Short Run Effects of Bleaker Prospects for Oligopolistic Producers of a Non-renewable Resource

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ABSTRACT

In a non-renewable resource market with imperfect competition, both the resource rent and the current market influence large resource owners' 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. We show, however, that it may slow down early extraction by producers with sufficiently large reserves and thus small resource rents. The reason is that the supply from such producers is driven more by current market considerations than concern about resource scarcity. As producers with relatively smaller reserves accelerate their supply in response to bleaker demand prospects, producers with sufficiently large reserves will reduce their current supply. The surge in shale gas production will reduce residual demand facing suppliers to the European gas market. We demonstrate the effects of this in a numerical model. Most gas producers accelerate their supply while Russia reduces its supply slightly and thus loses market shares even before the additional gas enters the market.

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

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1. INTRODUCTION

For decades the dominating suppliers to the European natural gas market have been Russia, Norway, the United Kingdom (UK), the Netherlands, and Algeria. Since the early 1980's these five countries have jointly supplied at least two thirds of the total gas supply to the European Union (EU). In 2013 Russia supplied 33% of the natural gas consumed in Europe (BP, 2014). Due to recent technological progress, increased supply of shale gas and other unconventional natural gas is expected in the coming decades, both in the U.S. and elsewhere (EIA, 2013; IEA, 2013; Gabriel et al., 2013). The International Energy Agency (IEA) considers the surge in U.S. shale gas production and reserves over the last 7–10 years game-changing events for the world's gas markets (IEA, 2012).

Regional gas markets are gradually becoming more integrated through increased trade in liquefied natural gas (LNG). LNG trade combined with unconventional gas production and the emergence of new gas exporters will alter patterns of trade in natural gas. The Middle East and

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Africa are expected to ship their LNG to Europe and Asia rather than to North America, and countries in and outside Europe, such as Poland and the U.S., may become new gas exporters on the international market.[1] Thus, the surge in shale gas production has undoubtedly affected the expectations for future market conditions for today's natural gas producers, also in Europe.

In determining their optimal production level, gas producers must consider the optimal dynamic extraction path since natural gas is a non-renewable resource; cf. the extensive literature on non-renewable resources building on Hotelling (1931). Intuitively, the optimal path depends on the size of the resource stock and, important to this discussion, on expected future market conditions.

Heal (1976) demonstrated that the presence of a backstop technology affects current extraction of non-renewable resources. Dasgupta and Heal (1979) showed that the timing of the availability of the backstop technology alters the whole price path. In particular, the price path shifts upward if the availability of the backstop technology occurs later in time. Further, Sweeney (1993) showed that an expected decline in future demand will tend to accelerate resource extraction. Thus, it was early recognized that revised expectations regarding future market conditions will tend to affect current extraction of non-renewable resources. Whereas Dasgupta and Heal (1979) considered the timing of the backstop technology, altered expectations could also, for example, be induced by new suppliers or policy changes (e.g. climate policies). New information about reduced future profitability, either through lower future demand or increased future supply by competing producers, give non-renewable resource owners incentives to shift some of their extraction toward the present. The Green paradox literature shows that this could produce some undesired effects of environmental policies (see e.g. Sinn (2008), Gerlagh (2011) and Hoel (2011)).

The literature on exhaustible resource extraction and revised expectations about the future, such as the Green paradox literature, has generally assumed competitive markets, but non-renewable resource markets are often dominated by one or a few suppliers. For instance, OPEC dominates the oil market and the European gas market 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).

Hence, another important strand of the non-renewable resource literature has considered oligopolistic producers. The so-called 'oil'igopoly theory was developed by Salant (1976) who modeled the oil market using a dynamic Nash-Cournot approach. This theory has later been extended by e.g. Loury (1986), Hartwick and Sadorsky (1990) and Polasky (1992). Polasky also 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 Vojtassak (2008) examined a model of 'oil'igopoly where exploration can be used strategically by the firms.

Our paper contributes to the literature by combining the insights from Dasgupta and Heal (1979) and Sweeney (1993) and the Green paradox literature with the theory of oil'igopoly to analyze the current impacts of changes in future market conditions. To our knowledge, this issue has not yet been examined. The case we have in mind is the surge in shale gas production, and its impacts on the European gas market. Importantly, the analysis takes into account heterogeneous reserves of the oligopolistic non-renewable resource suppliers to the European gas market; in particular Russia has substantially greater reserves than the other suppliers.[2] We find, both analytically

1. To illustrate, in 2007 EIA forecasted U.S. natural gas imports to increase and cover more than 20% of total U.S. natural gas consumption in 2030 (EIA, 2007b). EIA are now instead expecting the U.S. to be a net gas exporter some years prior to 2020 (EIA, 2014). In addition to the potential future supply from U.S. to Europe, this implies that LNG exporters will find it more profitable to ship their gas to Europe/Asia instead of the US.

2. Russia's remaining gas reserves were at the end of 2013 about four times bigger than the combined reserves of Norway, Algeria, the Netherlands and the UK (BP, 2014). Russia's expected future exports to Europe largely outstrip that of the other countries even when accounting for that most of Russia's production is consumed domestically (cf. e.g. BP, 2014).

and numerically, that considering oligopolists with unequal remaining reserves may produce results that differ qualitatively from the results with a competitive supply, and at first sight, our results may appear counter intuitive. Although this study is inspired by the surge in shale gas production, our findings may generalize to other non-renewable resource markets with imperfectly competitive and heterogeneous producers.

The paper proceeds by developing a dynamic, theoretical model of two Cournot producers that differ with respect to reserve levels.[3] The analytical results show that although total market supply increases initially as a response to a fall in future demand, producers who possess sufficiently large reserves may in fact reduce their current supply when future market conditions become less profitable. The reason is that the supply decision of a producer with sufficiently large reserves is driven more by the current market conditions than by the resource (scarcity) rent, as compared to a producer who possesses smaller reserves. As a result the smaller resource owner tends to move its extraction toward the present, while the large resource owner may find it profitable to decrease its initial production.

The paper continues by presenting a dynamic and more realistic numerical simulation model of the European gas market. The numerical model analyzes how new information about a future increase in unconventional gas supply affects producers' current supply decisions. The simulation results suggest that all Cournot producers except Russia will increase their initial gas exports to Europe. Russia will instead reduce its current exports to Europe. The explanation is that Russia's remaining reserves are vast compared to the other countries supplying gas to Europe (see footnote 2). Thus, Russia's per unit scarcity rent is relatively small compared to the other producers' scarcity rent. This induces Russia to put more weight on current market conditions and less weight on scarcity considerations, as compared with the other suppliers. Hence, whereas the other Cournot producers increase their joint market share by almost 3% initially, Russia's market share drops by 1.5%.

Our results imply that changes in future market conditions, such as the surge in shale gas production, affect the production profiles of heterogeneous oligopolistic firms differently. This is particularly relevant for 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, slightly relieving European dependence on gas imports from Russia. The tense situation between EU and Russia caused by the Ukrainian conflict stresses the importance of multiple natural gas suppliers to the European market. On the other hand, Russia's dependence on the European market for natural gas revenues was relieved by the recent agreement to deliver gas to China by 2020.

