecting equation 11 and the fixed tariff component.

In a welfare optimal setting, the NO extends the pipeline network largely on similar paths as in the regulatory setting. Again the North-Stream project leads to more available Russian gas on the onshore pipelines, which is redistributed via Austria to Italy and France, although the actual extension pattern between Austria, Hungary, Slovakia and the Czech Republic differs from the one in the regulatory setting. In total about 60% of the extension volume of the welfare optimal capacities is constructed in the regulatory case (Table 1). About 16% of the regulatory setting capacity does not overlap with constructions in the welfare case, showing that the general investment pattern of the regulated NO is quite similar to a social planner.

Table 1: Result comparison

	Base Case	Profit	Regulatory Approach	Welfare Approach
Surplus 2020 [bn € per a]				
Consumer surplus	103.85	103.85	117.30	118.24
Producer surplus	17.13	16.60	9.69	9.32
Sum	120.98	120.45	126.99	127.56
Prices in 2020 €/MWh				
Central EU	14.32	14.45	12.78	12.68
South EU	10.30	15.61	13.50	13.40
East EU	15.71	10.72	11.17	11.86
Realized Investments until 2020 [bcm/a]				
Total	0	117.0	267.6	432.4

If the regulatory cap is not implemented and the NO is maximizing its profits without balancing variable revenue and the fixed tariff, the total investment volume is significantly reduced. Less than 30% of the welfare optimal capacity volume is reached, of which about 25% are not connections considered in the welfare case. The regulatory approach thus provides an improvement compared to a simple unregulated setting.

This last result still holds when prices are compared. The regulatory approach reaches a similar price level as the welfare case in the final 2020 period, although prices in Central and South Europe are higher than in the regulatory case for earlier periods (Figure 3). For East Europe the welfare case shows a much faster price increase, and thus convergence with continental European price levels, than in the regulatory approach. The profit case shows a higher price level in Central and South Europe with intermediate price development in East Europe. The price differences between the regions remain through the last period; thus intra- European congestion is not significantly reduced in this case.

Furthermore, the overall consumer and producer surplus development shows that the regulatory approach indeed approaches the welfare levels over the periods under study. Both the absolute welfare level and the share of producer surplus in the regulatory case move in the direction of the welfare optimum (

Figure). Over the periods, a shift between producer and consumer surplus can be observed. In the profit setting the welfare development is similar to the base case in which no further additions take place. Further, due to congestion between the nodes, the producer surplus also remains high.

The basic simulation results show that the regulatory approach does provide a way to achieve an investment pattern close to welfare optimal conditions.

Figure 3: Price development; regulatory approach, pure profit, and welfare approach

