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a natural gas transportation network**

**by**

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# Optimal tariff and ownership structure for a natural gas transportation network

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**Abstract:** This paper discusses how the government can set transportation tariffs to induce socially optimal transportation of natural gas in a network owned by a syndicate of gas producers. In a setting where the gas is exported to end-user markets and a foreign third party has access to the gas grid, it would be optimal to differentiate the tariff. However, if the tariff scheme has to be based on the principles of open access on nondiscriminatory conditions, organizing the transportation network as a syndicate of gas producers rather than as a separate entity enables the syndicate to levy a common tariff acting as an imperfect substitute for unconstrained tariff discrimination between the network owners and the third party.

# 1 Introduction

Over the last two decades there has been a general trend towards liberalization of the natural gas pipeline sector. Norway is a major producer of natural gas in the European gas market. A small part of the production is used domestically and mainly for industrial purposes. Therefore, the national interests in the gas sector are almost completely aligned with export interests. This implies that the regulator's interests and profit incentives of domestically owned firms coincide. In Norway, the EU directives in the natural gas market has induced a reorganization of the gas transmission network. Hence, Norway has chosen to comply with the rules laid down in the EU directives. An important feature of the EU's deregulatory policies has been to liberalize access to networks, which prior to the reforms were under the control of incumbent monopolies. In particular, this applies to the gas sector. Many countries have designed pricing schemes for access to pipeline networks based on the principles of open access under nondiscriminatory conditions. The upstream pipeline networks and production facilities are, however, exempt from the general rules in the directives.

On the Norwegian continental shelf, there are several companies producing gas on separate gas fields. The gas producers have to transport the natural gas through the Norwegian gas grid to reach their downstream customers on the continent. In compliance with the EU directives, the selling and transportation roles have been separated. Therefore, the network has been reorganized as a syndicate consisting of the major part of the gas producers on the Norwegian continental shelf, and an independent system operator has been established with assignment of transportation rights as one of its main tasks. As an alternative to organizing the gas grid as a syndicate, it could be organized as an entity separate from extraction and marketing activities, possibly owned by the government. This is the case in the Norwegian electricity sector, where the transmission system is a separate company owned by the Norwegian government.

The North Sea network for transportation of natural gas is a prime example of a natural monopoly. Most of the costs of the infrastructure are fixed and sunk. This renders the transportation network an essential facility which is neither commercially nor socially worthwhile to duplicate, everything else equal. Therefore, the network owner has some market power over the gas producers that need access to the transportation network. The conditions

for access to the network should then be regulated.

Rules for access to the upstream pipeline network are given by the government. We assume that the government and the network owners have complete knowledge about the demand for gas in the downstream markets, the production technology and the costs of producing the gas. The governing principle for access is that it has to be given to natural gas undertakings and eligible customers. Shippers with a duly substantiated reasonable need have right to access on objective and nondiscriminatory terms. Given the capacity of the gas transportation system and the regulated transportation tariff, a gas producer chooses his optimal gas transportation volume. If the capacity becomes scarce, there has to be rationing to equate the demand to the transportation capacity. According to the present Norwegian allocation rules the members of the syndicate of producers have priority in booking transport capacity up to 200% of their owner share in the gas grid.

A syndicate of gas producers is related to the utilization agreements the owners of a gas field make to explore the gas in a most efficient way. The gas producers cooperate through utilization agreements to increase the overall production above the levels that would have been achieved from nonunitized production, while the network owners cooperate in the syndicate to lower their transportation costs to market their gas. The syndicate of gas producers is also related to an input joint venture, where the members share ownership of a facility that produces an important input. In our setting, the gas producers share the ownership of the transportation network, which is an essential facility to market the gas of the network owners.

There is an extensive literature on optimal access pricing, see e.g., Laffont and Tirole (1994). Cremer and Laffont (2002) as well as Cremer, Gasmi and Laffont (2003) discussed optimal access pricing in the natural gas pipeline sector. Cremer, Gasmi and Laffont examined optimal tariffs in a competitive market, while Cremer and Laffont discussed pricing of transportation of gas under perfect as well as imperfect competition. Hagen, Kind and Sannarnes (2007) discussed optimal tariffs in the case where the transport facilities are owned entirely by a national gas producer possibly with some public ownership share. Our paper is also related to Chen and Ross (2003) which discussed an input joint venture where the members cooperate upstream, while they are competing downstream.

More precisely, we discuss how the government can set transportation tariffs to induce socially optimal transportation of natural gas in a gas transportation network, where the gas grid is owned by a syndicate of gas pro-

ducers. We further discuss how the network owners' demand for transportation capacity affects the optimal tariff scheme for a gas producing country, where the tariff scheme is based on the principles of open access on nondiscriminatory conditions. We assume Cournot competition in the downstream markets.

The major insights of this paper is that for a tariff scheme based on the principles of open access on nondiscriminatory conditions, the regulator has to balance the effect on the syndicate's profits from the third party's transportation of gas against the efficiency loss of reduced transportation volume of the network owners in the downstream markets from a marginal increase in the tariff. Organizing the transportation network as a syndicate of gas producers rather than as a separate entity enables the syndicate to levy a tariff common to all users acting as an imperfect substitute for unconstrained tariff discrimination between the network owners and the third party.

In section 2, we develop a simplified two-stage economic model for analyzing these issues using backward induction. Section 3 takes a closer look at stage 2, discussing optimal short-term efficiency under Cournot competition. In section 4, we analyze stage 1, where a regulator sets the tariffs, with the aim of maximizing the profits of a gas exporting country. Section 5 discusses the effects from the network owners also competing in the downstream markets with a foreign gas producer with his own gas transportation facility. In section 6, we assume that some of a network owner's gas production is used domestically. Section 7 briefly concludes.

## **2 A simplified model for transportation of gas**

We shall consider the case where the transportation infrastructure is owned by a syndicate of gas producers, as in the Norwegian gas sector. There are assumed to be two gas producers participating in the syndicate, indexed by  $i = 1, 2$ . We assume that the network is fully domestically owned. The gas producers serve the end-user markets in several foreign countries, like the network owners of the Norwegian gas grid serving the end-user markets in the EU.

We assume that the capacity of the transportation infrastructure is given. With given tariffs, the gas producers maximize their individual profits independently. We assume that there is also a gas producer without any transportation infrastructure of his own, who depends on access to the established network in order to sell his gas. The nonfacility based producer is owned by foreigners and will be referred to as the third party, denoted by the subscript  $T$ . The gas producers compete in the downstream markets. A domestic regulator maximizes the national interests and sets transportation tariffs in order to maximize the profits of the syndicate. We can summarize the actions in the following two-stage game:

- Stage 1: The regulator sets the tariff in order to maximize the profits for the fully domestically owned gas producers.
- Stage 2: The gas producers maximize their individual profits by choosing optimal quantities in a downstream market subject to Cournot competition.

We solve the problem by backward induction. We first analyze the behavior in the stage 2 subgame and then work backward.

