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Universidade do Minho
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Trade, renewable energy, and market power in power markets*

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Abstract

Energy markets are undergoing a radical shift towards renewable energy and network integration. We study the effects of integrating regions with storable (hydro) and intermittent (wind) energy sources in the presence of market power. Based on a two-period model with price fluctuations in the wind power region and bottlenecks in transmission of energy between regions, we show that a dominant firm (facing a competitive fringe) has an incentive to reallocate more hydropower production to the low-price period in order to induce higher prices in the high-price period. This incentive might be so strong that the bottleneck in the low-price period is removed and the two regions become *de facto* integrated. Paradoxically, we find that higher hydropower production capacity and/or larger transmission capacity can lead to higher (average) prices in the hydropower region due to the strategic responses by the dominant firm. Moreover, we find that the presence of market power in many cases enables the dominant firm to appropriate a larger share of the surplus from trade without harming domestic consumers, implying that stronger competition in the hydropower region might not be welfare improving.

Keywords: Hydropower, trade, market power

JEL Classification: L13; L94: Q41

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1 Introduction

There is a dramatic transition taking place in energy markets with renewable energy replacing energy based on fossil fuels.[1] In Europe, coal, gas and oil are about to be replaced by renewable energy such as solar and wind power. A key challenge, though, is that these energy sources are intermittent. For example, wind power produces at full capacity in some time periods while production can be zero in others when the wind is not blowing. This irregularity generates high volatility in energy prices.

The radical shift towards intermittent energy sources implies a demand for storable energy sources to smoothen production over time and thus dampen the price fluctuations that is driven by exogenous changes in weather conditions. Energy can, in principle, be stored in batteries or transformed to hydrogen, but at present these storage technologies are not economically feasible at a large scale. One of the few feasible storage technologies at present is water reservoirs, which enable water to be stored and used for hydropower production in future time periods. In parts of Europe, such as Sweden, Switzerland and in particular Norway, hydropower production from reservoirs is quite common.[2] As pointed out by Newbery (2023b), integration of regions with hydropower and intermittent energy sources can be beneficial for both regions.

Figure 1 illustrates the price volatility (measured by hourly day ahead prices) in two regions with very different energy sources; Norway with mostly hydropower and Germany that has had a radical shift towards intermittent energy sources, especially wind power. The figure shows that the price volatility is much higher in the German region than in the Norwegian region where energy can be stored. It illustrate that storage can lead to more stable prices over time, and therefore network integration and trade across the two regions could be beneficial. This is a key motivation for our study and a starting point for our modelling approach.

[1] See, for instance, Newbery (2023a) for a description of the recent changes in Europe, Pommert and Schubert (2022) for the transition to renewable energy in the the Spanish electricity market, Moe et al. (2021) for changes in Norway, and Liski and Vehviläinen (2020) for an analsysis of the consumer welfare effects of subsidising investments in windpower in the Nordic electricity market.

[2] In Norway more than 90 percent of the production of electricity comes from hydropower.

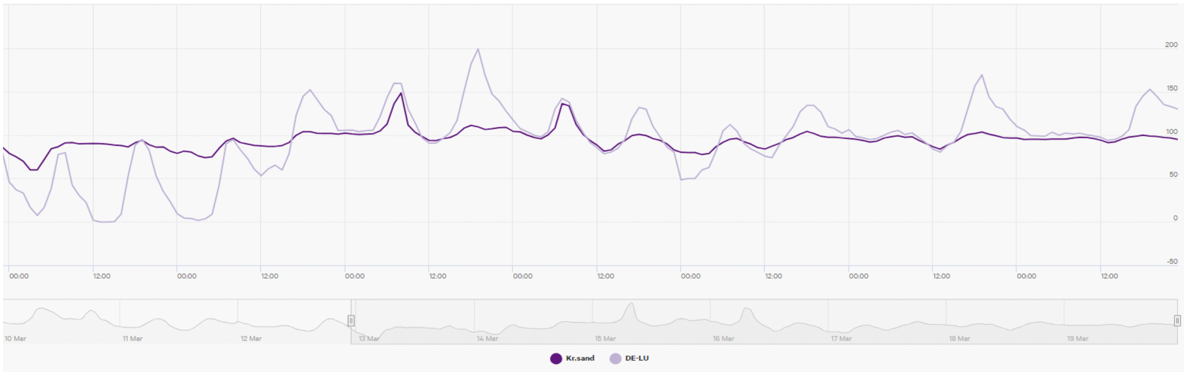

Figure 1: Hourly day ahead prices, 10-19 March 2023, Norway (NO2) and Germany (DE-LU)