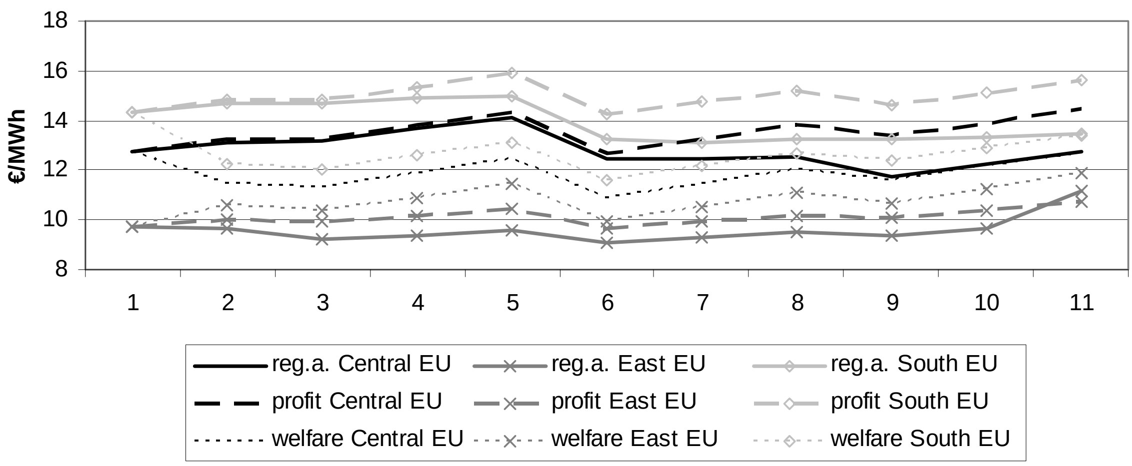
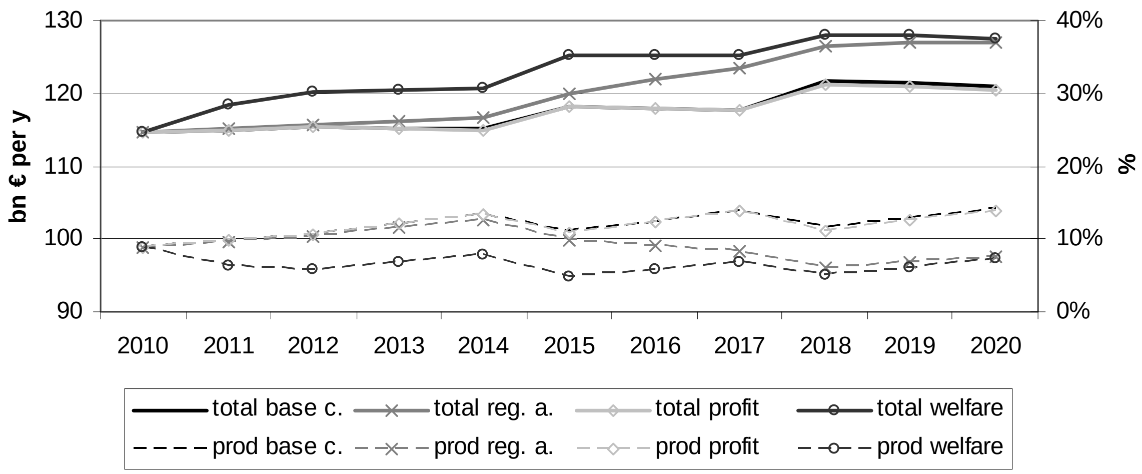


Figure 4: Welfare development and share of producer surplus



4.4 Sensitivities of model assumptions

The basic model assumption that the NO is only allowed to invest in Europe, while transmission revenue is collected from the entire grid is rather unlikely for real world implementation. Thus we adjust the model definition to evaluate the impact on the results by changing the profit function (equation 10) of the NO: the income from pipeline transport (first term, right hand side) only accounts for nodes connecting intra-European nodes, while transport on import pipelines into the European network are accounted with 50% assuming a profit/cost split with the NO of the exporting country. This approach represents a market framework in which a single entity (e.g. an independent system operator) can decide about network extensions within Europe whereas import projects would still require coordination with exporting countries, and are not considered within the regulatory approach. Second, we adjust this approach again by also leaving out the revenues and costs from import pipelines, thus limiting the regulatory approach completely to intra-European connections.

Under these more restrictive conditions, we nevertheless observe a lower price level (Figure 5) and a faster welfare convergence (Figure 6) than in the unrestricted regulatory approach (Section 4.1.2). The actual capacity extension is also lower in both cases. The case with a 50% on import lines reaches 86% of the total capacities of the normal regulatory case, while the pure EU case reaches 90%, both with a small share of different extended connections. Thus despite fewer capacity extensions, both cases slightly outperform the unrestricted regulatory approach. Furthermore, in both settings the fixed tariff component reaches a positive value after 2015.

Another model characteristic that is unlikely to hold in a real market setting is the assumed unrestricted capacity extensions between European countries within a ten-year timeframe. A total investment volume of more than 250 bcm per year of new capacity is rather challenging to implement. In a further sensitivity run, we therefore restrict capacity extensions to an upper limit of 5 bcm per year per connection. This small value provides a proper lower bound of the approach's performance. In this case, the price and welfare performance are worse than in the unrestricted regulatory approach. Especially toward the end of the considered time period, this case shows greater divergence (Figure 5). This is due to the increased demand in Europe requiring more transmission capacity, which is capped in this setting. The total invested capacity is only about 30% of the regulatory case, of which 30% are on different connections. Those are mainly utilized to allow for more flow from East European countries toward Italy, as the 5 bcm cap limits the use of the shortest connections. Nevertheless the majority of investment takes place on the same routes, highlighting the general superiority of those connections for investment projects.