Similar effects on the composition of gas supply may follow from policies that reduce future demand for gas (e.g., R&D subsidies to renewable energy). Moreover, we find that, compared to a competitive resource market, Cournot competition in strategic substitutes moderates the increase in aggregate current production induced by bleaker future prospects. This suggests that market power may lessen (but not remove) the Green paradox through its dampening effect on the increase in early production and emissions caused by lower future demand.

While the analytical model in Section 2 is relatively simple in order to derive transparent and intuitive analytical results, modeling the European gas market in sections 3 and 4 requires a more realistic numerical model. Section 5 concludes.

3. The results are also relevant for the Cartel-Fringe game (see, e.g., Salant, 1976; and Benchekroun and Withagen, 2012), which is frequently applied to analysis of the global oil market, see Subsection 2.2.

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.[4] 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 time t. The equilibrium concept is that of an open-loop Nash-Cournot equilibrium and we assume perfect information.[5]

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 firms' 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 ($t \in [T,\infty)$), where T is exogenous. Compared to period 1, period 2 is characterized by a drop in 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 drop in future residual demand is modeled as a reduction of the parameter K_t, i.e., $K_1 > K_2$. The fall may be caused by, e.g., 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 where the fall in future residual demand is caused by increased production of shale gas.

The model is best examined by backwards induction starting 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:

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

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, $\partial(\partial \pi_i / \partial S_{iT}) / \partial K_2 > 0$ for finite stock S_{iT}. The last inequality

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

5. The simplifying assumptions about costs and reserves are in line with much of the Green paradox literature (e.g., Chakravorty et al., 2011; Hoel, 2011), and are needed to derive transparent analytical results. Some studies assume that unit costs are increasing in accumulated extraction (e.g., Sinn, 2008; Gerlagh, 2011), which is the assumption we apply in the numerical model in Sections 3–4. Exploration is typically disregarded in this strand of the literature, but has been examined in some studies of non-renewable resources (e.g., Swierzbinski and Mendelsohn, 1989; Boyce and Vojtassak, 2008).

states that an increase in the resource stock is more valuable for a larger resource demand (due to a higher resource price).

2.2 Production in Period 1

In the first time period firm i maximizes profits:

$$\max_{q_{it}} \int_0^T e^{-rt} [(K_1 - q_{it} - q_{jt}) - c_i] q_{it} dt + \pi_i(S_{iT}) \tag{3}$$

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 interior solution profit maximizing extraction path must satisfy:

$$H_{q_t} = K_1 - c_i - 2q_{it} - q_{jt} - \lambda_{it} = 0 \tag{4}$$

$$_{it} - r\lambda_{it} = -H_{S_{it}} = 0 \tag{5}$$

$$\lambda_{iT} = \frac{\partial \pi_i}{\partial S_{iT}} \tag{6}$$

where equation (6) 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., $\partial\pi_i/\partial S_{iT}\partial$. 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 (5), 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 (4) yields $K_1 - c_i - 2q_{it} - q_{jt} - \lambda_{iT} e^{r(t-T)} = 0$. Solving this system of two equations and using (6), we obtain:

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

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:

$$\frac{\partial q_{it}}{\partial K_2} = \frac{1}{3}\left(\frac{\partial(\partial \pi_j/\partial S_{jT})}{\partial K_2} - 2\frac{\partial(\partial \pi_i/\partial S_{iT})}{\partial K_2}\right) e^{r(t-T)}. \tag{8}$$

Equation (8) 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 (8) is an *intertemporal effect:* a fall 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. Moving production from period 2 to period 1 offsets the relative fall in future net present value of the resource caused by the drop in future demand. The same reason, however, causes the competitor firm j to also increase its production in period 1. Because the firms' outputs are strategic substitutes there is a second and *static effect*, which is captured by the first term of the large parenthesis in (8): 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 increase, however, because the static effect is caused by the fall in price.[6] This may be seen from (8), which implies that the change in aggregate production is:

$$\frac{\partial q_{it}}{\partial K_2} + \frac{\partial q_{jt}}{\partial K_2} = -\frac{1}{3}\left(\frac{\partial(\partial \pi_i/\partial S_{iT})}{\partial K_2} + \frac{\partial(\partial \pi_j/\partial S_{jT})}{\partial K_2}\right)e^{r(t-T)} < 0. \tag{9}$$

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 Dasgupta and Heal (1979) and 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 $\lim_{S_{iT}\to\infty}(\partial(\partial \pi_i/\partial S_{iT})\partial K_2) = 0$. As long as firm j's reserves are finite, and firm j is producing in both periods, it will still be true that $\partial(\partial \pi_j/\partial S_{jT})/\partial K_2 > 0$. Equation (8) then reduces to:

$$\lim_{S_{iT}\to\infty} \frac{\partial q_{it}}{\partial K_2} = \frac{1}{3}\left(\partial \frac{\partial \pi_j/\partial S_{jT}}{\partial K_2}\right)e^{r(t-T)} > 0. \tag{10}$$

This implies that firm i will reduce supply in period 1 when demand falls in period 2 (i.e., a drop 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:

$$\lim_{S_{iT}\to\infty} \frac{\partial q_{jt}}{\partial K_2} = -\frac{2}{3}\left(\partial \frac{\partial \pi_j/\partial S_{jT}}{\partial K_2}\right)e^{r(t-T)} < 0. \tag{11}$$

Note that the smaller reserves firm j owns, the more profitable it may be for the firm to extract all its reserves in period 1. In that case, the first term in the parenthesis of equation (8) becomes zero. This implies that firm i will increase its initial extraction if future demand declines regardless of how large its reserves are.

We state the following result:[7]

6. Farrel and Shapiro (1990) show that an autonomous change in the supply of one firm moves total supply in the same direction, albeit in a smaller magnitude due strategic effects (in static Cournot equilibrium).

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

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

(i) Aggregate initial production increases.
(ii) A resource owner that owns sufficiently large reserves will reduce initial production.

Proof. The Proposition follows from equation (8).

The result arises from the two opposing mechanisms discussed immediately after equation (8) and the observation that the decisions of firms with ample reserves, 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 reserves. Indeed, at the limit, a firm with very large reserves 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 reduce its current extraction as other producers increase their extraction.

