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CESIFO WORKING PAPER NO. 4579
CATEGORY 9: RESOURCE AND ENVIRONMENT ECONOMICS
JANUARY 2014

Presented at CESifo Area Conference on Energy & Climate Economics, October 2013

CESifo *Working Paper No. 4579*

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Abstract

In a non-renewable resource market with imperfect competition, both the resource rent and current prices influence a large resource owner's optimal supply. New information regarding future market conditions that affect the resource rent will consequently impact current supply. Bleaker demand prospects tend to accelerate resource extraction. A more pessimistic outlook for future demand may, however, slow down the early resource extraction of producers with sufficiently large resource stocks and thus more limited resource rent, because the supply from these producers is driven more by current market considerations than by changes in the resource rent. As producers with relatively smaller resource stocks accelerate their supply in response to bleaker demand prospects, producers with sufficiently large resource stocks will reduce their current supply. A numerical model of the European gas market illustrates that the effect of the shale gas revolution is an accelerated supply by most gas producers, but a reduced supply by Russia who loses market shares even before the additional gas enters the market.

JEL-Code: Q310, Q330, Q420.

Keywords: resource extraction, Cournot competition, European gas market.

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1 Introduction

For decades the dominating suppliers of natural gas to the European market have been Russia, Norway, the United Kingdom (UK), the Netherlands, and Algeria. Since the early 1980's these five countries jointly accounted for two thirds or more of total gas supply to the European Union (EU). The European gas market therefore is typically modeled as a Cournot game in the economics literature (see, e.g., Golombek et al., 1995, 1998; Holz et al., 2008, 2009; Zwart, 2009).

Europe's five major natural gas supplying countries possess quite heterogeneously sized reserves, and their gas production-trajectories have developed differently. Whereas UK's gas production in 2011 was 60% below its peak supply of 2000, Russian and Algerian gas production and exports to Europe are expected to increase over the next couple of decades (see e.g. IEA, 2012). The diverging production-trajectories reflect to a large degree the countries' reserve-to-production ratio (R/P-ratio), i.e., remaining reserves (R) divided by current annual production (P). Russia and Algeria have R/P-ratios of 74 and 58 years, respectively, while the R/P-ratio of the UK is merely 4.5 years (BP, 2012). Norway and the Netherlands are in-between with R/P-ratios of 20 and 17 years, respectively. R/P-ratios are typically adjusted over time as a result of exploration and technical improvements.[1] The R/P ratios are sufficiently wideranging that one expects these countries' influence on future markets to be distinct.

The discussion of reserve levels of Europe's large natural gas suppliers point to the fact that natural gas is a non-renewable resource–gas resources extracted today cannot be extracted in the future. The producers must consider the optimal dynamic extraction path for their resource. Intuitively, this path will depend on the size of the resource stock and, importantly for this discussion, on expected future market conditions.

Substantial shifts in expected future supply or demand will impact the optimal extraction path including the current extraction rate. If new in-

[1] Remaining gas reserves in Russia *increased* from 2001 to 2011, and decreased far less than accumulated extraction over this period in Algeria and Norway.

formation projects a fall in demand or an increased market supply at some future point, non-renewable resource producers will as a first response shift some of their extraction toward the present in expectation of declining future profitability. This altered production strategy is the core of the Green paradox literature, which studies the effects of climate policies on non-renewable resource extraction (e.g., Sinn, 2008; Gerlagh, 2010; and Hoel, 2011).

The shale gas revolution in the United States (US), that is, the now substantially reduced cost of extracting shale gas, has resulted in increased US gas production. Moreover, it has led to expectations of an increased market supply of natural gas in the coming decades both in the US and elsewhere (EIA, 2012; IEA, 2012; Gabriel et al., 2013). Thus, the US shale gas revolution clearly has altered the future market expectations for today's natural gas producers.

This paper explores the consequences for current supply decisions from altered market expectations in the setting of an oligopolistic, non-renewable resource market. The focus is on the heterogeneity of remaining reserves among the producers, and in particular the effect reserve size has for individual producers' supply response. Although this study is inspired by the expected changes to the European gas market caused by the shale gas revolution, our results are also relevant for other imperfectly competitive, non-renewable markets with heterogeneous reserve sizes among producers such as the global oil market.

The paper proceeds by developing a theoretical model of two Cournot producers that differ with respect to reserve levels. Our analytical results show that although the market supply increases initially as a response to a fall in future demand, individual producers who possess sufficiently large reserves may in fact reduce their current supply when future market conditions become less profitable. The supply decision of a producer with a sufficiently large resource stock is driven more by the current market conditions than by the resource (scarcity) rent, compared to a producer who possesses a small resource stock. As a result the smaller resource owner tend to move its extraction toward the present, and as a response, the large resource owner may move some delay some of its production to future time periods.

The paper continues by presenting a dynamic and more sophisticated numerical simulation model of the European gas market that illustrates the theoretical model results. The numerical model analyzes how new information about a future increase in unconventional gas supply impacts producers' current supply decisions. The simulation results suggest that all Cournot producers except Russia will increase their initial gas supply to Europe, while, Russia with its vast reserves of gas, will reduce its current exports to Europe. Russia's remaining reserves are in fact almost six times greater than the combined reserves of the four other big suppliers to the European market that were referred to above (BP, 2012). And although a major share of Russian gas production is consumed domestically, natural gas is hardly a scarce resource in Russia. Thus, Russia's per unit scarcity rent is relatively smaller than other producers scarcity rent and this induces Russia to act somewhat like a static Cournot player in the model. Hence, when other gas producers increase their initial supply, Russia cuts back.

Our results imply that changes in future marked conditions have a different effect on the production profile of heterogeneous, oligopolistic firms. This is particularly relevant if one is concerned about the composition of supply. For example, our numerical results suggest that the Russian market share in the European gas market may decline even before the additional gas supply enters the market, alleviating European dependence on gas imports from Russia.[2] Similar effects may follow from policies that reduce future demand for gas (e.g., subsidies for development of renewable energy). Moreover, we find that Cournot competition in strategic substitutes moderates the increase in aggregate current production induced by bleaker future prospects, as compared to a competitive resource market. This suggests that market power may alleviate (but not remove) the Green paradox through its dampening effect on the increase in early production and emissions caused

[2] European dependence on Russian gas is discussed at: http://www.heritage.org/research/reports/2009/01/europe-should-reduce-dependence-on-russian-energy-and-develop-competitive-energy-markets.

by lower future demand.

The economics literature on optimal extraction of non-renewable resources goes back to the seminal paper by Hotelling (1931) who concluded that the resource price increases at the interest rate. The theory of 'oil'igopoly developed by Salant (1976) is of particular relevance to the present paper. By modeling the oil market using a dynamic Nash-Cournot approach, Salant (1976) captured two central aspects to many resource markets: imperfect competition and resource exhaustibility. Loury (1986) later extended the theory of 'oil'igopoly and Polasky (1992) found empirical support for the predictions of the theory using data on proven reserves and production for a cross-section of oil exporting countries. More recently, Boyce and Voitassak (2008) examined a model of 'oil'igopoly featuring exploration. They find that firms holding smaller proven reserves will be observed doing more exploration and claim that country-level production and reserve data for the post-World War II era support this prediction.