A network owner has to pay a tariff,  $\tau_N$ , per unit of transported gas in a period, while the third party pays  $\tau_T$ . However, if the tariff scheme is based on the principles of open access on nondiscriminatory conditions, the tariff scheme is the same both for the network owners and the third party,  $\tau = \tau_N = \tau_T$ . Then the income to the syndicate from the gas transported in a period is given by  $\tau(x_1 + x_2 + x_T)$ , where  $x_1$ ,  $x_2$ ,  $x_T$  are the transported volumes of network owner 1, network owner 2 and the third party, respectively. Network owner  $i$ 's part of the syndicate's tariff income is denoted by  $\alpha_i \tau(x_1 + x_2 + x_T)$ , where  $\alpha_i$  is member  $i$ 's owner share in the syndicate.

Because the depletion capacity of developed gas fields is limited, it is reasonable to assume that the firms compete in quantities in the downstream market.<sup>1</sup> The gas sales or gas transportation of a network owner  $i$  in a representative period is denoted  $x_i$ , with corresponding downward-sloping (inverse) demand curve  $p_i(x_1, x_2, x_T)$ . The activity-related costs in the gas sector consist of two parts. The first part, to be denoted  $c_i^a(x_i)$ , measures the

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<sup>1</sup>Intuitively, we are appealing to a game à la Kreps and Scheinkman (1983), where firms choose capacities prior to the stage we are analyzing. To a large extent, the capacity constraints facing different gas producers are common knowledge in the industry. Moreover, major capacity changes are both time consuming and expensive.

costs of gas extraction and of accessing the transportation pipeline.<sup>2</sup> This term depends solely on the producer's own volume. The other part is the transportation cost, which may depend on the transported volumes of gas, and will be denoted  $C^t(x_1, x_2, x_T)$ . We also assume that  $\partial C_i^t / \partial x_i > 0$  and  $\partial^2 C_i^t / (\partial x_i)^2 > 0$  and that  $\partial C_T^t / \partial x_T > 0$  and  $\partial^2 C_T^t / (\partial x_T)^2 > 0$ . The reason for this may for instance be that it is necessary to increase the pressure if too much gas is fed into the pipeline, which depends on the total volume transported. This will increase the marginal costs of transporting gas for all producers. The costs to the syndicate from gas transportation in a period incurred by owner  $i$  is denoted by  $\alpha_i C^t(x_1, x_2, x_T)$ .

For a given capacity  $x^K$  a network owner is maximizing profits given by:

$$\pi_i = \begin{matrix} p_i x_i - c_i^a(x_i) - \tau x_i + \\ \alpha_i (\tau(x_1 + x_2 + x_T) - C^t(x_1, x_2, x_T) - C^K(x^K)) \end{matrix}, \quad (1)$$

where  $C^K(x^K)$  is capacity cost in a period and is assumed to be fixed and sunk. If not explicitly stated the network capacity is not scarce.

The profit of the third party is given by:

$$\pi_T = p_T x_T - c_T^a(x_T) - \tau x_T \quad (2)$$

### 3 Stage 2: Competition in the downstream markets

We assume that the domestically owned gas producers and the third party compete in quantities in the downstream markets. This means that the markets are connected, so that gas delivered by one producer is a (possibly imperfect) substitute for gas delivered by the other producers. Member  $i$  chooses the optimal quantity in a period to maximize his profits,  $\pi_i$ , given by equation (1). The first order condition for network owner  $i$  is:

$$p_i + \frac{\partial p_i}{\partial x_i} x_i - \frac{\partial c_i^a}{\partial x_i} - \tau + \alpha_i \left( \tau - \frac{\partial C^t}{\partial x_i} \right) = 0. \quad (3)$$

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<sup>2</sup>The part of the costs,  $c_i^a(x_i)$ , could alternatively be seen as an opportunity cost of using the gas; i.e., the value of the gas transported by boat as liquefied gas to other downstream markets or the value of the gas stored and sold at a later point in time.



The optimal quantities in our setting differ from a situation with perfect competition because a network owner knows that increasing quantity will reduce his price, given the other owners' quantities. This is represented by  $\frac{\partial p_i}{\partial x_i} x_i$  in equation (3).

With perfect competition, the syndicate members take the gas price in the downstream markets as given. For an optimal transportation volume in the case of perfect competition, the owner's marginal willingness to pay ( $p_i$ ) is equated to the marginal costs of increased transportation ( $\frac{\partial c_i^a}{\partial x_i} + \tau$ ). However, in the present case we have to adjust for the fact that a marginal increase in network owner  $i$ 's transportation leads to changed profits for the syndicate, part of which is accruing to  $i$ 's owner share.

The first order condition for the third party is given by maximizing equation (2) with respect to  $x_T$ .

$$p_T + \frac{\partial p_T}{\partial x_T} x_T - \frac{\partial c_T^a}{\partial x_T} - \tau = 0. \quad (4)$$

## 4 Stage 1: The regulator sets the tariffs

We assume that a regulator maximizing the profits of a gas exporting country will maximize the total profits for the domestically owned gas producers. Then the regulator's maximization problem for given capacity  $x^K$  is:

$$\max_{\tau_N, \tau_T} W = \sum_{i=1}^2 \left[ \alpha_i \left( \tau_T x_T + \tau_N (x_1 + x_2) - C^t(x_1, x_2, x_T) - (C^k(x^k)) \right) \right], \quad (5)$$

where  $\tau_N = \tau_T = \tau$  if the regulator cannot differentiate the tariffs.

### 4.1 Perfect competition as a benchmark

As a benchmark, we assume that there is perfect competition in the downstream market and that the regulator can differentiate the tariff between the network owners and the third party. Then the first order condition for the optimal tariff to the third party is given by maximizing (5) with respect to  $\tau_T$  which implies:

$$\left( \tau_T - \frac{\partial C^t}{\partial x_T} \right) \frac{dx_T}{d\tau_T} + x_T = 0. \quad (6)$$

Rewriting this equation gives the inverse elasticity rule (the Lerner index), which is the monopoly markup, and is equal to:

$$\frac{\left( \tau_T - \frac{\partial C^t}{\partial x_T} \right)}{\tau_T} = \frac{1}{\varepsilon_T}, \quad (7)$$

where  $\varepsilon_T = -\frac{dx_T}{d\tau_T} \frac{\tau_T}{x_T}$  is the elasticity of demand for the third party's gas transportation with respect to the tariff rate. An explicit characterization of the optimal monopoly tariff is obtained by rewriting (7)

$$\tau_T = \frac{1}{1 - \frac{1}{\varepsilon_T}} \frac{\partial C^t}{\partial x_T}. \quad (8)$$

The optimal tariff for the network owners is given by maximizing (5) with respect to  $\tau_N$ . The first order condition is equal to:

$$\sum_{i=1}^2 \left[ p_i - \frac{\partial c_i^a}{\partial x_i} - \tau_N + \alpha_i \left( \tau_N - \frac{\partial C^t}{\partial x_i} \right) \right] \frac{dx_i}{d\tau_N} + \sum_{i=1}^2 \left[ (1 - \alpha_i) \left( \tau_N - \frac{\partial C^t}{\partial x_i} \right) \right] \frac{dx_i}{d\tau_N} = 0. \quad (9)$$

At the profit maximizing volumes for the network owners, the terms in the first square brackets vanish, so that we have:

$$\sum_{i=1}^2 \left[ (1 - \alpha_i) \left( \tau_N - \frac{\partial C^t}{\partial x_i} \right) \right] \frac{dx_i}{d\tau_N} = 0. \quad (10)$$

The optimal tariff for the network owners is given by equation (10) and is equal to marginal costs ( $\tau_N = \frac{\partial C^t}{\partial x_i}$ ). Therefore, with perfect competition in the downstream markets, if it is possible to differentiate tariffs between the network owners and the third party, the optimal tariff for the domestically owned gas producers is marginal costs, while the third party has to pay a monopoly tariff.