As a final sensitivity adjustment, an *RPI* factor is included into the regulatory cap (equation 11). As the underlying market conditions change in the model, the regulator would need to adjust the cap accordingly to account for general demand and production changes outside the NO's influence. We simulate this by including a factor similar to the average demand increase in European countries. In this setting, the performance of the normal regulatory approach can slightly be outperformed with a lower price level (Figure) and a higher welfare level (

Figure). This is also confirmed by actual investment patterns. By including the RPI factor, the total added capacity is more than 60% higher than in the unrestricted regulatory approach, and reaches 92% of the welfare optimum with 82% of those investments taking place on the same connections. Thus, by calibrating the target factors the regulator can achieve a slightly faster convergence to the welfare optimum.

In sum the carried out sensitivity scenarios show that the basic performance of the regulatory approach remains stable over critical model assumptions.

Figure 5: Price comparison

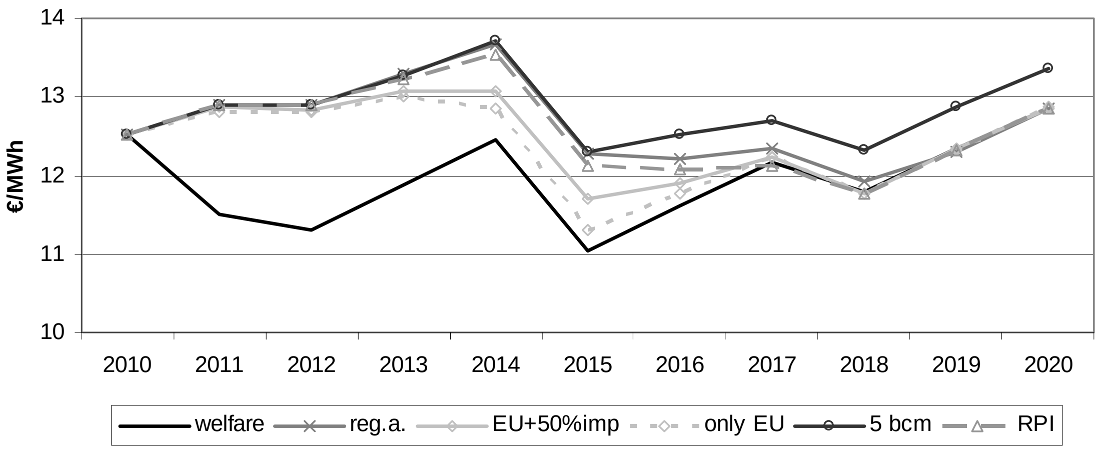
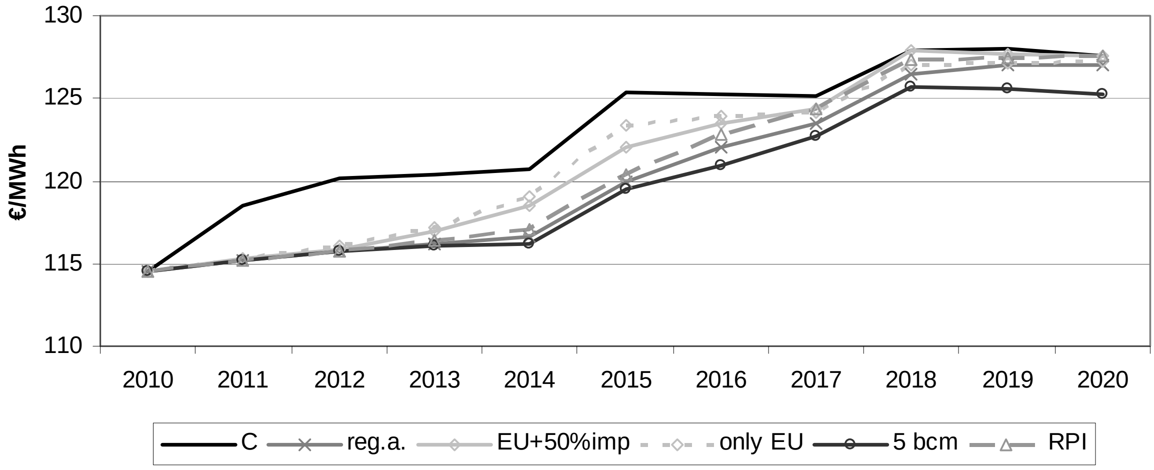