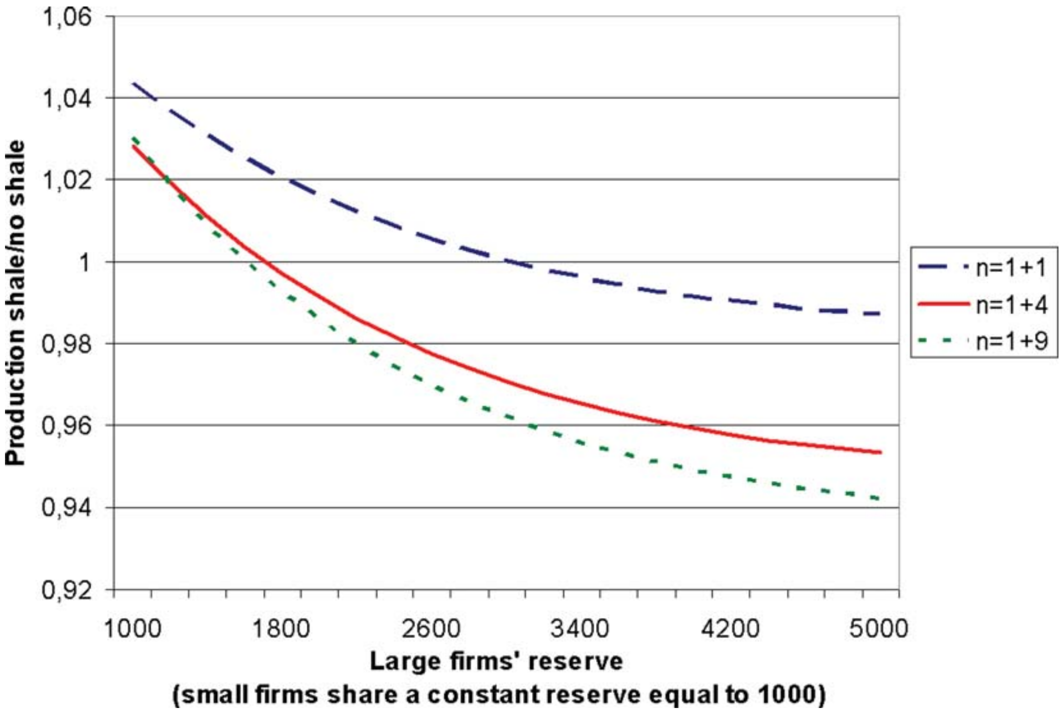
We observe that Proposition 1 arises from different resource stocks and does not require marginal extraction costs to differ across firms, i.e. it remains valid if $c_i = c_j$. On the other hand, Proposition 1 requires the marginal revenue for each firm to be decreasing in aggregate output (strategic substitutes). In Proposition 1 this is guaranteed by the assumption of linear demand. Note that, if the assumption about linear demand is relaxed, the requirement for strategic substitutes, which is necessary for Proposition 1 to be valid, would equal that of a static Cournot setting in the limiting case where the large firm's resource stock approaches infinity (infinitesimal resource rent).

Proposition 1 is illustrated in Figure 1. The figure was created using a numerical model (in GAMS) that exactly replicates the theoretical model. The parameter values are set to $K_1 = 500$, $c_i = c_j = 0$, and $r = 0.04$. The large firm's resource stocks range from 1000 to 5000 along the horizontal axis. The small firm's resource stock is kept constant at 1000. We set $K_1 = 500$ in the "no-shale scenario". We then reduce this parameter to 400 in the "shale scenario", to illustrate a fall in future demand. The duopoly case discussed above is labeled $n = 1 + 1$. 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 a scenario with one large and four small firms, where 'small' firm is defined as having initial reserves of $S_{j0} = 1000/4$. In addition, the figure shows a scenario with one large and nine small firms, where 'small' now is defined as having initial reserves of $S_{j0} = 1000/9$. In the latter case, the oligopoly rents of the nine small firms are negligible and they behave very similar to competitive firms. Thus, this case approximates the well-known cartel versus fringe model (see, e.g., Salant 1976).

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 causes 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 reserves left to produce in the future. This weakens the intertemporal effect for the large firm. As a result, 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

Figure 1: Production Ratios of a Large Firm in the First Period with Various Number of Firms (*n*)



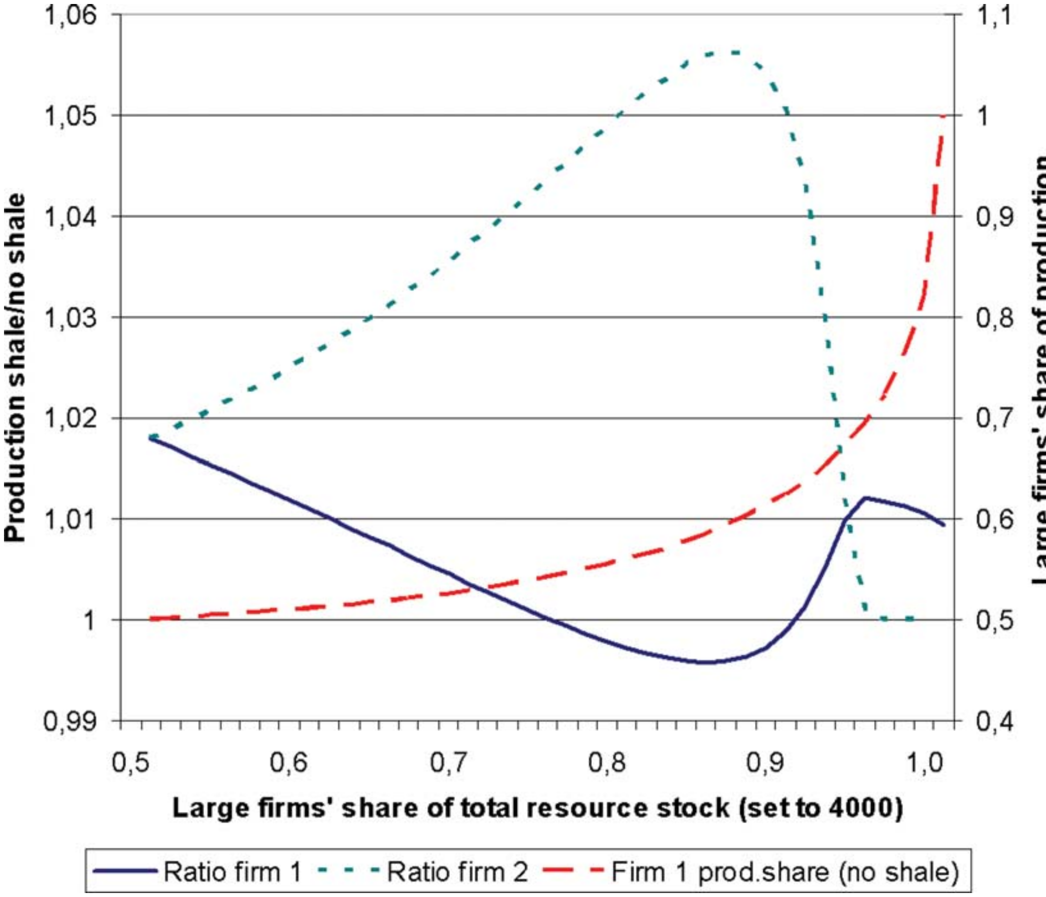
the intertemporal effect is more pronounced. The curves in Figure 1 then shift upward meaning that a larger reserve level is required to induce the big firm to decrease its initial supply.

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 increase its 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. In that case the resource rent does not drop as much when future demand decreases (the large player attempts to keep a high price), and the intertemporal effect for the small firm is rather limited.