## 4.2 Cournot competition and differentiated tariff rates

With Cournot competition and differentiated tariff rates, the optimal tariff charged to the third party is given by maximizing (5) with respect to  $\tau_T$ . As shown in Appendix A, at the profit maximizing volumes for the network owners, the first order condition takes the form:

$$\begin{aligned} & \underbrace{\left(\tau_T - \frac{\partial C^t}{\partial x_T}\right) \frac{dx_T}{d\tau_T}}_2 + \underbrace{\left(x_1 \frac{\partial p_1}{\partial x_T} + x_2 \frac{\partial p_2}{\partial x_T}\right) \frac{dx_T}{d\tau_T}}_3 + \underbrace{x_T}_1 + \\ & \underbrace{\sum_{i=1}^2 \left[ (1 - \alpha_i) \left(\tau_N - \frac{\partial C^t}{\partial x_i}\right) + x_j \frac{\partial p_j}{\partial x_i} \right] \frac{\partial x_i}{\partial x_T} \frac{dx_T}{d\tau_T}}_4 = 0 \quad \text{for } j \neq i.. \end{aligned} \quad (11)$$

The various terms of equation (11) can be explained as follows:

1. A marginal increase in the tariff to the third party will ceteris paribus increase the tariff income to the syndicate. This first order effect is given by  $x_T$  in equation (11).
2. However, a marginal increase will also alter the third party's transportation volume of gas. A higher tariff will decrease the third party's gas sales and ceteris paribus reduce the profits of the syndicate. This second order effect is given by  $\left(\tau_T - \frac{\partial C^t}{\partial x_T}\right) \frac{dx_T}{d\tau_T}$  in equation (11).
3. The decrease in the third party's transportation of gas will cause externalities in the form of price effects on the network owners' gas sales. This is because of the fact that a decrease in the third party's gas sales will have a positive effect on the prices of the network owners' gas sales, which is represented by  $\left(x_1 \frac{\partial p_1}{\partial x_T} + x_2 \frac{\partial p_2}{\partial x_T}\right) \frac{dx_T}{d\tau_T}$  in equation (11). Ceteris paribus this will increase the profits of network owners.
4. A decrease in the third party's gas sales because of a marginal increase in  $\tau_T$  will also increase the network owners' gas sales and therefore increase the syndicate's profits as long as  $\tau_N$  is higher than marginal costs. This total indirect effect on the network owners' gas sales is given by  $\sum_{i=1}^2 \left[ (1 - \alpha_i) \left(\tau_N - \frac{\partial C^t}{\partial x_i}\right) + x_j \frac{\partial p_j}{\partial x_i} \right] \frac{\partial x_i}{\partial x_T} \frac{dx_T}{d\tau_T}$  for  $j \neq i$  in equation (11).

In maximizing profits, a network owner will take into account the tariff he has to pay to the syndicate. Because network owners act both as shippers of gas and owners of the network, they will internalize the part of the tariff above marginal costs that accrue to them from their owner share,  $\alpha_i$ , of the syndicate. However, part of the tariff payments from network owner  $i$  is indirectly paid to the other network owner because he owns  $(1 - \alpha_i)$  of the syndicate. The increased profits from the induced increase in gas sales of network owners is also reduced because of the fact that increased gas transportation of a network owner decreases the price and profits for the other owner. This latter effect for network owner  $i$  is given by  $x_i \frac{\partial p_i}{\partial x_j}$ .

Reorganizing this equation gives the inverse elasticity rule (the Lerner index) corrected for externalities from the change in the third party's gas sales induced by the marginal increase in  $\tau_T$  and is given by:

$$\frac{\tau_T - \left[ \frac{\partial C^t}{\partial x_T} - \sum_{i=1}^2 \left( x_i \frac{\partial p_i}{\partial x_T} + x_j \frac{\partial p_j}{\partial x_i} \frac{\partial x_i}{\partial x_T} \right) - \sum_{i=1}^2 (1 - \alpha_i) \left( \tau_N - \frac{\partial C^t}{\partial x_i} \right) \frac{\partial x_i}{\partial x_T} \right]}{\tau_T} = \frac{1}{\varepsilon_T} \quad \text{for } j \neq i.. \quad (12)$$

The first term in the square brackets in the numerator is the marginal cost of transporting a marginal unit of gas for the third party. The second term is the net repercussions for the network owners' profits from the induced increase in the gas producers' quantities sold and transported. The third term is the increased profits for the syndicate from an increase in the network owners' gas sales because of the decrease in gas sales of the third party.

Because  $\frac{\partial p_i}{\partial x_T} < 0$  and  $\frac{\partial x_i}{\partial x_T} < 0$ , the optimal tariff to the third party is higher than in the monopoly case, given by equation (7), as long as the indirect price effects from an increase in the network owners gas sales,  $\sum_{i=1}^2 x_j \frac{\partial p_j}{\partial x_i} \frac{\partial x_i}{\partial x_T}$ , are lower than the effect of the other externalities; i.e., the value of the last two terms in the square brackets in the numerator of (12) is negative. Setting the tariff, the regulator will, in addition to exerting market power, also internalize the externalities from indirect price effects and from the fact that increased gas sales for network owner  $i$  will increase the owner share profits for the other network owner.

The optimal tariff for the network owners is given by maximizing (5) with respect to  $\tau_N$ . As shown in Appendix A, at the profit maximizing volumes for the network owners, the first order condition takes the form:

$$\sum_{i=1}^2 \left[ \overbrace{\left(1 - \alpha_i\right) \left(\tau_N - \frac{\partial C^t}{\partial x_i}\right)}^1 + \overbrace{x_j \frac{\partial p_j}{\partial x_i}}^2 \right] \frac{dx_i}{d\tau_N} + \overbrace{\left(\tau_T - \frac{\partial C^t}{\partial x_T} + x_1 \frac{\partial p_1}{\partial x_T} + x_2 \frac{\partial p_2}{\partial x_T}\right) \frac{dx_T}{d\tau_N}}^3 = 0 \quad \text{for } j \neq i. \quad (13)$$

The various terms in the first order conditions can be explained as follows

1. The first term in the square brackets is the adverse effect on profits of a marginal increase in the tariff on network owners' transportation volume in the downstream markets. Absent of any other effects, the optimal tariff is equal to marginal costs ( $\tau_N = \frac{\partial C^t}{\partial x_i}$ ) as occurs in perfect competition. However, under Cournot competition the optimal tariff may differ from marginal costs because of externalities. If the tariff is greater than marginal costs this will alter the optimal gas sales of the network owner in the second stage. Because the network owners both act as shippers of gas and owners of the network, they will internalize the tariff effects on profits that accrue to their owner share,  $\alpha_i$ , of the syndicate profits. However, the part of the effects on profits that accrues to the other network owner through his owner share,  $(1 - \alpha_i)$ , will act as an externality in the network owner's second stage profit maximization. To correct for this externality, the regulator maximizing domestic profits will reduce the tariff to the network owners towards marginal costs.
2. In setting the tariffs, the regulator might try to coordinate the volumes of gas sales so as to maximize total profits, while the individual network owner would maximize his profits, given the others' gas sales. A planner could use the tariff scheme strategically (setting higher tariffs) to reduce the network owners' gas sales and thereby increase the total profits. A change in gas transported by network owner  $i$  through higher tariffs changes the gas price for the other network owner  $j$ . This effect is captured by the second part in the square brackets, where  $x_j \frac{\partial p_j}{\partial x_i} < 0$ .