Another strand of literature relevant to the present paper examines current effects of changes in future values of resource stocks induced by such factors as future competition (e.g. a backstop technology) or policy changes, see e.g. Heal (1976) and Sinn (2008). Finally, Chakravorty et al. (2011) show that when technological progress in an alternative energy source occurs through learning-by-doing, resource owners face competing incentives to extract rents from the resource and to prevent expansion of the new technology. In that case, scarcity-driven higher energy prices over time may be insufficient to induce alternative energy supply as resources are exhausted.

2 Theoretical analysis

We consider a non-renewable resource market with two Cournot firms i and j, each with resource extraction flow rate at time t given by $q_{it} \geq 0$ and $q_{jt} \geq 0$, respectively.[3] Constant marginal extraction costs are denoted c_i and c_j, whereas S_{it} and S_{jt} denote the finite resource stocks of the firms at

[3] The theoretical analysis is at firm level, whereas the players are countries in the numerical model in Sections 3 and 4.

time t.

The resource price is given by $p_t = K_t - q_{it} - q_{jt}$, where K_t is an exogenous, time-dependent choke price expressing the level of the residual demand. We assume that the choke price always exceeds the firm's marginal costs ($K_t > c_i, c_j$). While the model is formulated in continuous time, the planning horizon encompasses two discrete time periods; period 1 ($t \in [0, T)$) and period 2 ($t \in [T, \infty)$). Compared to period 1, period 2 is characterized by a reduced residual demand. To simplify, we assume that K_t is constant in each time period, i.e., $K_t = K_1$ in time period 1 and $K_t = K_2$ in time period 2. We assume that it is optimal for the firms to produce in both periods.

The decline in future residual demand is modelled as a fall in the parameter K_2, i.e., $K_1 > K_2$. The fall may be caused by the entry of new producers, the development of viable renewable substitutes, introduction of end-use taxes, or changes in consumer preferences. In the numerical analysis in Sections 3-4 we examine the European gas market with the decline in future residual demand caused by increased shale gas production in the US.

The model is best examined by backwards induction, and thus we start with period 2.

2.1 Production in period 2

In the second time period firm i maximizes profits π_i, where r refers to the discount rate:

$$\pi_i(S_{iT}) = \max_{q_{it}} \int_T^\infty e^{-rt}[(K_2 - q_{it} - q_{jt}) - c_i]q_{it}dt, \tag{1}$$

subject to:

$$\dot{S}_{it} = -q_{it} \tag{2}$$

and $S_{it} \geq 0$. The remaining resource stock of producer i at time t is $S_{it} = S_{iT} - \int_T^t q_{i\tau}d\tau$. We observe that the profits earned in period 2 equals the salvage value of the resource at the end of period 1. The shadow value of the resource stock is positive for finite resource stocks ($\partial\pi_i/\partial S_{iT} > 0$) and increasing in the parameter K_2, that is, $\partial\left(\partial\pi_i/\partial S_{iT}\right)/\partial K_2 > 0$ for finite stock S_{iT}.

2.2 Production in period 1

In the first time period firm i maximizes profits:

$$\max_{q_{it}} \int_0^T e^{-rt}[(K_1 - q_{it} - q_{jt}) - c_i]q_{it}dt + \pi_i(S_{iT})$$

subject to equations (1) and (2), and $S_{it} \geq 0$. The current value Hamiltonian is $H = [(K_1 - q_{it} - q_{jt}) - c_i - \lambda_{it}]q_{it}$ (see e.g. Sydsæter et al., 2008), which is concave in q_{it}. According to the Maximum principle, the profit maximizing extraction path must satisfy:

$$H_{q_t} = K_1 - c_i - 2q_{it} - q_{jt} - \lambda_{it} = 0, \tag{3}$$

$$\dot{\lambda}_{it} - r\lambda_{it} = -H_{S_{it}} = 0, \tag{4}$$

$$\lambda_{iT} = \frac{\partial\pi_i}{\partial S_{iT}}, \tag{5}$$

where equation (5) is the transversality condition. It states that the shadow price of the resource at time T must equal the marginal contribution of the resource to the salvage value, i.e., $\partial\pi_i/\partial S_{iT}$. In other words, the marginal discounted value of the resource must be equal across the two time periods. Otherwise, the firm could increase the present value of profits by moving resource extraction from one period to the other.

Solving the differential equation (4) we get $\lambda_{it} = Ce^{rt}$, where the constant C solves the boundary condition $Ce^{rT} = \lambda_{iT}$. Hence, we have $\lambda_{it} = \lambda_{iT}e^{r(t-T)}$. Insertion in (3) yields $K_1 - c_i - 2q_i - q_j - \lambda_{iT}e^{r(t-T)} = 0$. Solving this system of two equations and using (5), we obtain:

$$q_{it} = \frac{1}{3}\left(A_i + \left(\frac{\partial\pi_j}{\partial S_{jT}} - 2\frac{\partial\pi_i}{\partial S_{iT}}\right)e^{r(t-T)}\right), \tag{6}$$

with $A_i = K_1 - 2c_i + c_j$. Differentiating (7) with respect to K_2, i.e., the demand parameter in period 2, yields:

$$\frac{\partial q_{it}}{\partial K_2} = \frac{1}{3}\left(\frac{\partial(\partial \pi_j/\partial S_{jT})}{\partial K_2} - 2\frac{\partial(\partial \pi_i/\partial S_{iT})}{\partial K_2}\right) e^{r(t-T)}. \tag{7}$$

Equation (7) captures two opposing effects on firm i's production caused by a reduction in future demand ($-\partial q_{it}/\partial K_2$). The second term of the large parenthesis in (7) is an *intertemporal effect:* a decline in future demand induces the resource owning firm i to increase current production. The reason is that the discounted net present value of the resource must be equalized across time, and moving production from period 2 to period 1 offsets the relative fall in future net present value of the resource caused by the decline in future demand. The same reason, however, causes the competitor firm j to also increase their production in period 1. Because the firms' output are strategic substitutes there is a second and *static effect,* which is captured by the first term of the large parenthesis in (7): when firm j increases current production, the product price decreases and induces firm i to produce less. This is a well known result from analysis of Cournot competition (Tirole, 1988).

The overall effect, expansion or contraction of production in period 1, is ambiguous for the individual firm and depends on whether the intertemporal or the static effect dominates. The current market supply will, however, increase because the static effect is caused by the fall in price. This may be seen from (7), which implies that the change in aggregate production is:

$$\frac{\partial q_{it}}{\partial K_2} + \frac{\partial q_{jt}}{\partial K_2} = -\frac{1}{3}\left(\frac{\partial(\partial \pi_j/\partial S_{jT})}{\partial K_2} + \frac{\partial(\partial \pi_i/\partial S_{iT})}{\partial K_2}\right) e^{r(t-T)} < 0.$$

This term is negative for finite resource stocks S_{i0} or S_{j0} (and zero if both stocks are infinite). That is, a decrease in future demand (fall in K_2) increases current aggregate production. In the particular case of identical firms, both firms will increase their production in period 1. This result relates to the Green paradox literature (see Section 1).