Figure 6: Welfare comparison



5 Conclusion

In this paper we study the structure of incentives to expand natural-gas transportation pipelines in Europe. We proposed the implementation of a bi-level price-cap model and compared the obtained results with a base case, a no-regulation case, and a welfare benchmark. The lower level of the bi-level price-cap program maximizes social welfare (consumer surplus minus production costs, transport costs and LNG costs) subject to an upper limit on natural gas production, pipeline capacity, LNG capacity (both liquefaction and regasification capacity limits), and storage capacity. The upper level models the maximization of the flow of profits of a network operator, subject to a cap constraint on its two-part tariff. The rebalancing of the fixed and the variable parts achieved, over time, the needed capacity investment for the European natural gas pipeline network system, and converged to the efficient steady-state equilibrium.

More specifically, we find that in the welfare-optimal benchmark setting, the NO extends the pipeline system largely on similar paths and capacity levels as in the regulatory two-part tariff setting. Meanwhile, a NO that unrestrictedly maximizes profits (without rebalancing its variable revenue and the fixed tariff) will invest smaller amounts, expanding capacity less than the welfare optimal. Convergence of prices in the regulatory case also resembles that of the welfare-optimal benchmark, while overall consumer and producer surplus development furthermore confirms that the regulatory approach indeed approaches the welfare levels over time. The NO invests in transmission capacities to increase the accessibility of Russian gas in Central Europe and Italy via Slovakia, Hungary, and Austria. Furthermore, the North Stream pipeline will provide excess gas quantities in Germany allowing routing toward southern and more western markets via new connections. Thus, the regulatory approach, based on Vogelsang (2001) and Hogan et al. (2010), does provide a way to achieve an investment pattern in the European pipeline network close to welfare optimal conditions.

We obtain these results for the case when the NO was only allowed to invest in Europe, while transmission revenue was collected from the entire grid. This is rather unlikely in real world implementation, so we further assume that the income from pipeline transport was only accounted for nodes connecting intra-European nodes, while transport on import pipelines into the European network accounted for a 50% profit/cost split with the exporting country. Successively, we also adjust this last approach by leaving out the revenues and costs from import pipelines, thus completely limiting the regulatory approach to intra-European connections. Under all these more restrictive conditions, we observe a lower price level and a faster welfare convergence of the regulatory two-part tariff approach than in the original setting.

Furthermore, when in our ten-year timeframe we constrain capacity extensions to less than 5 bcm per year per connection (acknowledging the real-world challenge of achieving larger investment capacity volumes), the majority of investment is ultimately carried out on the same routes as before. Additionally, the inclusion of an *RPI* factor into the regulatory cap also confirmed that under all the sensitivity scenarios that the basic welfare-optimal performance of the regulatory two-part tariff approach prevailed.

Our analyses thus suggest that an incentive mechanism as the one proposed in this paper could contribute to the development of the entire European pipeline system, generating price convergence, capacity increases and considerable welfare improvements. This approach would also be coherent with the establishment of a harmonized European regulatory framework that would stimulate pipeline investment via stable market conditions. Directive 2009/713/EC provides a first step in this direction: vertical integration, ownership unbundling, and an ISO are required of all EU countries no later than March 3, 2012. Such a framework, as well as the creation of a European Agency for the Cooperation of Energy Regulators (ACER), provides a real world institutional setting prone for a Hogan et al. (2010) type of mechanism.

Of course, to reach fully applicability, more granular data for pipeline, LNG and storage capacity should be considered, a fact that would increase the computational intensity of simulations. Likewise, other issues need to be considered in future research work, such as uncertain conditions in demand and supply, existence of market power, various distinct NOs and, probably more importantly, the investment trade-off among in pipelines, LNG terminals, and storage facilities.

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