Ceteris paribus, it would be optimal for the regulator to set higher tariffs to reduce the gas transportation by the network owners and by adjusting for the negative externality that gas transportation of one agent has on the price of the other network owners' gas.

3. A marginal increase in  $\tau_N$  will increase the optimal gas sales of the third party and thereby increase the profits for the syndicate of network owners. This will ceteris paribus increase the optimal tariff for the network owners. The increase in profits is given by  $\left(\tau_T - \frac{\partial C^t}{\partial x_T}\right) \frac{dx_T}{d\tau_N}$ . However, the increase in the third party's gas sales also induces indirect price effects, which decrease the price and the profits of the network owners and are given by the terms  $x_1 \frac{\partial p_1}{\partial x_T} \frac{dx_T}{d\tau_N}$  and  $x_2 \frac{\partial p_2}{\partial x_T} \frac{dx_T}{d\tau_N}$ . The effects are indeterminate.

Compared with the situation under perfect competition, Cournot competition with differentiated tariff rates changes the optimal tariff to the network owners in several ways. Maximizing his profits under Cournot competition a network owner does not take into account that a decrease in his gas sales will increase the price and the profits of the other owners and increase the gas sales of the third party. The latter effect will increase the syndicate's profits, but also induce a decrease in the gas prices of the network owners. The optimal tariff is characterized by equating the increase in profits from the third party's transportation of gas to the costs of network owners of a marginal increase in the tariff, corrected for indirect price effects.

Instead of organizing the network as a syndicate of gas producers, the network could be organized as an entity separated from extraction and marketing activities. In our setting, this would be equivalent to  $\alpha_i = 0$ . In that case, the optimal tariff is given by:

$$\sum_{i=1}^2 \left[ \left( \tau_N - \frac{\partial C^t}{\partial x_i} \right) + x_j \frac{\partial p_j}{\partial x_i} \right] \frac{dx_i}{d\tau_N} + \left( \tau_T - \frac{\partial C^t}{\partial x_T} + x_1 \frac{\partial p_1}{\partial x_T} + x_2 \frac{\partial p_2}{\partial x_T} \right) \frac{dx_T}{d\tau_N} = 0 \quad \text{for } j \neq i. \quad (14)$$

Organizing the gas grid as a syndicate rather than as a separate entity<sup>3</sup> increases the optimal tariff for the network owners because of the fact that the network owners take their owner shares in the syndicate into account

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<sup>3</sup>On the Norwegian continental shelf, the government has to buy or expropriate the gas grid to organize the transportation network as a separate entity.

when they are deciding on optimal transport quantities. Therefore, the gas producers' owner shares in the syndicate reduce the adverse effect of a marginal increase in the tariff for the transportation volume in the downstream markets.

Both cost conditions and the externality that gas sales of one gas producer has on the price for other network owners may vary among the network owners. Because of this fact it would be optimal to have a separate tariff scheme for each network owner. The adverse effect from an equal tariff scheme for the network owners will however be present regardless of whether the network is organized as a syndicate or as a separate entity.

### 4.3 Equal tariff rates

We now assume that the network is owned by a syndicate of gas producers and that the tariff scheme is to be based on the principles of open access on nondiscriminatory conditions. Therefore, the tariffs have to be the same for the network owners and the third party,  $\tau = \tau_N = \tau_T$ . Hence, the optimal equal tariff is given by maximizing (5) with respect to  $\tau$ . The first order condition in this case is:

$$\begin{aligned} & \overbrace{\left( \tau - \frac{\partial C^t}{\partial x_T} \right) \frac{dx_T}{d\tau}}^2 + \overbrace{\left( x_1 \frac{\partial p_1}{\partial x_T} + x_2 \frac{\partial p_2}{\partial x_T} \right) \frac{dx_T}{d\tau}}^3 + \overbrace{x_T}^1 = \\ & - \underbrace{\sum_{i=1}^2 (1 - \alpha_i) \left( \tau - \frac{\partial C^t}{\partial x_i} \right) \frac{dx_i}{d\tau}}^4 - \underbrace{\sum_{i=1}^2 x_j \frac{\partial p_j}{\partial x_i} \frac{dx_i}{d\tau}}^5 \quad \text{for } j \neq i. \end{aligned} \tag{15}$$

The left-hand side of equation (15) is the syndicate's increased profits from the third party's transportation of gas because of a marginal increase in the tariff. The right-hand side is the adverse effect on network owners because of a marginal increase in the tariff for the gas transported to the downstream markets. The optimal tariff is characterized by equating the increase in profits to the costs for network owners from a marginal increase in the tariff. The various terms in the first order conditions can be explained as follows.

1. A marginal increase in the tariff increases ceteris paribus the syndicate's profits by  $x_T$ .

2. However, the increase in the syndicate's profits is reduced because of the fact that a higher tariff reduces the gas transported by the third party,  $\left(\tau - \frac{\partial C^t}{\partial x_T}\right) \frac{dx_T}{d\tau}$ .
3. The positive effect from increased profits is strengthened by the effect that reduced gas transportation of the third party has on the price of the network owners' gas. A marginal increase in the tariff reduces the gas transported by the third party and hence, increases the prices and profits of the network owners. This increase in profits is represented by  $\left(x_1 \frac{\partial p_1}{\partial x_T} + x_2 \frac{\partial p_2}{\partial x_T}\right) \frac{dx_T}{d\tau}$  on the left-hand side of equation (15). These effects on the syndicate's profits are similar to the effects of a marginal increase in a specific third party tariff as in equation (11).
4. The costs of a marginal increase in the tariff because of reduced gas transported by the network owners, is given by  $-\sum_{i=1}^2 (1 - \alpha_i) \left(\tau - \frac{\partial C^t}{\partial x_i}\right) \frac{dx_i}{d\tau}$  on the right-hand side of equation (15). The gas producers participating in the syndicate act both as shippers of gas and as owners of the network. An externality occurs because network owner  $i$  does not take into account that  $1 - \alpha_i$  of his tariff payments, in excess of marginal costs, will increase the profits for the other network owners. Optimizing the common tariff, the regulator has to take into account this externality. A marginal increase in the tariff will increase this externality and therefore increase the efficiency loss from the network owners' second stage optimization problem.
5. Because a marginal increase in the tariff reduces the gas transported by a network owner, the reduced transportation from network owner  $i$  will increase the price and profits for the other owner. This indirect price effect on network owner  $j$ 's gas price is given by  $x_j \frac{\partial p_j}{\partial x_i} \frac{dx_i}{d\tau}$  and will reduce the costs of a marginal increase in the tariff.