Now, assume instead that the two firms differ and that firm i has the most reserves. For the sake of argument, let firm i's reserves be near infinite, i.e., $S_{iT} \to \infty$ with the resource rent consequently approaching zero, i.e., $\lim_{S_{iT}\to\infty} \lambda_{iT} = 0$. It follows that $\lim_{S_{iT}\to\infty} \partial\pi_i/\partial S_{iT} = 0$ for any finite level of K_2, and thus it must be that $\lim_{S_{iT}\to\infty} \frac{\partial(\partial\pi_i/\partial S_{iT})}{\partial K_2} = 0$. As long as firm j's reserves are finite, and firm j is producing in both periods, it will still be true that $\partial\frac{\partial\pi_j/\partial S_{jT}}{\partial K_2} > 0$. Equation (7) then reduces to:

$$\lim_{S_{iT}\to\infty} \frac{\partial q_{it}}{\partial K_2} = \frac{1}{3}\left(\partial\frac{\partial\pi_j/\partial S_{jT}}{\partial K_2}\right) e^{r(t-T)} > 0.$$

This implies that firm i will reduce supply in period 1 when demand decreases in period 2 (i.e., a fall in K_2), given that the reserves of firm i are sufficiently large. Because aggregate production increases, it must be that firm j, the firm with the smaller reserves, increases production more than firm i decreases its production:

$$\lim_{S_{iT}\to\infty} \frac{\partial q_{jt}}{\partial K_2} = -\frac{2}{3}\left(\partial\frac{\partial\pi_j/\partial S_{jT}}{\partial K_2}\right) e^{r(t-T)} < 0.$$

Note that the smaller the reserves of firm j are, the more apt the firm is to extract all its resources during period 1. In that case, the first term in the parenthesis of equation (7) becomes zero, and firm i will increase its initial extraction if future demand declines regardless of how large its reserves are.

We state the following result:[4]

Proposition 1 *Consider a non-renewable resource market with two Cournot players, linear demand and two time periods, where both Cournot players produce in each period. Consider a downward shift in the second period demand. We then have:*

i) Aggregate initial production increases.

ii) A resource owner that endows sufficiently large reserves will reduce

[4] It can be shown that the Maximum principle leads to the equation $r\widetilde{T}_i + e^{-r\widetilde{T}_i} = 1 + 3rS_i/A_i + rT - e^{rT}$ in period 2, with $A_i = K_1 - 2c_i + c_j$ and $\widetilde{T}_i$ being the last period of production (in period 2). These equations do not admit analytical solutions for $\widetilde{T}_i$. Therefore, a reduced form solution for $\partial q_{it}/\partial K_2$ is not possible.

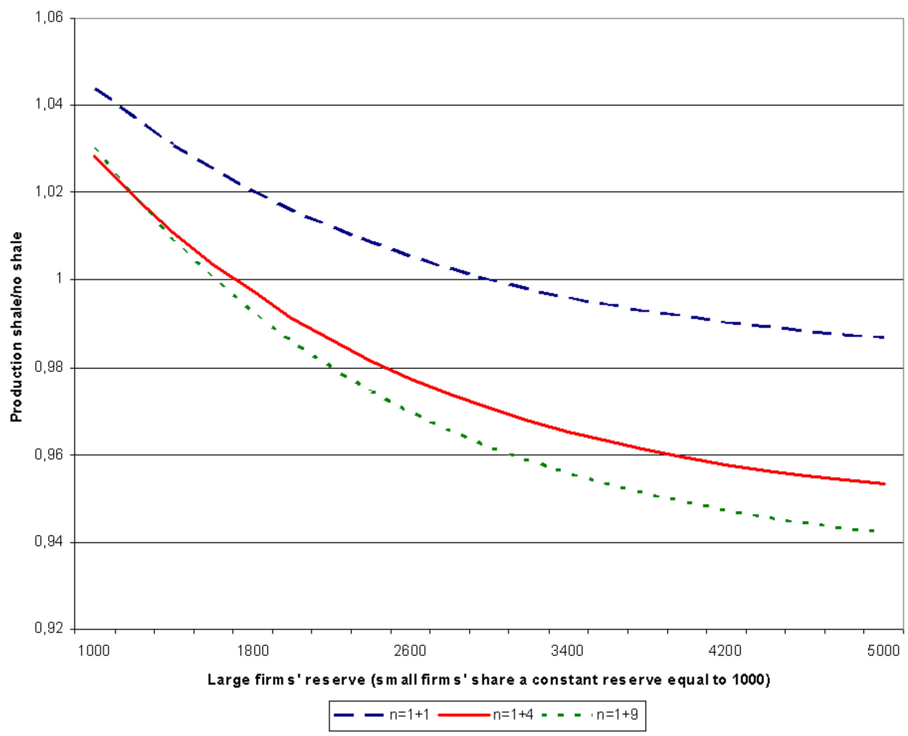

Figure 1: Production ratios of large firm in first period with various number of firms (n).

initial production.

Proof. The Proposition follows from equation (7). ∎

The result arises from the two opposing mechanisms discussed under equation (7) and the observation that the decisions of firms with ample resources, and thus low scarcity values, are dominated by market power considerations. In other words, the intertemporal effect is weak and the static effect dominates for owners of sufficiently large resource stocks. Indeed, at the limit, a firm with very large resources may have approximately zero net present value of an additional unit of the resource. Such a firm does not delay any production due to scarcity considerations. Instead it concerns itself only with strategic effects and will thus decelerate its current production.

Proposition 1 is illustrated in Figure 1. Figure 1 shows the large firm's initial production levels expressed as a ratio of its initial production *with* a future fall in demand (caused e.g. by US shale gas production) to its production *without* such a fall in future demand for a range of reserve levels for the large firm. The figure was created using a numerical model (in GAMS) replicating the theoretical model. The parameter values are set to $K_1 = 500$, $c_i = 0$ and $r = 0.04$ where the large firm's resource stocks ranges from 1000 to 5000 while the small firm's resource stock is kept constant at 1000. Without a fall in future demand we set $K_2 = 500$ but reduce this parameter to 400 with a future demand fall. The duopoly case discussed above is labelled $n = 1 + 1$. For the chosen parameter values, the large firm reduces early production when it controls approximately three times as large initial reserves as the small firm. The figure also depicts scenarios with one large and four small firms (small is defined as having initial reserves of $S_{j0} = 1000/4$), and one large and nine small firms (each with initial reserves $S_{j0} = 1000/9$). As small firms are added to the market, they become less responsive to the fall in price induced by their own increased supply. Thus, the decline in future demand induces a stronger acceleration in the small firms' extraction profiles than in the duopoly case. This acceleration impacts the large firm in two ways: First, increased current supply strengthens the static effect. Second, as the small firms shift production forward in time, they have less resources left to produce in the future. This weakens the intertemporal effect for the large firm, and it becomes even more profitable for the large firm to delay production as compared with the duopoly case.