A common feature of energy markets is market power, and we know from the economics literature that the existence of a dominant firm can have a large impact on market outcomes and effects of policies.[3] In this paper, we therefore take market power into account when studying the effects of integrating regions with different renewable energy sources, such as hydropower and wind power. In particular, we develop a two-period model where a dominant firm facing a competitive fringe decides on the amount of hydropower to produce in each period. The periods differ in the price level in the region with intermittent (wind power) energy source, with a high price in the first period (little wind) and a low price in the second period (much wind). The competitive fringe thus produces all its capacity in the first period, whereas the dominant firm is a monopolist on the residual demand and decides on the allocation of production across the two periods. Energy can be traded across regions within the limits of a fixed transmission capacity. It is a potential for bottlenecks both in the first period with export from the hydropower region to the wind power region and in the second period where the hydropower region imports energy from the wind power region.

While network integration should facilitate gains of trade and be beneficial for both regions, we show that market power may yield counterintuitive and potentially adverse effects. In fact, we show that the opportunity for the dominant firm to export energy in the first period makes the residual demand less price elastic. This implies that, for equal prices across the two periods,

[3] For instance, Fabra and Imelda (2023) analyse whether market power can counteract the price depressing effect of renewable energy which can be produced at very low (close to zero) marginal costs. See also Ito and Reguant (2016) on the role of market power in sequential markets and arbitrage applied to the Iberian electricity market.

the marginal revenue is lower in the first period than in the second period. The dominant firm has therefore an incentive to reallocate more production towards the second period in order to increase the first-period price and thereby increase its export revenues.

The incentive for the dominant firm to create intertemporal price differences is even stronger when there is an integrated market in the second (low-price) period. In absence of a bottleneck, it is profitable for the dominant firm to sell a large quantity in the second period, as the price in this period is given by the low price of the imported energy from the wind power region. We also show that it can be optimal for the dominant firm to allocate production such that the bottleneck in the second period is removed and the two regions become *de facto* integrated. This is opposite of what has been argued in the literature.[4]

Based on this set up, we derive several, at first glance, counterintuitive results, which are mostly due to the strategic responses by the dominant firm. First, we show that higher *production capacity* in the hydropower region not necessarily leads to lower prices, but can in fact result in a higher average price across the two periods. A higher capacity may lead to a regime shift by triggering the dominant firm to increase its supply in the second period to induce an integrated market in this period. In this case, there is no price effect in the second period, and the dominant firm can dump all additional capacity in the second period to ensure a high price in the first period. As a benchmark for comparison, we also we derive the equilibrium under the special case of perfect competition, which implies uniform pricing across periods, and show that larger production capacity no longer can lead to higher prices.

Second, we find that increased *transmission capacity* also has ambiguous price effects, which is surprising given that this allows for more trade and should therefore in principle reduce the scope for bottlenecks. If there is net import to the hydropower region (i.e., the import in the second period is larger than the export in the first period), then more transmission capacity will lead to larger net imports and thus lower average prices. But if the two regions are already integrated in the second period (i.e., no bottleneck), then more transmission capacity has no longer any price effects in this period and will instead allow for a higher price in the first (export)

[4] In the literature the main focus has been on strategic behaviour that leads to bottlenecks, see for example Borenstein et al. (2000). Mirza and Bergland (2015) found empirical support for such strategic behaviour in the Norwegian electricity market. See also McRae and Wolak (2017) and Tangerås and Mauritzen (2018), who find empirical support for the exercise of market power in, respectively, the Colombian and Swedish electricity sectors that are dominated by hydropower. None of them focus on our main issue, which is the interplay between hydropower and a region with intermittent power production. See also Massol and Banal-Estañol (2018), who propose a test for whether markets are integrated and how oligopolistic behaviour can affect the potential for bottlenecks.

period. Furthermore, we show that increased transmission capacity can have the paradoxical effect of *increasing* the scope for transmission bottlenecks to occur in both periods, due to the strategic incentives of the dominant producer.