The optimal common tariff is between the optimally differentiated tariffs. The presence of a foreign third party calls for a monopoly tariff adjusted for the indirect price effects of the gas sales from the third party. However, a higher tariff than marginal cost gives an adverse effect on the short-run optimal use of the gas grid for the network owners. The optimal common tariff, adjusted for this adverse effect and indirect price effects takes the form



of an adjusted Lerner index as given below where the numerator on the left-hand side of (16) is marginal profits for the syndicate per unit change in gas transport for the third party.

$$\frac{\tau - \frac{\partial C^t}{\partial x_T} + \overbrace{x_1 \frac{\partial p_1}{\partial x_T} + x_2 \frac{\partial p_2}{\partial x_T}}^1 + \overbrace{\sum_{i=1}^2 \left[ x_j \frac{\partial p_j}{\partial x_i} + (1 - \alpha_i) \left( \tau - \frac{\partial C^t}{\partial x_i} \right) \right] \frac{dx_i}{d\tau}}^2}{\tau} = \frac{1}{\varepsilon_T} \quad \text{for } j \neq i. \quad (16)$$

Equation (16) shows that the indirect price effects increase the optimal tariff, while the adverse effect of the network owners' transportation of gas reduces the optimal tariff compared to the monopoly case, given by equation (7). Equation (16) deviates from equation (7) for the following reasons.

1. Indirect price effects represented by  $x_1 \frac{\partial p_1}{\partial x_T}$  and  $x_2 \frac{\partial p_2}{\partial x_T}$  in the numerator on the left-hand side of equation (16) take into account that a decrease in the third party's gas sales will increase the prices of the network owners' gas sales.
2. The last part of the numerator on the left-hand side of (16) represents both indirect price effects and the externality because of the fact that a marginal increase in the tariff has an adverse effect on network owners' transportation volume in the downstream markets. Ceteris paribus, the adverse effect on transportation volume reduces the optimal tariff and is given by  $(1 - \alpha_i) \left( \tau - \frac{\partial C^t}{\partial x_i} \right)$ . The indirect price effects are given by  $x_j \frac{\partial p_j}{\partial x_i}$  and shows that a higher tariff reduces the gas transported by a network owner and thereby increases the price and profits for the other owner. Both these externalities are evaluated per unit change in the third party's gas sales initiated by a change in the tariff, to make them comparable to the other terms in the numerator of (16).

An explicit characterization of the optimal tariff is obtained by rewriting (16)

$$\tau = \overset{1}{\widetilde{m}u}(\overset{2}{cb} - \overset{3}{\widetilde{p}e}), \quad (17)$$

where  $\widetilde{m}u$  represents the mark up factor and is given by  $\widetilde{m}u = \frac{1}{1 + \frac{(1-\alpha_1)\frac{dx_1}{d\tau} + (1-\alpha_2)\frac{dx_2}{d\tau}}{\frac{dx_T}{d\tau}} - \frac{1}{\varepsilon_T}}$ .

The auxilliary variable  $\widetilde{c}b$  represents the cost base and is given by  $\widetilde{c}b = \frac{\partial C^t}{\partial x_T} + \frac{(1-\alpha_1)\frac{\partial C^t}{\partial x_1}\frac{dx_1}{d\tau} + (1-\alpha_2)\frac{\partial C^t}{\partial x_2}\frac{dx_2}{d\tau}}{\frac{dx_T}{d\tau}}$ , while  $\widetilde{p}e$  represents the price effects and is given by  $\widetilde{p}e = \left[ \frac{x_2\frac{\partial p_2}{\partial x_1}\frac{dx_1}{d\tau} + x_1\frac{\partial p_1}{\partial x_2}\frac{dx_2}{d\tau}}{\frac{dx_T}{d\tau}} + x_1\frac{\partial p_1}{\partial x_T} + x_2\frac{\partial p_2}{\partial x_T} \right]$ .

The various terms in equation (17) could be explained as follows.

1. The markup factor on net incremental costs in the optimum tariff formula is given by  $\frac{1}{1 + \frac{(1-\alpha_1)\frac{dx_1}{d\tau} + (1-\alpha_2)\frac{dx_2}{d\tau}}{\frac{dx_T}{d\tau}} - \frac{1}{\varepsilon_T}}$ . This is in the nature of a

monopoly markup as in equation (8), except for the factor  $\frac{(1-\alpha_1)\frac{dx_1}{d\tau} + (1-\alpha_2)\frac{dx_2}{d\tau}}{\frac{dx_T}{d\tau}}$  in the denominator. Because of the fact that the gas producers have owner shares in the syndicate the markup is increased. For the limiting case, where  $\alpha_1 = \alpha_2 = 1$ , we are left with the monopoly mark up. This factor is also dependent on how an increase in the tariff decreases the transportation of network owners' gas relative to the corresponding effect on the third party's transportation volume.

2. Given market independence, the net cost base for the optimal tariff is larger than in the monopoly case because of the fact that the network owners bear only part of the marginal costs when they choose optimal short-term transportation of gas. This is represented by  $\frac{\partial C^t}{\partial x_T} + \frac{(1-\alpha_1)\frac{\partial C^t}{\partial x_1}\frac{dx_1}{d\tau} + (1-\alpha_2)\frac{\partial C^t}{\partial x_2}\frac{dx_2}{d\tau}}{\frac{dx_T}{d\tau}}$  in equation (17). A marginal increase in the tariff will reduce the gas sales of the gas producers and therefore the costs of transporting the gas. The effect of a change in the transportation costs because of a change in the network owners' gas sales is evaluated per unit change in the third party's gas sales initiated by a change in the tariff, to make them comparable to the change in the transportation costs from a change in the gas sales of the third party.
3. If the downstream markets are dependent, the socially optimal tariff will increase with stronger market dependence; i.e., with higher  $\frac{\partial p_i}{\partial x_j}$  and higher  $\frac{\partial p_i}{\partial x_T}$ . The indirect price effects are represented in the square bracket in equation (17). The indirect price effects between the network

owners are adjusted with the effect from an increased  $\tau$  on the network owners' transportation volume relative to the corresponding effect on the third party's transportation volume.

The optimal tariff is characterized by a mark up factor and a cost base and is given by equation (17). Equation (17) shows that it is not optimal to fully exert market power because a higher tariff has an adverse effect on network owners' transportation volumes. In equation (17), this is shown by a smaller mark up factor than in the monopoly case, because of the fact that a higher tariff increases the externality and thereby increases the efficiency loss in transportation. If there were only one network owner ( $\alpha_i = 1$ ), he would internalize this externality and the mark up factor in equation (17) would be equal to the monopoly mark up. If the network were organized as a separate entity ( $\alpha_i = 0$ ), the optimal tariff would be lower than in the syndicate case. Compared with organizing the gas grid as a separate entity, organizing the grid as a syndicate would make it more profitable to exert market power as to the foreign third party without violating the nondiscriminating condition. The owners in their roles as shippers will have reduced negative effects from a marginal increase of the transportation tariff as increased efficiency loss in transportation is to some extent compensated by increased profits.