The slope and vertical placement of the graphs in Figure 1 depend on the chosen parameter values. For example, with a lower discount rate r, future profits become more valuable and hence the intertemporal effect is more pronounced. The curves in Figure 1 shift upward meaning that a higher reserve level is required to induce the big firm to decrease its initial supply.

Proposition 1 assumes that both Cournot players produce in both periods. As mentioned above, if the smaller player has quite small reserves, it is more likely that it will deplete its resources in the first period. Hence, the intertemporal effect vanishes for this producer, and the large player will

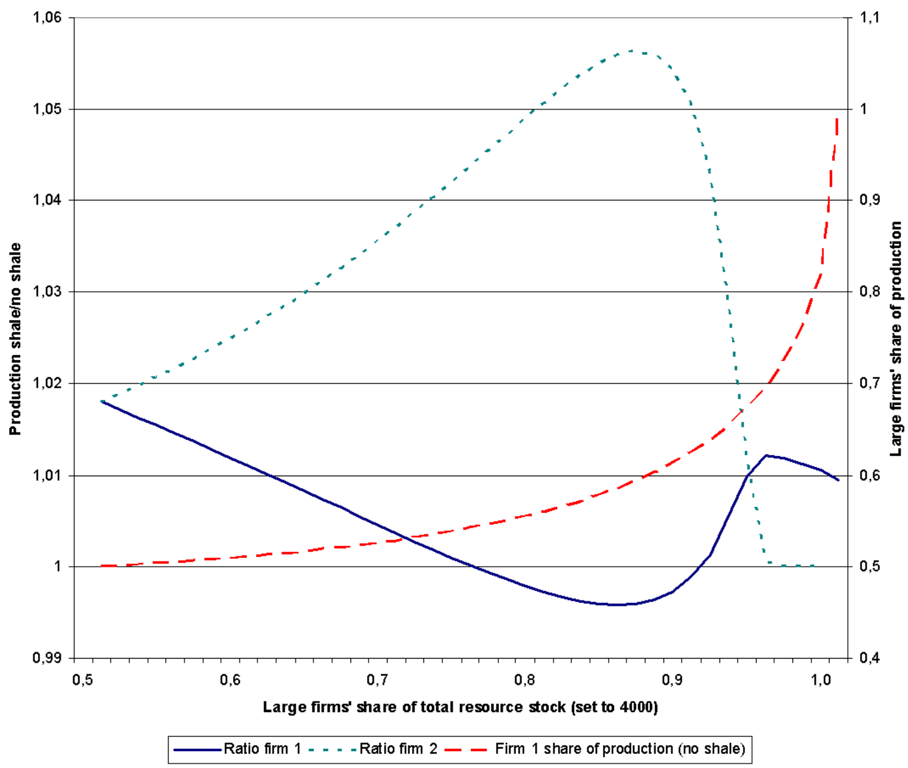

Figure 2: Production ratios and production share in first period.

increase initial supply. This is illustrated in Figure 2. Here we keep the sum of reserves of the two Cournot players constant and instead shift reserves from the small to the large producer as we move along the horizontal axis (i.e., from symmetric duopoly towards monopoly). When the large producer has a sufficiently large share of the market (at least 95 percent in our case), the smaller firm stops producing before period 2 and thus the large firm increases initial supply when future demand declines. This is also the case when the large firm has a slightly lower market share ($91 - 95$ percent in our case), in which case the small firm produces very small amounts in the second period. Then the resource rent does not drop that much when future demand decreases (the large player tries to keep a high price), and the intertemporal effect for the small firm is rather limited.

Proposition 1 was derived for the case of two players with strict assumptions on the functional forms. Still, the economic intuition behind the result suggests that it may be valid in real-world cases. The following sections demonstrates the proposition for a numerical model specifically developed for the European gas market, which is characterized by several heterogeneous Cournot players.

3 Numerical model description

We now turn to the European gas market and simulate the effects of a future positive supply-shift.[5] A relevant interpretation here is the prospects of unconventional gas production. Major technological progress in hydraulic fracturing and horizontal drilling have substantially increased the expected supply of shale gas in the US over the next few decades (Gabriel et al., 2013),[6] as well as in Europe and elsewhere in the world in the longer term (EIA, 2012; IEA, 2012).

The European gas market currently has five large suppliers: Russia, Norway, the Netherlands, the UK and Algeria. Several other European

[5] The numerical model was developed in GAMS and is available upon request.

[6] Compare e.g. the completely different trade projections for the US in EIA (2007) and EIA (2012).

countries produce some gas domestically, and there are imports from other parts of the world (mainly through LNG). Consistent with previous models of the European gas market (cf. Section 1 for references), we model the large suppliers as Cournot players. The exception is the UK where remaining reserves are low and production is not coordinated across companies.[7] The supply from the UK and other smaller European producers is considered exogenous to simplify the model.[8] A function that linearly increases in price models the joint supply of LNG and pipeline imports from other sources than Russia and Algeria: $q_t^{imp} = q_0^{imp} + \kappa_t p_t^E$, where $\kappa_t > 0$. The inverse supply function tilts downward over time in the model (i.e., κ_t is increasing) reflecting the expectation of increased availability of gas imports over the next few decades (cf. e.g. IEA, 2012).

This paper focuses mainly on the supply side effects in the European gas market. A single representative gas consumer is the basis for the model of EU gas demand. In addition, the demand model incorporates the remaining European gas demand (including Ukraine and Belarus). The model assumes that European gas demand (D^E) decreases in the gas price, but instead of a linear demand schedule as in Section 2, we assume a fixed long-run price elasticity ϵ^E (set equal to $\epsilon^E = -0.5$), i.e., $D^E = \bar{D}_t^E \cdot \left(p_t^E\right)^{\epsilon^E}$, where $\bar{D}_t^E$ is an exogenous variable.[9] Over time, gas demand increases due to growth in GDP. The income elasticity is calibrated based on IEA (2011) projections of gas consumption. This is also captured by $\bar{D}_t^E$.

The four Cournot players take the other players' supply as given in their optimization problem. They do, however, take into account the demand-

[7] There is no explicit supply coordination among companies on the Norwegian continental shelf either. However, Norwegian authorities can to a large degree regulate the total extraction level through licensing of fields and pipelines. Moreover, Statoil has a dominant position in Norway. The Dutch authorities explicitly regulate the extraction rate of the major Groningen field.

[8] We assume that production from these countries declines by a fixed annual rate, so that accumulated production over time equal reported reserves at the end of 2009. Total supply in 2015 from these countries is then only slightly above Dutch supply in 2009. Hence, modelling this supply as competitive would not alter our qualitative results.