Whereas the theoretical results are driven by opposing mechanisms and are ambiguous unless one of the player's resource stock approaches infinity, the outcome for a particular case can be investigated using numerical methods. The following section develops a numerical model for the European gas market, which is characterized by several heterogeneous Cournot players.[8]

8. The major differences between the theoretical and the numerical models are provided in Table A1 in the appendix.

Figure 2: Production Ratios and Production Share in First Period



3. NUMERICAL MODEL DESCRIPTION

We now turn to the European gas market and simulate the effects of a negative shift in future residual demand for incumbent producers caused by increased supply of unconventional gas.[9] Major technological progress in hydraulic fracturing and horizontal drilling have substantially increased the expected supply of shale gas in the U.S. over the next few decades (Gabriel et al., 2013),[10] as well as in Europe and elsewhere in the world in the longer term (EIA, 2012; IEA, 2012). The base year of the simulation model is 2013, and it runs with one-year time periods.

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

9. The numerical model was developed in GAMS and is available upon request. Selected model parameters are given in Tables A2–4 in the appendix.

10. Compare e.g. the completely different trade projections for the U.S. in EIA (2007a) and EIA (2012).

Cournot players. The exception is the UK where remaining reserves are low and production is not coordinated across companies.[11] The supply from the UK and other smaller European producers is considered exogenous to simplify the model.[12] Joint supply of LNG and pipeline imports from other sources than Russia and Algeria is modeled as a linear and increasing function of the gas price: $q_t^{imp} = q_0^{imp} + \kappa_t p_t^E$, where $\kappa_t > 0$. The parameters q_0^{imp} and κ_0 are calibrated based on data for 2013 (BP, 2014). The inverse supply function tilts slightly 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, 2013).

A single representative gas consumer is the basis for the model of European gas demand, which also includes Ukraine and Belarus. The model assumes that gas demand in Europe (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 $\varepsilon^E = -0.5$), i.e., $D^E = \bar{D}_t^E \cdot (p_t^E)^{\varepsilon^E}$ where $\bar{D}_t^E$ is an exogenous variable.[13] Gas demand changes over time, e.g. due to growth in GDP, and the level of $\bar{D}_t^E$ is calibrated based on IEA (2013) projections of gas consumption towards 2035. After 2035 we assume a slight decrease in the gas demand growth, implying a rather constant level of $\bar{D}_t^E$ from 2050.

The four Cournot players take into account the price-responsiveness of the demand-side and the supply of imported gas from other countries than Russia and Algeria, and thus have the following maximization problem:[14]

$$\pi_i = \max_{q_{it}} \sum_{t=0}^{T} (1+r)^{-t} (p_t^E(q_t) - c_{it}(A_{it}) - c_{it}^{\tau}) q_{it}, \tag{12}$$

subject to:

$$A_{it+1} = A_{it} + q_{it} \tag{13}$$

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 inverse demand schedule facing the oligopolistic producers, and r is the producer discount rate. The discount rate is set to four percent in the simulations, reflecting that long-run supply of gas from these four countries is highly influenced by government decisions. We assume that unit extraction costs increase in accumulated production according to the following function:

11. 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.

12. 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 2013. After five years, total supply from these countries is less than Dutch supply in 2013. Hence, modeling this supply as competitive would not alter our qualitative results.

13. 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.

14. 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.

$$c_{it}(A_{it}) = c_i^0\, e^{\eta_i A_{it} - \theta_i t}, \tag{14}$$

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 but adjusted to 2013-\$. 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 on reserve data from BP (2014).[15] Note that we do not assume a fixed resource stock here as we do in the theoretical model. Nevertheless, at any given point in time only a finite amount of resources will have unit extraction costs below the prevailing price.

From the optimization problem above we derive the following first order condition for the Cournot players (the derivation is shown in the Appendix):

$$c_{it}(A_{it}) + c_{it}^T + \lambda_{it} = p_t^E \cdot \left(1 + \frac{q_{it}}{\varepsilon^E D^E - \kappa_t p_t^E}\right), \tag{15}$$

where λ_{it} now denotes the (positive) shadow price of the resource. This condition corresponds to equation (4) in Section 2, with total marginal cost (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:

$$\lambda_{it} = (1 + r)\lambda_{it-1} - \eta_i c_{it}(A_{it}) q_{it}. \tag{16}$$

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., $D^R = \bar{D}_t^R \cdot (p_t^R)^{\varepsilon^R}$ is also assumed to characterize Russian gas demand, but the Russian elasticity is assumed to be -0.25, i.e., half of the European.[16]

Russian gas prices are highly regulated, but have been increased over the last few years. From a Russian welfare perspective, the optimal policy may 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 for the base year 2013 is slightly higher than the actual domestic gas tariff in Russia that year.[17] We then have the following first order condition for the Russian gas market:

$$c_{Rt}(A_{Rt}) + \lambda_{Rt} = p_t^R. \tag{17}$$

15. We simply assume that all reported reserves in the base year can be economically extracted at the base year price. In other words: We assume that unit costs (plus transport costs) become equal to the base year 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%.

16. 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.

17. http://www.reuters.com/article/2013/02/25/gazprom-tariffs-idUSL6N0BP8Z820130225.

Note that equations (13) and (16) must be adjusted 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 U.S. LNG exports, other LNG volumes that are rerouted from the U.S. 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.[18]

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 Shale gas and Benchmark scenarios. 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 notice that Russian exports to Europe grow by almost 40% towards 2050, increasing Russia's market share from 36% in 2009 to 51% in 2050 (remember that Europe here includes Ukraine and Belarus). Norway and the Netherlands reduce their exports by one half and three quarters, respectively, while Algerian exports first increase and then decrease somewhat.[19] LNG and other imports besides from Russia/Algeria more than double over this period, while other domestic production in Europe declines substantially (by assumption). Total gas consumption is fairly constant until 2050.[20] 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 390 to 600 $ per toe (in real prices) during the period 2013–2050 (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). Russian domestic prices increases from 110 $ to 160 $ per toe during the period 2013–2050 (Russian gas demand increases by 15% during this time period).

18. The surge in shale gas production has probably had some impacts on the European gas market already, but the larger effects will most likely come after 2020. Furthermore, there is no consensus about the size of this effect nor its impact on the European gas market. To put our numbers into perspective, however, in 2007 EIA expected that the U.S. would import around 150 bcm in 2030. Five years later, EIA expected an *export* level in 2035 of 70 bcm (EIA, 2007a, 2012). IEA (2013) projects global unconventional gas supply to increase by 770 bcm in the period 2011–2035 (New Policies Scenario).

19. 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 less than half of Norwegian output.

20. The IEA (2013) projects a moderate growth until 2035. However, remember that the Benchmark scenario by construction has an outdated view on future supply of unconventional gas (as shale gas production is not included). Hence, the gas price in this scenario rises more steeply than in the Shale gas scenario. In the latter scenario European gas demand increases by around 10% until 2035, and is then rather constant to 2050.