*Therefore, organizing the network as a syndicate results in a discrimination of the effective tariffs between the network owners and the third party that is similar to explicit tariff discrimination. Hence, the organizational design can be seen as an imperfect substitute for unconstrained tariff discrimination.*

We can illustrate this by a numerical example of equation (17). Assume that  $\frac{\partial C^t}{\partial x_T} = \frac{\partial C^t}{\partial x_1} = \frac{\partial C^t}{\partial x_2} = MC$ ,  $\frac{dx_1}{d\tau} = \frac{dx_2}{d\tau} = \frac{dx_T}{d\tau}$ ,  $\varepsilon_T = 2$  and that the downstream markets are independent (the terms in the square brackets in equation (17) are equal to zero). With only one owner of the infrastructure, the inverse elasticity rule will give an optimal tariff equal to:

$$\tau = \frac{1}{1 - \frac{1}{2}} [MC] = 2MC. \quad (18)$$

With two network owners and  $\alpha_2 = \alpha_1 = 0,5$ , the syndicate version of the inverse elasticity rule will give:

$$\tau = \frac{1}{2 - \frac{1}{2}} [2MC] = \frac{4}{3}MC. \quad (19)$$

The numerical example shows that for given investment decisions the optimal tariff for a gas grid owned by a syndicate of gas producers is between the monopoly tariff, given by equation (18), and the optimal tariff when a third party is not using the gas grid ( $\tau = MC$ ).

The government would prefer a differentiated tariff, setting the tariff for the network owners at marginal costs, while the tariff to the third party equals the monopoly tariff, both corrected for externalities from the fact that changes in gas sales from a gas producer change the optimal price and transportation volumes of the other gas producers. Because the EU directives require equal treatment as to the conditions for access to the transportation network, the optimal uniform tariff is between the optimally differentiated tariffs.

Alternatively, we may assume that the government is the owner of the gas grid. Therefore, according to the numerical example above, the optimal tariff equals:

$$\tau = \frac{1}{3 - \frac{1}{2}} [3MC] = \frac{6}{5}MC. \quad (20)$$

The numerical examples confirm that from a national point of view that it can be preferable to organize the transportation network as a syndicate of gas producers rather than as an entity separated from extraction and marketing activities.

#### 4.4 Scarce capacity

To the extent that the scarce capacity is showing up as increasing marginal transportation costs, this is taken care of in the equation for the optimal tariff (15). We therefore assume that there is an absolute capacity limit given by  $x^K$ . We further assume that the downstream markets are independent,  $\frac{\partial p_2}{\partial x_1} = \frac{\partial p_1}{\partial x_2} = \frac{\partial p_1}{\partial x_T} = \frac{\partial p_2}{\partial x_T} = 0$ , and that the tariff scheme has to be based on the principles of open access on nondiscriminatory conditions. The problem is to maximize equation (5) with respect to  $\tau$ , subject to the constraint that  $x_1 + x_2 + x_T \leq x^K$ .

The optimal tariff is given by:

$$\begin{aligned} & \left( \tau - \frac{\partial C^t}{\partial x_T} - \mu \right) \frac{dx_T}{d\tau} + x_T = \\ & - \sum_{i=1}^2 \left[ (1 - \alpha_i) \left( \tau - \frac{\partial C^t}{\partial x_i} \right) - \mu \right] \frac{dx_i}{d\tau}, \end{aligned} \quad (21)$$

where  $\mu$  is the shadow price of capacity. If there is scarce capacity,  $\mu > 0$ , and an optimal tariff will take this into account by increasing the tariff until the demand for transport capacity equals the capacity limit. Because the network owners and the third party compete for scarce capacity, their willingness to pay for capacity must match the scarcity value in addition to the optimal tariff in a situation where the transportation capacity is not scarce.

It follows from (21) that the rationing of scarce capacity should be handled through a calculated capacity cost increment for the network owners and the third party. However, the regulator may choose to ration the capacity in order to equate supply and demand for the transportation capacity. In the Norwegian gas grid, the allocation rule gives the members of the syndicate priority in booking transport capacity. Therefore, the network owners pay a lower price than the value generated by having the third party using the transportation capacity. Hence, the rationing is inefficient. However, if this rationing rule is combined with an effective second-hand market for transportation capacity<sup>4</sup>, the situation is different. The network owners can then transfer the transport rights at a higher price than they have paid in the first-hand market. Therefore, the rationing rule combined with an effective second-hand market may function in the same way as a tariff adjusted for the scarcity value including the opportunity cost of foregoing the value of third party use.

## 5 Downstream competition with a foreign gas producer having his own network

Suppose that gas producers 1, 2 and T compete with a foreign gas producer F in the downstream market. Firm F has its own gas grid supplying gas to the

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<sup>4</sup>In the Norwegian gas transportation system there exists a second-hand market for transport capacity.

downstream consumers. If the gas producers 1, 2 and T use the Norwegian gas grid, we could think of firm F as Russian gas producers transporting their gas to a common downstream gas market, e.g., EU. The gas production of firm F sold in the downstream markets is denoted  $x_F$  and the maximization problem for a Norwegian regulator is:

$$\max_{\tau} W = \sum_{i=1}^2 (p_i(x_1, x_2, x_T, x_F)x_i - c_i^a(x_i)) + \tau x_T - C^t(x_1, x_2, x_T) - (C^k(x^k)). \quad (22)$$

Substituting in from the first order conditions of the network owners, the optimal tariff rate is given by:

$$\left( \tau - \frac{\partial C^t}{\partial x_T} + x_1 \frac{\partial p_1}{\partial x_T} + x_2 \frac{\partial p_2}{\partial x_T} \right) \frac{dx_T}{d\tau} + x_T = x_2 \frac{\partial p_2}{\partial x_F} \frac{dx_F}{d\tau} + x_1 \frac{\partial p_1}{\partial x_F} \frac{dx_F}{d\tau} - \sum_{i=1}^2 \left[ x_j \frac{\partial p_j}{\partial x_i} + (1 - \alpha_i) \left( \tau - \frac{\partial C^t}{\partial x_i} \right) \right] \frac{dx_i}{d\tau}, \quad (23)$$

where  $\frac{dx_F}{d\tau} = \sum_{i=1}^2 \frac{\partial x_F}{\partial x_i} \frac{dx_i}{d\tau} + \frac{\partial x_F}{\partial x_T} \frac{dx_T}{d\tau}$ . Compared with equation (15) equation (23) differs with the following term,  $x_2 \frac{\partial p_2}{\partial x_F} \frac{dx_F}{d\tau} + x_1 \frac{\partial p_1}{\partial x_F} \frac{dx_F}{d\tau}$  on the right-hand side. This term represents an indirect effect on the network owners gas price because of a different amount of gas sold in the downstream market by firm F because of a marginal increase in the common tariff. Firm F's gas supply in the downstream market is changed indirectly with a marginal tariff increase because a tariff increase changes the gas transported by the gas producers using the gas grid and hence, firm F's gas sold in the downstream market. Equation (23) shows that ceteris paribus a foreign firm supplying gas to a downstream market with Cournot competition will lower the socially optimal tariff. A higher tariff will reduce the market share of the domestic producers and reduce the welfare from a national point of view.