[9] There is no clear consensus in the literature regarding direct price elasticities for natural gas (see, e.g., Andersen et al., 2011). -0.5 is well within the range of long-run estimates found in the literature.

side price-effects and the supply of imported gas from other countries than Russia and Algeria. That is, they know that an increase in production lowers the gas price due to the demand-side response but that this price reduction is moderated by reduced gas import. Formally, the Cournot players have the following maximization problem:[10]

$$\pi_i = \max_{q_{it}} \sum_{t=0}^{T} (1+r)^{-t} \left(p_t^E(q_t) - c_{it}(A_{it}) - c_{it}^{\tau} \right) q_{it}, \tag{8}$$

subject to:

$$A_{it+1} = A_{it} + q_{it} \tag{9}$$

where A_{it} denotes accumulated production, c_{it}^{τ} is the transport costs to the European market, $p_t^E(q_t)$ is the residual demand schedule facing the oligolipolistic producers, and r is the producer discount rate. The discount rate is set to five percent in the simulations. Note that we do not assume a fixed resource stock here as we do in the theoretical model. Instead we assume that unit costs increase in accumulated production so that only a finite resource level will have unit extraction costs below the prevailing price at a given point in time. Specifically, to add realism to the numerical model we assume that unit extraction costs increased in accumulated production according to the following function:

$$c_{it}(A_{it}) = c_i^0 e^{\eta_i A_{it} - \theta_i t}, \tag{10}$$

which permits for exogenous technological progress through the annual rate θ_i. Here c_i^0 is the initial unit extraction costs, which are based on IEA (2009) numbers. The parameter η_i determines how quickly unit costs rise as accumulated production increases and will, intuitively, be higher the less reserves a country has. We calibrate this parameter for each country based

[10] In the numerical model we simulate the market for a sufficiently high but finite number of years, T. We have tested the effects of increasing the level of T ($T = 150$ in the reported simulations), checking that the reported results (i.e., until 2050) are unaffected by the choice of T.

on reserve data from BP (2012).[11]

From the optimization problem above we derive the following first order condition for the Cournot players:

$$c_{it}(A_{it}) + c_{it}^{T} + \lambda_{it} = p_t^E \cdot \left(1 + \frac{q_{it}}{\epsilon^E D^E - \kappa_t p_t^E}\right), \tag{11}$$

where λ_{it} now denotes the (positive) shadow price of the resource. This condition corresponds to equation (3) in Section 2, with total marginal costs (which is the marginal costs of production and transport plus the shadow price) equal to marginal revenue.

The shadow price λ_{it} develops according to:

$$\lambda_{it} = (1+r)\lambda_{it-1} - \eta_i c_{it}(A_{it}) q_{it}. \tag{12}$$

Russia is the largest supplier of gas to the European market. The biggest share of Russian gas production is consumed domestically, and we, therefore, also model the Russian gas market in order to model Russian gas export to Europe more accurately. A fixed price elasticity ϵ^R, i.e., $D^R = \bar{D}_t^R \cdot \left(p_t^R\right)^{\epsilon^R}$ is also assumed to characterize Russian gas demand, but the Russian elasticity is assumed to be half of the European.[12]

Russian gas prices are highly regulated. Because Russian authorities have signalled that prices to a larger degree should reflect European market prices, Russian gas prices have been increased over the last few years. But given the significant price increases in the European market over the last five years, full netback pricing (i.e., prices equal to European prices minus

[11] We simply assume that all reported reserves in the baseyear can be economically extracted at the baseyear price. In other words: We assume that unit costs (plus transport costs) become equal to the baseyear price when all reported reserves have been extracted (and there is no technological change). For Algeria, however, we take into account that a large share of Algerian production is consumed domestically or exported elsewhere. Thus, we reduce the reserves destined for Europe by 50%.

[12] There are few studies of Russian price elasticities for gas. Solodnikova (2003) finds no significant price effects at all, partly because a large part of Russian gas consumers is not facing any price on their marginal gas consumption. Tsygankova (2010) uses an elasticity of -0.4, as market reforms are expected to bring on more price responsiveness in the Russian gas market.

transport costs to Europe) seems less likely than before. Moreover, from a Russian welfare perspective, netback pricing is not optimal given that Russia exploits its market power in the European market. The optimal policy may rather be to set prices equal to the full marginal costs of production, including the shadow costs of the resource. Hence, in our model we assume that Russia will follow such a price policy in the long run. The simulated price is fairly consistent with actual gas prices in Russia in the baseyear 2009. We then have the following first order condition for the Russian gas market:

$$c_{Rt}(A_{Rt}) + \lambda_{Rt} = p_t^R. \tag{13}$$

Equations (9) and (12) must then be extended for the Russian producer to account for both supply to the domestic market and exports.

So far we have described what we refer to as the Benchmark scenario. Next, we assume that in the Shale gas scenario, large volumes of extra gas are supplied into the European market. This could be a mixture of US LNG exports, other LNG volumes that are rerouted from the US to the European market, and European shale gas (e.g., in Poland). We treat these extra volumes, which gradually come into the market after 2020 and reach a plateau of 150 bcm in 2035, as exogenous.[13]

Since the model does not distinguish between investments and production decisions, or account for costs of adjustments, the model will tend to overestimate the initial effects of a shift in expectations. However, we are mostly interested in the *direction* of change in initial supply, and not so much in the size.

[13] The shale gas revolution has probably had some impacts on the European gas market already, but the larger effects will most likely come after 2020. Furthermore, although there is no doubt that there has been a major shift in expectations regarding future production of unconventional gas, there is no consensus about the size of this shift nor its impact on the European gas market. To put our numbers into perspective, however, in 2007 EIA expected that the US would import around 150 bcm in 2030. Five years later, EIA expects an *export* level in 2035 of 70 bcm (EIA, 2007, 2012). Moreover, EIA (2011) expects European unconventional gas production to increase from practically nothing in 2015 to around 70 bcm in 2035. IEA (2012) is less optimistic about European unconventional gas production, but projects global unconventional gas supply to increase by 800 bcm in the period 2010-2035 (New Policies Scenario).