Figure 3: Supply of Gas to the European Market in Benchmark Scenario. Bcm Per Year

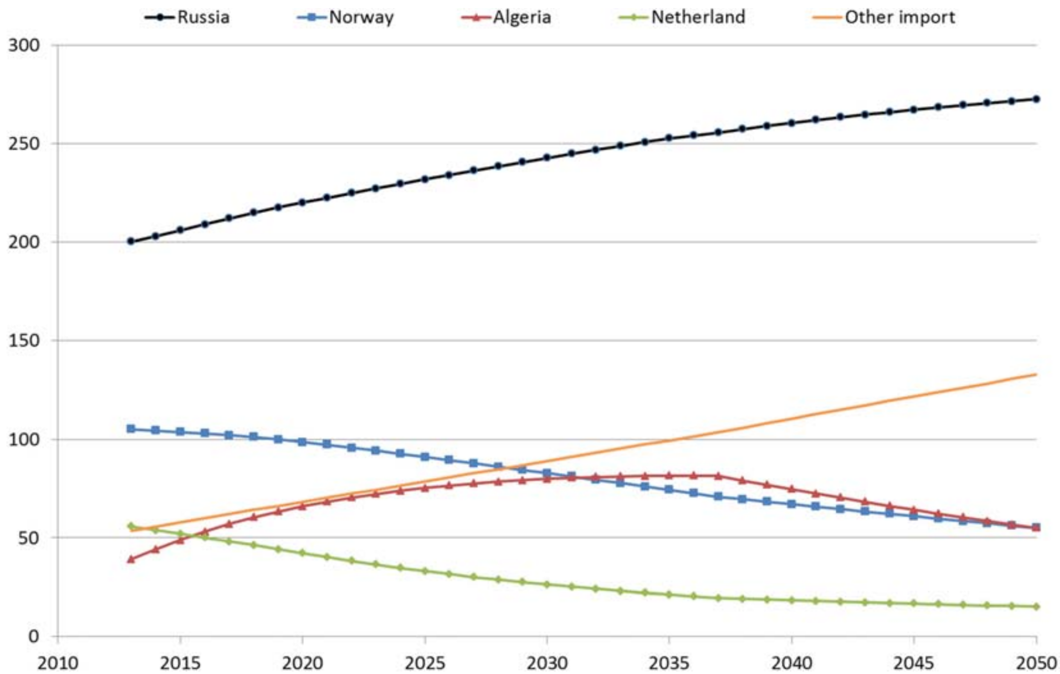


Figure 4: Price of Gas in the European and Russian Market in Benchmark and Shale Gas Scenarios. $ Per Toe

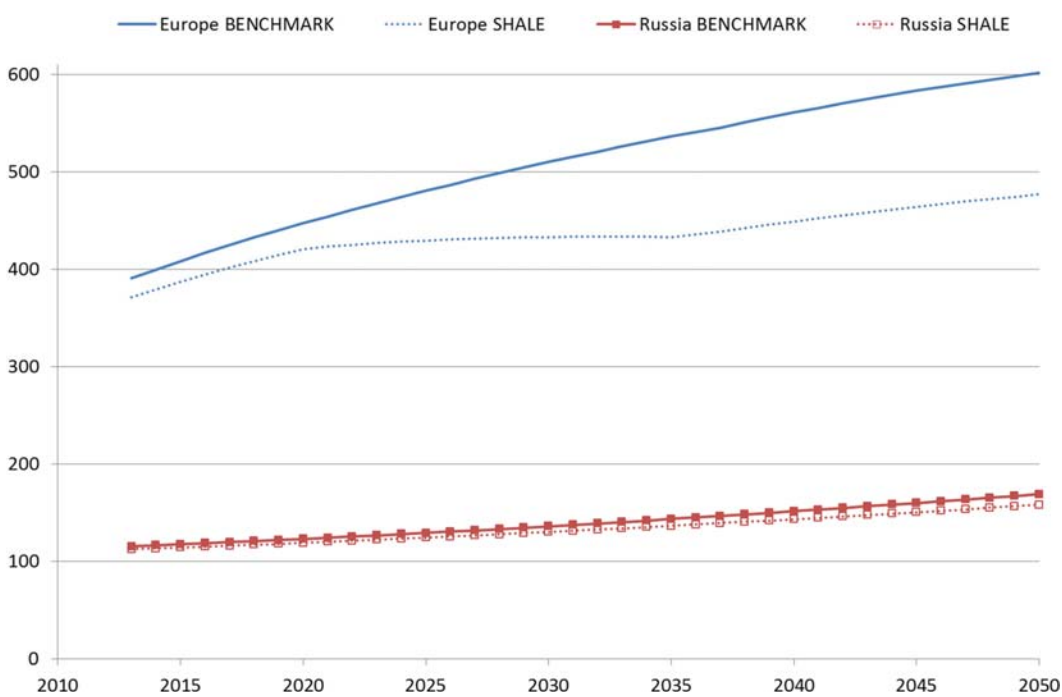
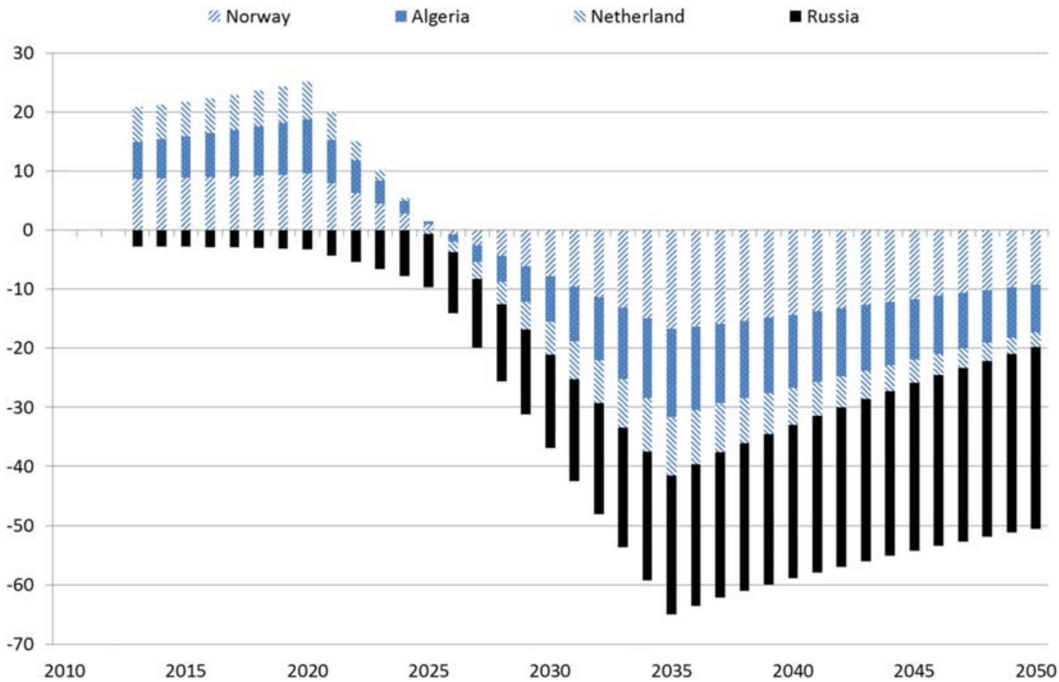