## 6 Domestic consumption of gas

In Norway, only a small part of gas production is used domestically. However, in other gas producing countries such as Russia and Great Britain a large

part of the gas produced is consumed domestically. There are also plans in Norway to increase domestic consumption of gas. If a larger proportion of gas production is used domestically, this will alter the optimization problem for the regulator. In setting the optimal tariff, a regulator, who maximizes the national interests, will also have to take into account the interests of the domestic consumers.

We assume that gas producer 1 is selling part of his gas production to domestic consumers. The quantity sold domestically is denoted  $\beta_1 x_1 = x_D$ , while the gas exported is denoted  $(1 - \beta_1)x_1 = x'_1$ . The price of the exported gas from producer 1 is denoted  $p'_1(x'_1, x_2, x_T)$ . Although part of the gas is sold domestically, we assume that the gas producer has to use the gas grid to transport the gas to the domestic consumers. Therefore, gas producer 1 has to pay a part of the tariff  $\gamma\tau$  for his domestic supply of gas, where  $0 \leq \gamma \leq 1$ . The regulator sets the domestic price  $p_D$ . The gross consumer surplus is denoted by  $S_D(x_D)$  while the net consumer surplus is given by  $S_D(x_D) - p_D x_D$ . From a national point of view, it is socially optimal to maximize the sum of the net consumer surplus and the domestic gas producers' profits. We assume that the net consumer surplus and the gas producers' profits are valued equally in the regulator's welfare function. Therefore, the regulator's maximization problem for given capacity  $x^K$  is:

$$\begin{aligned} \max_{\tau} W = & p'_1(x'_1, x_2, x_T)x'_1 - c_1^a(x'_1, x_D) + S_D(x_D) + \\ & p_2(x'_1, x_2, x_T)x_2 - c_2^a(x_2) + \tau x_T - C^t(x'_1, x_D, x_2, x_T) - (C^k(x^k)). \end{aligned} \quad (24)$$

In order to simplify, we assume the downstream markets are independent; i.e.,  $\frac{\partial p_2}{\partial x_1} = \frac{\partial p_1}{\partial x_2} = \frac{\partial p_1}{\partial x_T} = \frac{\partial p_2}{\partial x_T} = 0$ . Substituting in from the first order conditions of the network owners and after some manipulation the first order condition for the optimal solution can be written as:

$$\begin{aligned} \left( \tau - \frac{\partial C^t}{\partial x_T} \right) \frac{dx_T}{d\tau} + x_T = & - \left[ (1 - \alpha_1) \left( \tau - \frac{\partial C^t}{\partial x'_1} \right) \right] \frac{dx'_1}{d\tau} - \\ \left[ (1 - \alpha_2) \left( \tau - \frac{\partial C^t}{\partial x_2} \right) \right] \frac{dx_2}{d\tau} - & \left[ (1 - \alpha_1) \left( \gamma\tau - \frac{\partial C^t}{\partial x_D} \right) \right] \frac{dx_D}{d\tau} + x_D \frac{\partial p_D}{\partial x_D} \frac{dx_D}{d\tau}. \end{aligned} \quad (25)$$

Compared to equation (15), equation (25) has two additional terms. The penultimate term shows the adverse effect of a marginal increase in the tariff for the optimal transportation volume in the domestic market. In order to simplify, we assume that for the optimal tariff the markup on marginal cost

of transportation of producer 1's gas to the domestic market is equal to the markup on the marginal cost of his gas exports,  $\left(\gamma\tau - \frac{\partial C^t}{\partial x_D}\right) = \tau - \frac{\partial C^t}{\partial x'_1} = \tau - \frac{\partial C^t}{\partial x_1}$ , this implies that  $\left[(1 - \alpha_1) \left(\tau - \frac{\partial C^t}{\partial x'_1}\right)\right] \frac{dx'_1}{d\tau} + \left[(1 - \alpha_1) \left(\gamma\tau - \frac{\partial C^t}{\partial x_D}\right)\right] \frac{dx_D}{d\tau} = \left[(1 - \alpha_1) \left(\tau - \frac{\partial C^t}{\partial x_1}\right)\right] \frac{dx_1}{d\tau}$ . Then equation (25) only differs from equation (15) by the last term,  $x_D \frac{\partial p_D}{\partial x_D} \frac{dx_D}{d\tau}$ . This term is the cost of a marginal increase in the tariff for the domestic consumers. Therefore, the presence of domestic consumers of the gas production will reduce the socially optimal tariff because a higher tariff will increase the domestic gas price and hence, reduce consumer surplus.

## 7 Conclusion and discussion

In this paper, the government sets the transportation tariff to induce socially optimal transportation of natural gas in a gas transportation network owned by a syndicate of gas producers, where the gas producers both act as shippers of gas and owners of the gas grid. We discuss how the network owners' demand for transportation capacity affects the optimal tariff scheme based on the principles of open access on nondiscriminatory conditions, assuming Cournot competition in the downstream markets.

In a setting where gas is exported to end-user markets and a foreign third party has access to the gas grid, it would be optimal to differentiate the tariff. With differentiated tariffs to network owners and the third party, tariffs to the domestically owned gas producers should be equal to marginal costs corrected for price effects and increased syndicate profits of an marginal increase in the tariff. With respect to the third party a tariff equal to the monopoly tariff corrected for the price effects and increased syndicate profits from an induced increase in gas sales of the network owners appears to be preferable.

However, if the tariff scheme is based on the principles of open access on nondiscriminatory conditions, the regulator has to balance the effect on the syndicate's profits from the third party's transportation of gas against the efficiency loss of reduced transportation volume of the network owners in the downstream markets from a marginal increase in the tariff. Organizing



the transportation network as a syndicate of gas producers rather than as a separate entity enables the syndicate to levy a common tariff acting as an imperfect substitute for unconstrained tariff discrimination between the network owners and the third party. The actual tariff paid by the network owners is lower than the tariff paid by the third party. The owners in their roles as shippers will have reduced negative effects from a marginal increase of the transportation tariff as increased efficiency loss in transportation is compensated by increased profits.

Market dependence in the downstream markets increases the incentives to charge higher tariffs. The regulator will then try to take into account the externality that gas transportation of one network owner has on the gas price of the other network owners. Domestic consumption of gas and a foreign gas producer with his own gas grid, competing downstream, will decrease the optimal tariff. A high tariff decreases the sum of consumer and producer surplus in the domestic market and reduces the domestic producers' market share in the downstream markets.