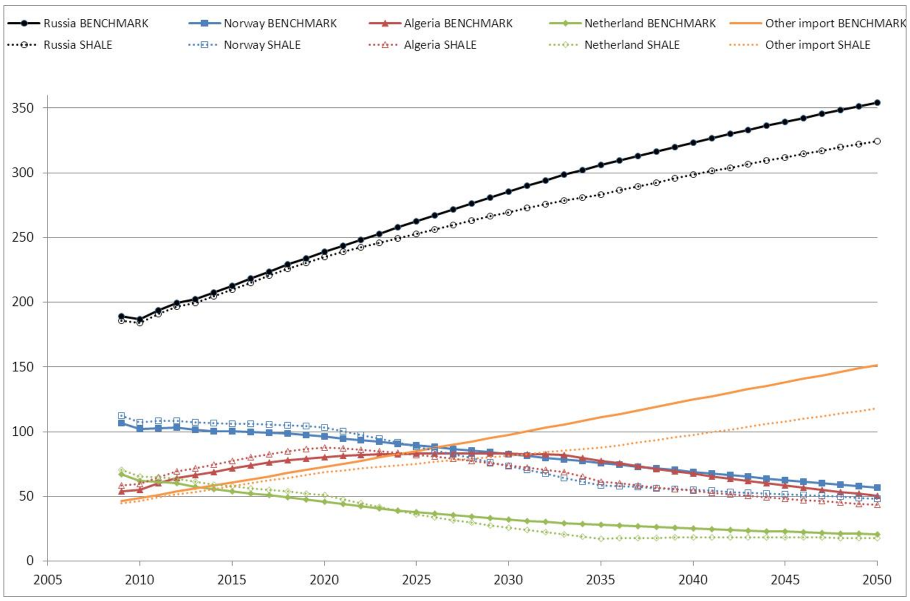

Figure 3: Supply of gas to the European market in Benchmark and Shale_gas scenarios. Bcm per year.

4 Simulation results

4.1 Benchmark scenario

The simulation results show the effects of a shift in expectations regarding future supply to the European gas market, that is, the difference between the scenarios Shale gas and Benchmark. First, we consider the Benchmark scenario and check that it fits reasonably well with actual and projected supply and demand. Figure 3 displays how supply from different producers develop until 2050. We see that Russian exports to Europe almost double during this period, increasing Russia's market share from 32% in 2009 to 54% in 2050. Norway and the Netherlands reduce their exports by one third and two thirds, respectively, while Algerian exports first increase and

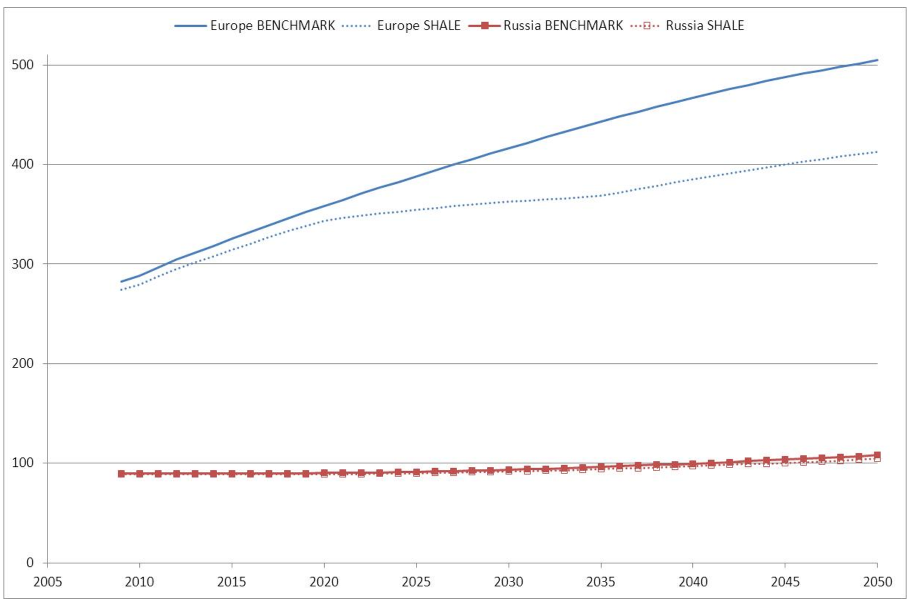

Figure 4: Price of gas in the European market in Benchmark and Shale gas scenarios. $ per toe.

then decrease to around baseyear levels.[14] LNG and other imports besides from Russia/Algeria triple over this period, while other domestic production in Europe declines substantially (by assumption). Total gas consumption increases by around 10% until 2050. This is less than what the IEA (2012) and others now project since the Benchmark scenario by construction has an outdated view on future supply of unconventional gas in that shale gas production is not included.[15] Without shale gas in the Benchmark scenario, the gas prices are higher and as a result, the gas consumption lower than in the IEA projections. The direction of changes in market shares observed in the figure are in line with most expectations about the European gas market, whether or not unconventional gas supply is accounted for.

The gas price in Europe increases from 280 to 500 $ per toe (in real prices) during the period 2009-2050 (see Figure 4), reflecting diminishing levels of profitable gas resources in most countries. The exceptions are Russia, which still holds large volumes of fairly cheap gas in 2050, and imports from other regions (e.g., LNG). As a consequence, Russian domestic prices stay around 100 $ per toe during the whole time horizon (Russian gas demand increases by two thirds during this time period).

4.2 Increased supply of unconventional gas

We next consider the effects of adding substantial volumes of unconventional gas to the European gas supply, gradually increasing the conventional gas supply from zero in 2020 to 150 bcm from 2035 onwards. Figure 4 shows that the gas price increases more slowly in the Shale gas scenario than in the Benchmark scenario, and is 50-90 $ per toe below the Benchmark price during the last 20 years of our time horizon. We further notice that the gas price drops in the Shale gas scenario even before the extra volumes of

[14] In calibrating the model, we added a temporary cost element for Algeria, which declines to zero after 25 years. This cost element reflects political and other unquantified costs (cf. e.g. the attack on the gas facility near In Amenas in January 2013) that may explain why Algeria, with total unit costs comparable with Norway but more reserves, produce only two thirds of Norwegian output.

[15] In the Shale gas scenario, European gas demand increases by around 20% during the same period.

unconventional gas enter the market.

The future price decrease gives non-renewable resource owners incentives to move some of their production forward in time, which explains the immediate price effect, cf. the theoretical discussion above. As seen in Figure 3, all gas producers reduce their supply from around 2025 in the Shale gas scenario (compared to the Benchmark scenario). Moreover, Norway, Algeria and the Netherlands all produce more in the shale gas scenario than in the Benchmark scenario in the first 15 years. Hence we obtain the immediate price drop.

The results so far are as expected, given the findings in previous literature (e.g., the Green paradox literature referred to in Section 1). Figure 3 shows, however, that Russian gas exports to Europe do not increase initially–it declines continously throughout our time horizon in the Shale gas scenario vis-a-vis the Benchmark scenario. Thus, Russia acts quite differently from the other Cournot players. Russia's vast amounts of gas reserves cause this behavior because decisions are more driven by the current market situation than by future market expectations. Figure 5 confirms this result. Figure 5 shows how unit production costs, the shadow price of the resource, and the oligopoly rent for Russia develop over time in the two scenarios. In Figure 5, the shadow price ranges from10 to 20 $ per toe, whereas the oligopoly rent increases from 150 $ per toe initially to 350 $ per toe in 2050 in the Benchmark scenario. Thus, the non-renewability issue is not particularly pressing for Russia. When the other Cournot players produce more initially in the shale gas scenario, Russia optimally cuts back on its supply to Europe.