Figure 5: Changes in Cournot Producers' Gas Supply to the European Market in the Shale Gas Scenario (Relative to the Benchmark Scenario). Bcm Per Year



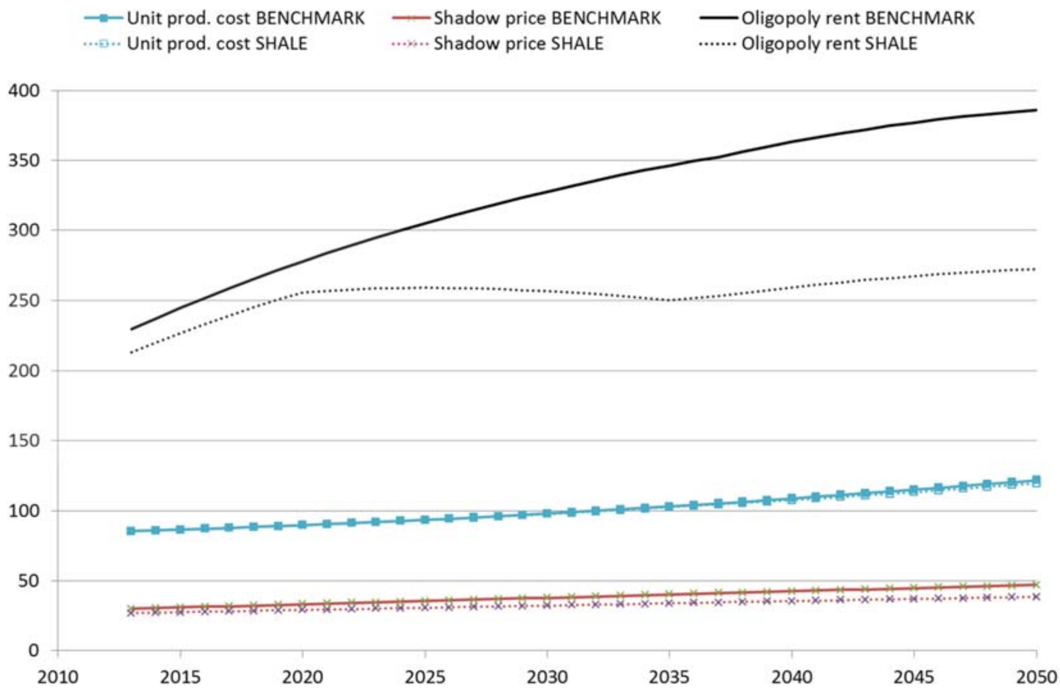
4.2 Increased supply of unconventional gas

We next consider the effects of adding substantial volumes of unconventional gas to the European gas supply, gradually increasing the unconventional 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 75–125 $ 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 unconventional gas enter the market.

The future price decrease gives non-renewable resource owners incentives to move some of their production toward the present, which explains the immediate price effect, cf. the theoretical discussion in Section 2. As seen in Figure 5, after 2025 all gas producers reduce their supply 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 until 2025. Hence we obtain the immediate price drop.

The results so far are as expected, given the findings in previous literature referred to in Section 1. Figure 5 shows, however, that Russian gas exports to Europe do not increase initially–it declines continuously throughout our time horizon in the Shale gas scenario vis-a-vis the Benchmark scenario. The initial output decrease is not big though–1.4%. Still, Russia acts quite differently from the other Cournot players. Whereas the other Cournot producers increase their joint market share by almost 3% initially, Russia's market share drops by 1.5%. The country'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 6 confirms this result. It shows how unit production

Figure 6: Unit Production Costs, Shadow Price and Oligopoly Rent for Russia. $ Per Toe



costs, the shadow price of the resource, and the oligopoly rent for Russia develop over time in the two scenarios. In Figure 6, the shadow price ranges from 25 to 45 $ per toe, whereas the oligopoly rent increases from 230 $ per toe initially to 390 $ 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 vast reserves. In the simulations, 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 reason is that Russia's gas reserves are large enough that current market considerations dominate scarcity concerns.

Figures A1–A3 in the Appendix show 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, i.e., quite the contrary of what we see for Russia in Figure 6. The qualitative results, i.e., that Russia cuts back on its supply to Europe while the other Cournot players produce more initially, are robust to various assumptions about when, how quickly and how extensively unconventional gas supply enters the European gas market. The qualitative results are also robust to changes in most uncertain parameters of the model. Table A5 in the appendix shows the results of sensitivity analyses where we either halve or double the value of crucial parameters. Naturally, both the Benchmark scenario and the Shale gas scenario change in all these cases. In Table A5 we display the percentage changes in initial supply from respectively Russia and non-Russian Cournot producers to the European market, when shifting from the Benchmark scenario to the Shale gas scenario. As shown in Table A5, in 16 of the 18 sensitivity analyses Russian gas supply drops initially when more shale gas supply is expected in the future.

The two exceptions are directly related to the resource rent (shadow price) and the oligopoly rent, respectively (cf. Figure 6): If Russia's gas reserves are halved, the shadow price of its resources increases, and hence the intertemporal effect becomes more important. Initial supply then increases by 0.8% instead of decreases by 1.4% in the Shale gas scenario (compared to the Benchmark scenario). If the price elasticity in Europe is doubled, Russia is less able to increase the price by holding back supply, and hence the oligopoly rent is lower. Russia's initial supply is then almost the same in the two scenarios (cf. Table A5). If we quadruple the elasticity to -2, Russia increases its initial supply by almost one percent. This shows that the numerical results are somewhat sensitive to the assumptions about some central parameters. Furthermore, if the additional shale gas did not enter before around 2045 (and this was known today), Russia would no longer decrease its initial supply. The reason is that the other Cournot players have less profitable resources left after 2045, and will therefore shift less extraction towards the present (see also the discussion of Figure 3 above).

It could be argued that Russia is more impatient about monetizing its gas reserves than the other producers, e.g. due to fiscal constraint. If we incorporate this into the model by increasing the discount rate in Russia to say 10% (instead of 4%), Russia's initial extraction increases, both in the Benchmark scenario and the Shale gas scenario. However, when shifting from the (new) Benchmark scenario to the (new) Shale gas scenario, the initial gas extraction in Russia decreases a bit more strongly than in our main scenarios. The reason is that when Russia is more impatient, the dynamic aspect is less important, and thus the country is more concerned about the current (static) Cournot game.

So far this paper has focused on additional supply of unconventional gas, but other mechanisms could alter future residual demand for gas, too. We have investigated whether these mechanisms would yield the same qualitative results for the Cournot producers' initial supply. Using our numerical model we have 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. Whereas i) and ii) give the same qualitative outcome as in the Shale gas scenario, we find that a future unit tax *increases* initial supply from Russia. For details and explanations of these simulations, we refer to our working paper Grimsrud et al. (2014).

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 heterogeneous producers and Cournot competition in strategic substitutes. We find that 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 reserves are less concerned about scarcity issues and the resource rent, whereas current market considerations remain important. As producers with relatively smaller reserves will tend to accelerate their supply, it may be optimal for a producer with a relatively large reserve to cut back on its initial supply to counteract the associated fall in the resource price.