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## 8 Appendix A

The optimal differentiated tariffs are given by:

$$\max_{\tau_N, \tau_T} W = \sum_{i=1}^2 \left[ p_i(x_1, x_2, x_T)x_i - c_i^a(x_i) - \tau_N x_i + \alpha_i (\tau_T x_T + \tau_N(x_1 + x_2) - C^t(x_1, x_2, x_T) - (C^k(x^k))) \right]$$

The first order condition with respect to  $\tau_T$  is equal to:

$$\begin{aligned} \frac{\partial W}{\partial \tau_T} &= \sum_{i=1}^2 \left[ p_i + x_i \frac{\partial p_i}{\partial x_i} - \frac{\partial c_i^a}{\partial x_i} - \tau_N + \alpha_i \left( \tau_N - \frac{\partial C^t}{\partial x_i} \right) \right] \frac{\partial x_i}{\partial x_T} \frac{dx_T}{d\tau_T} + \\ &\quad \sum_{i=1}^2 \left[ x_i \frac{\partial p_i}{\partial x_j} + \alpha_i \left( \tau_N - \frac{\partial C^t}{\partial x_j} \right) \right] \frac{\partial x_j}{\partial x_T} \frac{dx_T}{d\tau_T} + \\ &\quad \sum_{i=1}^2 \left[ x_i \frac{\partial p_i}{\partial x_T} + \alpha_i \left( \tau_T - \frac{\partial C^t}{\partial x_T} \right) \right] \frac{dx_T}{d\tau_T} + x_T = 0 \quad \text{for } j \neq i.. \end{aligned}$$

The profit maximizing volume of network owner  $i$  is given by:

$$p_i + \frac{\partial p_i}{\partial x_i} x_i - \frac{\partial c_i^a}{\partial x_i} - \tau + \alpha_i \left( \tau - \frac{\partial C^t}{\partial x_i} \right) = 0.$$

Substituting in from the first order conditions of the network owners, the optimal tariff is given by:

$$\begin{aligned} &\sum_{i=1}^2 \left[ x_i \frac{\partial p_i}{\partial x_T} + \alpha_i \left( \tau_T - \frac{\partial C^t}{\partial x_T} \right) \right] \frac{dx_T}{d\tau_T} + \sum_{i=1}^2 \alpha_i x_T + \\ &\sum_{i=1}^2 \left[ x_i \frac{\partial p_i}{\partial x_j} + \alpha_i \left( \tau_N - \frac{\partial C^t}{\partial x_j} \right) \right] \frac{\partial x_j}{\partial x_T} \frac{dx_T}{d\tau_T} = 0 \quad \text{for } j \neq i.. \end{aligned}$$

Rewriting, using that  $\sum_{i=1}^2 \alpha_i = 1$  and that  $\alpha_i = 1 - \alpha_j$  gives:

$$\begin{aligned} &\left( \tau_T - \frac{\partial C^t}{\partial x_T} \right) \frac{dx_T}{d\tau_T} + \left( x_1 \frac{\partial p_1}{\partial x_T} + x_2 \frac{\partial p_2}{\partial x_T} \right) \frac{dx_T}{d\tau_T} + x_T + \\ &\sum_{i=1}^2 \left[ x_i \frac{\partial p_i}{\partial x_j} + (1 - \alpha_j) \left( \tau_N - \frac{\partial C^t}{\partial x_j} \right) \right] \frac{\partial x_j}{\partial x_T} \frac{dx_T}{d\tau_T} = 0 \quad \text{for } j \neq i.. \end{aligned}$$

Rewriting, using that  $\sum_{i=1}^2 \left[ x_i \frac{\partial p_i}{\partial x_j} + (1 - \alpha_j) \left( \tau_N - \frac{\partial C^t}{\partial x_j} \right) \right] \frac{\partial x_j}{\partial x_T} \frac{dx_T}{d\tau_T}$  is equal to  $\sum_{i=1}^2 \left[ (1 - \alpha_i) \left( \tau_N - \frac{\partial C^t}{\partial x_i} \right) + x_j \frac{\partial p_j}{\partial x_i} \right] \frac{\partial x_i}{\partial x_T} \frac{dx_T}{d\tau_T}$  gives:

$$\begin{aligned} & \left( \tau_T - \frac{\partial C^t}{\partial x_T} \right) \frac{dx_T}{d\tau_T} + \left( x_1 \frac{\partial p_1}{\partial x_T} + x_2 \frac{\partial p_2}{\partial x_T} \right) \frac{dx_T}{d\tau_T} + x_T + \\ & \sum_{i=1}^2 \left[ (1 - \alpha_i) \left( \tau_N - \frac{\partial C^t}{\partial x_i} \right) + x_j \frac{\partial p_j}{\partial x_i} \right] \frac{\partial x_i}{\partial x_T} \frac{dx_T}{d\tau_T} = 0 \quad \text{for } j \neq i.., \end{aligned}$$

which is identical to equation (11).

The first order condition with respect to  $\tau_N$  is equal to:

$$\begin{aligned} \frac{\partial W}{\partial \tau_N} &= \sum_{i=1}^2 \left[ p_i + x_i \frac{\partial p_i}{\partial x_i} - \frac{\partial c_i^a}{\partial x_i} - \tau_N + \alpha_i \left( \tau_N - \frac{\partial C^t}{\partial x_i} \right) \right] \frac{dx_i}{d\tau_N} + \\ & \sum_{i=1}^2 \left[ x_i \frac{\partial p_i}{\partial x_j} + \alpha_i \left( \tau_N - \frac{\partial C^t}{\partial x_j} \right) \right] \frac{dx_j}{d\tau_N} + \\ & \sum_{i=1}^2 \left[ x_i \frac{\partial p_i}{\partial x_T} + \alpha_i \left( \tau_T - \frac{\partial C^t}{\partial x_T} \right) \right] \frac{\partial x_T}{\partial x_i} \frac{dx_i}{d\tau_N} = 0 \quad \text{for } j \neq i.. \end{aligned}$$

Substituting in from the first order conditions of the network owners and using that  $\sum_{i=1}^2 \alpha_i = 1$  and that  $\alpha_i = 1 - \alpha_j$ , the optimal tariff is given by:

$$\begin{aligned} & \sum_{i=1}^2 \left[ x_i \frac{\partial p_i}{\partial x_j} + (1 - \alpha_j) \left( \tau_N - \frac{\partial C^t}{\partial x_j} \right) \right] \frac{dx_j}{d\tau_N} + \\ & \left( \tau_T - \frac{\partial C^t}{\partial x_T} + x_1 \frac{\partial p_1}{\partial x_T} + x_2 \frac{\partial p_2}{\partial x_T} \right) \frac{dx_T}{d\tau_N} = 0 \quad \text{for } j \neq i. \end{aligned}$$

Rewriting, using that  $\sum_{i=1}^2 \left[ x_i \frac{\partial p_i}{\partial x_j} + (1 - \alpha_j) \left( \tau_N - \frac{\partial C^t}{\partial x_j} \right) \right] \frac{dx_j}{d\tau_N}$  is equal to  $\sum_{i=1}^2 \left[ (1 - \alpha_i) \left( \tau_N - \frac{\partial C^t}{\partial x_i} \right) + x_j \frac{\partial p_j}{\partial x_i} \right] \frac{dx_i}{d\tau_N}$  gives:

$$\begin{aligned} & \sum_{i=1}^2 \left[ (1 - \alpha_i) \left( \tau_N - \frac{\partial C^t}{\partial x_i} \right) + x_j \frac{\partial p_j}{\partial x_i} \right] \frac{dx_i}{d\tau_N} + \\ & \left( \tau_T - \frac{\partial C^t}{\partial x_T} + x_1 \frac{\partial p_1}{\partial x_T} + x_2 \frac{\partial p_2}{\partial x_T} \right) \frac{dx_T}{d\tau_N} = 0 \quad \text{for } j \neq i, \end{aligned}$$

which is identical to equation (13).