The simulation results are consistent with the findings in Section 2, which considered a producer with sufficiently large resources. In the simulations Russia's gas reserves are sufficiently larger than the reserves of other gas suppliers to the European market that an increased future supply of shale gas to the European market reduces Russian supply both today and in the time after the entry of shale gas.

The Appendix shows the development of costs and rents for the three other Cournot players. We see that the shadow prices of their gas resources are significantly greater than the oligopoly rents for all these three players,

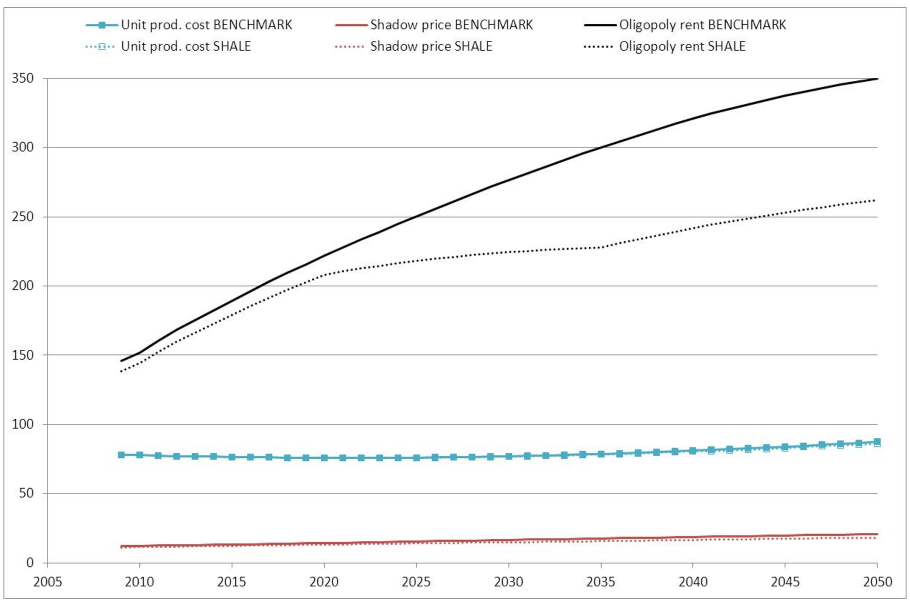

Figure 5: Unit production costs, shadow price and oligopoly rent for Russia. $ per toe.

i.e., quite the contrary of what we see for Russia in Figure 5.

As a consequence of lower gas prices and reduced market share for Russia throughout our model horizon, Russian discounted profits over the period 2009-2050 decline by 15%. Russia is the biggest Cournot producer and has the largest willingness to reduce production after entrance of the shale gas in order to prevent a price drop. Russia therefore suffers a relatively large loss of profits. The other Cournot players also lose profits, but somewhat less (10-11%).

The qualitative results, i.e., that Russia cuts back on its supply while the other Cournot players produce more initially, is robust to various assumptions about when, how quickly and how extensively unconventional gas supply enters the European gas market.

How much smaller would Russian reserves have to be before Russia, too, increases initial exports? Simulations suggest that their remaining reserves would have to be more than 60 percent lower for this to happen. Thus, the results are also robust with respect to Russia's remaining reserve level.[16]

4.3 Other potential reductions in future residual demand

So far the paper has focused on additional supply of unconventional gas, but other mechanisms could alter future residual demand for gas, too. Here we investigate whether these mechansims would yield the same qualitative results for the Cournot produsers' initial supply. Using our numerical model we, therefore, simulated the effects of *i*) a downward shift in the inverse supply function of LNG/pipeline imports, *ii*) a downward shift in gas demand, and *iii*) the introduction of a unit tax on gas consumption.

Increased gas imports through LNG and pipelines (i.e., besides Russian/Algerian and unconventional gas) is implemented in the model through a more rapid fall in the inverse supply function of such imports after 2025 (increased κ_t), and produces similar results to those of the Shale gas scenario. That is, Russian exports to Europe decline initially, while exports from Norway, the

[16] It is not straightforward to relate the reserve levels of the four Cournot players to the analytical model in Section 2, as Russia also supplies its domestic market in the numerical model.

Netherlands and Algeria increase. Note that the construction of this scenario differs qualitatively from the Shale gas scenario–in the latter scenario we make an exogenous quantity shift while in the former scenario the import supply function becomes more price-responsive.

A downward shift in the gas demand function after 2025 produces the same qualitative results as increased gas imports with respect to initial supply from the four Cournot players.

Introducing a unit tax on gas consumption from 2025 and onwards, on the other hand, *increases* initial supply from Russia as well as the other Cournot players' initial supply. The consumption tax shifts down the inverse demand function facing the producers, implying that the producers face a less elastic demand. As a result, large producers curb production after 2025 in order to raise the price they receive. Being the biggest producer (especially after 2025), Russia cuts back on its supply to Europe relatively more than the other Cournot players. Hence, Russia's incentives to save resources before 2025, which are small but not negligible, are reduced more than in the other scenarios with reduced future residual demand. At the same time, the other Cournot players' incentives to accelerate extraction is dampened compared to the other scenarios since Russia, to a larger degree, cuts back on its future supply. Altogether, all Cournot players find it profitable to slightly increase their initial supply.

The theoretical model also explains the effect of introducing a consumption tax after 2025: the largely dominant producer, Russia, reduces future supply substantially in order to exploit the enhanced market power granted by the decline in demand elasticity. This strengthens the intertemporal effect inducing Russia to accelerate production and to save less resources for the future. It weakens the intertemporal effect on the other Cournot players, as well. The decline in future Russian supply reinforces the effect of the future taxation. The limited acceleration of supply from non-Russian producers implies that the static effect on Russia to reduce current production is also limited. This explains why a tax policy that decreases both future demand level and future demand elasticity may induce Russia to increase initial supply, whereas changes that primarily reduce future demand level induce Russia to cut back initial supply.

The last example illustrates that Russia does not have endless resources after all. It is optimal for this producer, too, to consider future as well as current market conditions. Because Russia must supply to its large domestic market as well to European gas consumers, the impacts on initial market shares of changes in future market conditions depend not only on whether residual demand increases or decreases, but also on the *mechanism* that alters the demand.

5 Conclusions

In a non-renewable resource market, supply is governed both by current prices and the resource rent. As is well known, new information about bleaker future market conditions reduces the resource rent and thereby accelerates total supply.

This paper has investigated how altered expectations about future market conditions affect the current supply in a non-renewable market characterized by Cournot competition in strategic substitutes. We find that a firm with sufficient market power may limit the increase in initial production induced by bleaker future prospects as compared to a resource market with competitive firms. Indeed, a firm that endows sufficiently large amounts of reserves may reduce current production if the net present value of the resource declines in the future. The reason is that producers with extensive resources are less concerned about scarcity issues and the resource rent, whereas current market considerations remain important. As the producers with relatively smaller reserves accelerate their supply, it may be optimal for a producer with relatively large reserves to cut back on its initial supply in order to counteract the associated fall in the resource price.