Our results demonstrate that firms' production profiles may be quite differently affected by changes in future demand under oligopoly with heterogeneous firms than under oligopoly with homogenous firms or under competitive supply. 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. 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. While other Cournot producers increase their initial supply by on average 10% when future prospects become bleaker, Russia actually cuts back by 1–2%.

Our results also suggest that market power may weaken 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 therefore remains, although weakened.[21]

In order to derive our theoretical results, the analytical model featured quite strict assumptions on functional forms. Still, 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 realistic numerical model.

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21. Note that the green paradox is weakened by market power also if firms are symmetric, because Cournot firms are less willing to increase production due the associated fall in price (as compared with competitive firms).

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APPENDIX

In order to derive equation (16), i.e., the first order condition for the Cournot players, we set up the Lagrange function, optimizing wrt. p_t^E instead of q_{it}:[22]

$$L = \sum_{t=0}^{T}(1+r)^{-t}(p_t^E - c_{it}(A_{it}) - c_{it}^{\tau})\left(\bar{D}_t^E \cdot (p_t^E)^{\varepsilon^E} - (q_0^{imp} + \kappa_t p_t^E) - \sum_{j \neq i} q_{jt} - q_t^{exog}\right) \tag{18}$$

$$+ \sum_{t=0}^{T} \lambda_{it}^r \left(A_{it+1} - A_{it} - \left(\bar{D}_t^E \cdot (p_t^E)^{\varepsilon^E} - (q_0^{imp} + \kappa_t p_t^E) - \sum_{j \neq i} q_{jt} - q_t^{exog}\right)\right)$$

Here we have inserted for $q_{it} = D_E - q_t^{imp} - \sum_{j \neq i} q_{jt} - q_t^{exog}$ (q_t^{exog} denotes the exogenous supply from small European producers). λ_{it}^r is the (discounted) shadow price on the resource constraint in (13). Differentiating with respect to p_t^E gives the first order condition:

$$(1+r)^{-t}\left(\bar{D}_t^E \cdot (p_t^E)^{\varepsilon^E} - (q_0^{imp} + \kappa_t p_t^E) - \sum_{j \neq i} q_{jt} - q_t^{exog}\right) \tag{19}$$

$$+ (p_t^E - c_{it}(A_{it}) - c_{it}^{\tau})(\varepsilon^E \bar{D}_t^E \cdot (p_t^E)^{\varepsilon^E - 1} - \kappa_t) - \lambda_{it}^r(\varepsilon^E \bar{D}_t^E \cdot (p_t^E)^{\varepsilon^E - 1} - \kappa_t) = 0$$

This can be simplified as follows:

$$q_{it} + (p_t^E - c_{it}(A_{it}) - c_{it}^{\tau} - \lambda_{it})\left(\frac{\varepsilon^E D^E}{p_t^E} - \kappa_t\right) = 0 \tag{20}$$

where we have replaced $\lambda_{it}^r(1+r)^t$ with the undiscounted shadow price λ_{it}. Reorganizing we get (15).

Similarly, by differentiating (18) wrt. A_{it}, using (14) and inserting back for q_{it}, we get (16).

22. The normal procedure in Cournot models is to optimize wrt. output, as output is the strategic variable in Cournot models. However, since there is a one-to-one relationship between output and prices in the optimization problem for the individual Cournot player (assuming interior solution), optimizing wrt. output is equivalent with optimizing wrt. prices. Moreover, since it is not possible to derive a reduced form expression for the inverse residual demand function in this case, we choose to optimize wrt. price.

Figure A1: Unit Production Costs, Shadow Price and Oligopoly Rent for Norway. $ Per Toe

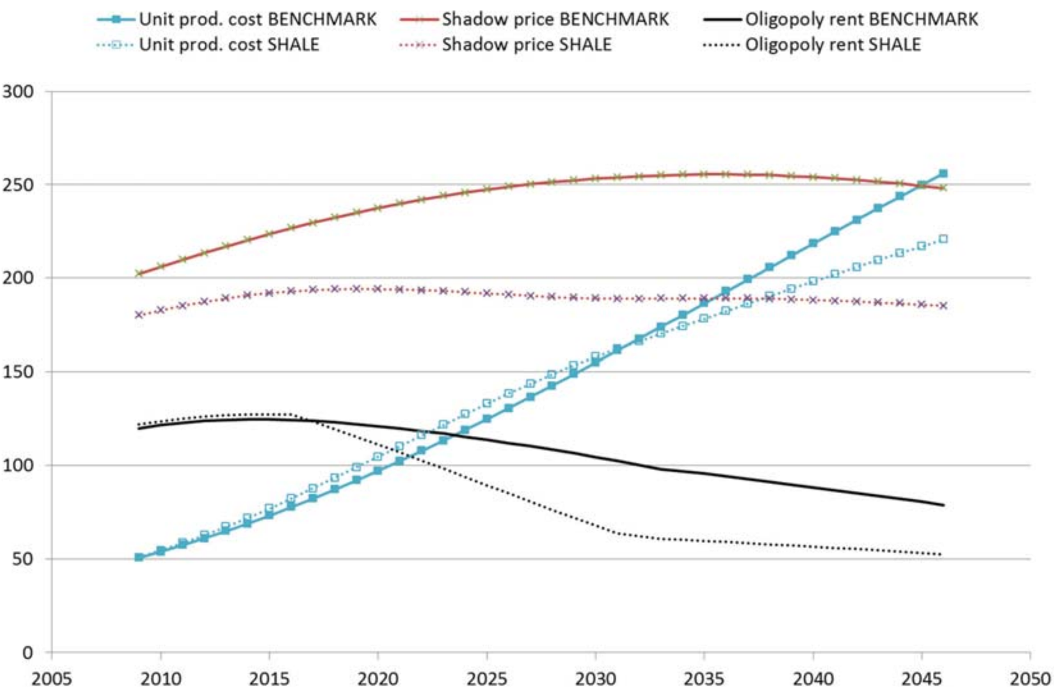

Figure A2: Unit Production Costs, Shadow Price and Oligopoly Rent for Algeria. $ Per Toe