Our results demonstrate that heterogeneous firms' production profiles may be differently affected by changes in future demand under oligopoly. This is particularly relevant if one is concerned about the composition of supply, e.g. for energy security reasons. In this respect, it is interesting that our numerical simulations suggest that bleaker prospects for oligopolistic gas suppliers in Europe, e.g., due to more supply of unconventional gas, will induce Russia to reduce exports of gas to Europe even before the additional gas enters the market whereas all other producers increase current production. Russia has limited incentives to curb its current extraction in order to save more resources for the future because of its vast natural gas reserves. Russia, therefore, acts almost like a static Cournot player, and while other gas producers increase their initial supply when future prospects become bleaker, Russia actually cuts back.

Our results also suggest that market power may alleviate the so-called Green paradox because the acceleration of production and emissions caused by lower future demand is dampened. Importantly, however, aggregate production unambiguously increases in the short run also under Cournot competition. The Green paradox is therefore not completely removed.

In order to derive our theoretical results, the analytical model featured quite strict assumptions about functional forms. It is reasonable to expect that the mechanisms detected will be present in more general cases. In this respect, we observe that the theoretical results are supported by the more sophisticated numerical model.

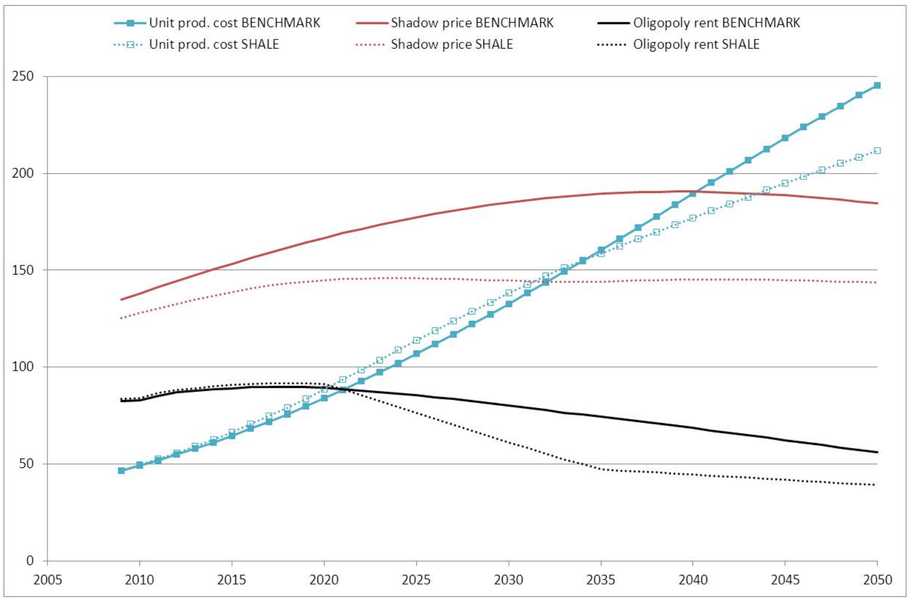

Figure 6: Unit production costs, shadow price and oligopoly rent for Norway. $ per toe.

6 Appendix

Here we present three figures from the numerical simulations, referred to in the main text.

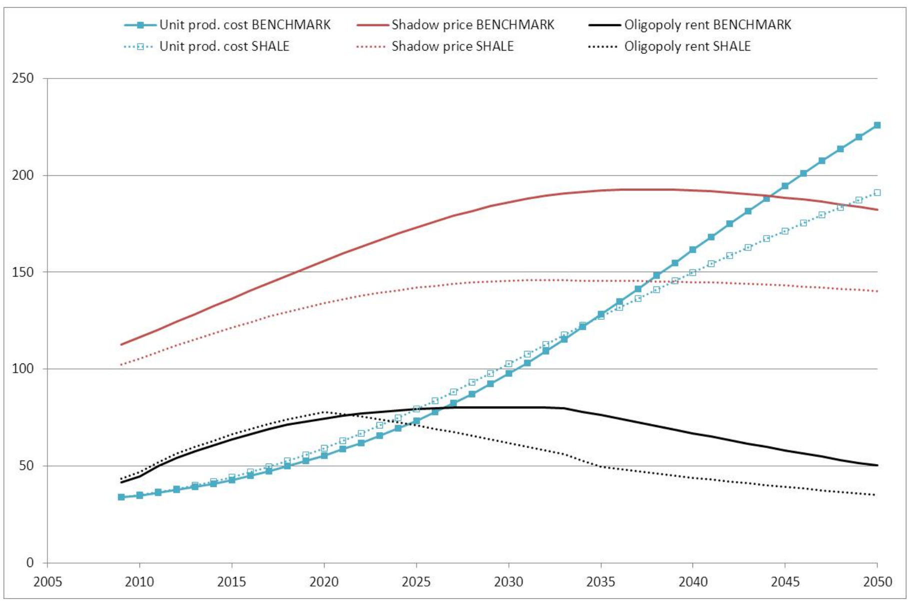

Figure 7: Unit production costs, shadow price and oligopoly rent for Algeria. $ per toe.

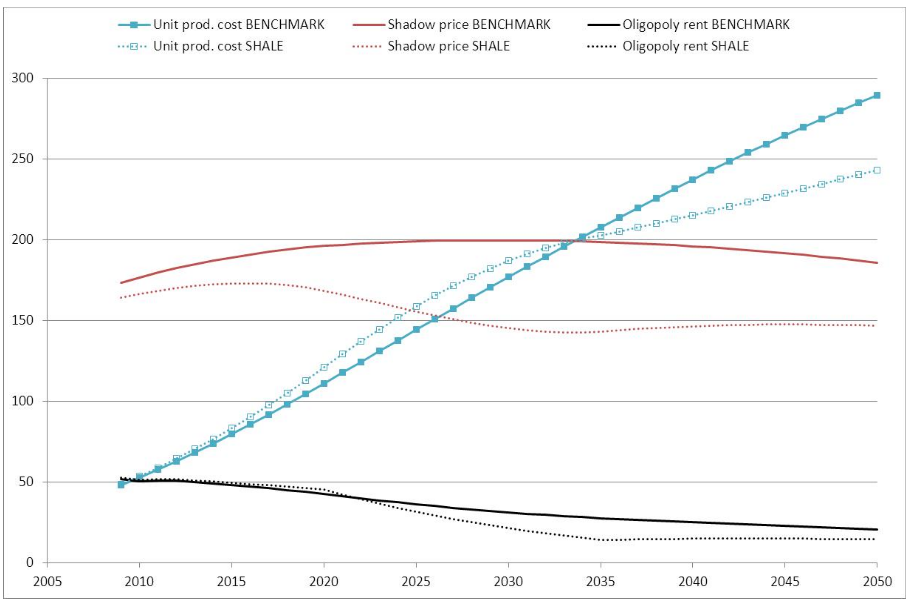

Figure 8: Unit production costs, shadow price and oligopoly rent for the Netherlands. $ per toe.

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