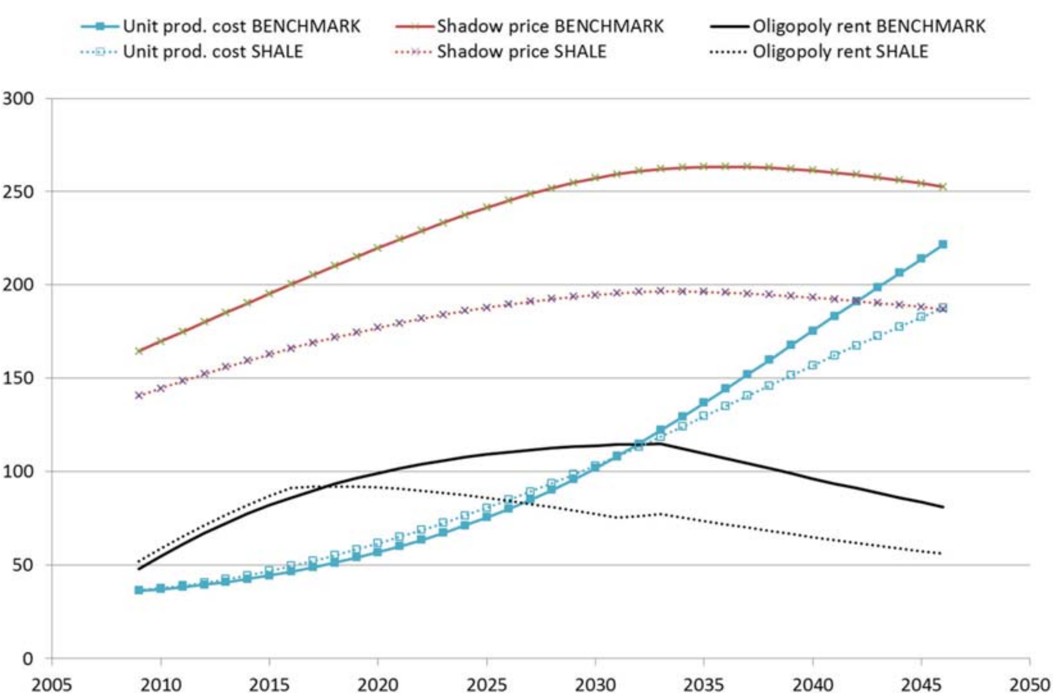

Figure A3: Unit Production Costs, Shadow Price and Oligopoly Rent for the Netherlands. $ Per Toe

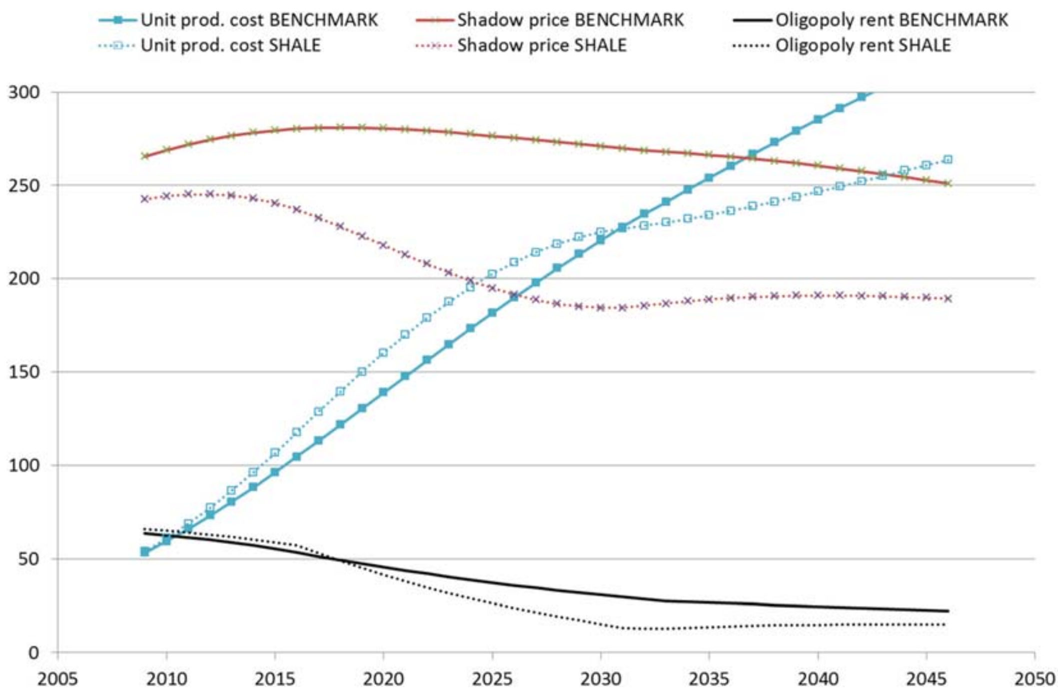

Table A1: Comparison of Theoretical and Numerical Models

	Theoretical Model	Numerical Model
Market structure	Two Cournot producers	Four Cournot producers; exogenous supply from other European producers; price-responsive import of gas
Time	Continuous	Discrete
Demand	Linear	Iso-elastic
Marginal cost of extraction	Constant	Stock dependent, increasing
Resource Stock	Finite	Infinite
Transportation cost	Zero	Positive, constant
Shale gas	Introduced in Period 2	Gradual introduction

Table A2: Demand Side Parameters

European consumption of natural gas in base year $\bar{D}_t^E$ (bcm)	558
Russian consumption of natural gas in base year $\bar{D}_t^R$ (bcm)	413
European gas price in base year $\bar{p}^E$ (U.S. dollars per 1000 cm)	383
Russian gas price in base year $\bar{p}^R$ (U.S. dollars per 1000 cm)	99
Long-run price elasticity Europe ε^E	−0.5
Long-run price elasticity Russa ε^R	−0.25
Income elasticity Europe (first 25 years)*	0.42
Income elasticity Russia (first 25 years)*	0.15

* The income elasticities decline over time (cf. main text)

Table A3: Supply Side Parameters Cournot Producers

	Russia	Norway	Netherlands	Algeria
Initial unit extraction costs c_i^0	83	46	46	35
Cost parameter (accumulated production) η_i	0.044	0.80	2.45	1.00
Discount rate r	4 %	4 %	4 %	4 %
Technological progress θ_i	2 %	2 %	2 %	2 %

Table A4: Supply Side Parameters Other

Constant in LNG import supply function q_0^{imp}	17.6
Initial slope parameter in LNG import supply function κ_0	0.18
Annual (exponential) increase in κ_t	1%
Shale gas supply from 2035 (bcm)	150
Initial supply from European, non-Cournot producers	99

Table A5: Sensitivity Analysis. Percentage Changes in Initial Russian and Non-Russian Cournot Supply in SHALE Scenario (Compared to BENCHMARK Scenario)

	Lower parameter value		Higher parameter value	
	Russia	Non-Russia	Russia	Non-Russia
Price elasticity Europe	−3.0 %	8.9 %	0.1 %	10.6 %
Price elasticity Russia	−1.3 %	10.5 %	−1.5 %	10.4 %
Income elasticity Europe and Russia	−1.4 %	10.1 %	−1.4 %	11.1 %
Initial costs Non-Russian Cournot players	−1.9 %	9.4 %	−1.0 %	12.4 %
Initial costs Russia	−0.6 %	11.4 %	−3.0 %	9.2 %
Reserves Non-Russian Cournot players	−1.1 %	14.3 %	−1.4 %	6.4 %
Reserves Russia	0.8 %	10.0 %	−1.9 %	10.7 %
LNG inverse supply slope	−1.2 %	9.0 %	−1.3 %	12.2 %
Discount rate	−1.3 %	21.9 %	−1.1 %	4.0 %
	Russia		Non-Russia	
Benchmark	−1.4 %		10.4 %	

Note: "Lower parameter value": The parameter is divided by 2. "Higher parameter value": The parameter is multiplied by 2.