Third, we find that *intensified competition*, captured by a larger competitive fringe, in many instances does not lead to lower prices. If there are bottlenecks in transmission of energy between the two regions in both periods, a larger fringe implies more production in the first period, as the fringe always sell all their capacity in this period, but the dominant firm responds by reallocating more production to the second period, which neutralises the negative price effect. However, this result does no longer holds if the market outcome is an integrated market (i.e., no bottleneck) in the second period. In this case, a larger fringe results in lower prices in the first period and no price effect in the second period. On the contrary, we show that a larger fringe increases the scope for bottlenecks in transmission of energy across regions and thus reduces the scope for a price reducing effect of competition.

Finally, we show that the presence of market power has some non-trivial implications for welfare in the hydropower region (which we in our model refer to as the *domestic* region). Perhaps surprisingly, we find that market power is not only beneficial for producers, but in many cases consumers are not harmed and might even benefit. If the domestic production capacity is such that there are bottlenecks in both periods, the presence of market power leads to an intertemporal reallocation of production that simultaneously leads to an increase in both producers' and consumers' surplus, thus unambiguously increasing domestic welfare unless the domestic region receives a disproportionately large share of the congestion revenues (which are lower in the presence of market power). The standard conflict of interest between producers and consumers only resurfaces when the production capacity is so high that the bottleneck in the low-price period is removed in equilibrium, in which case increased market power might reduce domestic welfare due to a detrimental effect on consumers' surplus.

There is a large literature on how the market works in a deregulated electricity industry.[5] Close to our study are those that analyse a mixed system, such as for example Crampes and Moreaux (2001) and Bushnell (2003), who analyse the mixture of hydropower and thermal production. See also von der Fehr and Johnsen (2002), von der Fehr and Sandsbråthen (1997), Johnsen et al. (1999), Johnsen (2001) and Skaar and Sørgard (2006), who focus on the Norwe-

[5] See for example Green and Newbery (1992), von der Fehr and Harbord (1993) on the British electricity market, Borenstein and Bushnell (1999) and Borenstein et al. (1999) on the Californian electricity industry, and Hjalmarsson (2000) and Amundsen and Bergman (2002) for the Nordic electricity industry.

gian electricity market and the potential for bottlenecks. However, none of these studies consider the mix of hydropower and intermittent power production and the role of trade between regions as we do.[6] Closest to our study is Newbery (2023b), studying the interplay between a hydropower system in Tasmania and a mainly intermittent power system in Australia. See also Yang (2022) that focuses on interconnections and intermittent power production. However, the main focus in their studies is the gains from trade between those two systems and not market power as such.

The rest of the paper is organised as follows. In the next section we present our model. In Section 3 we derive the equilibrium outcomes under different regimes with bottlenecks in trade either in both periods or only in the first period. In Section 4 we discuss the equilibrium price effects of different policy alternatives, such as increased production and transmission capacities. In Section 5 we consider the impact of intensified competition by a larger competitive fringe, and characterise the equilibrium outcome under the special case of perfect competition. In Section 6 we analyse the implications of market power on domestic welfare and ask whether increased competition is always welfare improving. Finally, in Section 7 we offer some concluding remarks.

2 Model

Consider two regions, denoted by H (Home) and F (Foreign), and two time periods, denoted by 1 and 2, which have a combined duration of one unit of time, with the relative durations of the first and second periods given by α and $(1-\alpha)$, respectively.[7] The two time periods can be interpreted broadly, from different seasons of the year to different hours of the day.

A key difference between H and F is that the two regions use different technologies for energy production, such that the ability to shift production between the two time periods is higher in H than in F. For simplicity, we take this difference to the extreme by assuming that production in H is based on hydropower while production in F is based on wind power (except for some reserve capacity that is very expensive and can be used when there is no wind). Since water can be stored in reservoirs and wind cannot be stored, this implies that it is possible to shift production between time periods in region H but not in region F.[8]

[6] Ambec and Crampes (2012) do look at intermittent sources of energy. However, their main focus is the design of the price mechanism in a competitive market. Andréz-Cerezo and Fabra (2020) discuss storage and the possible exploitation of market power, but not in a setting with two regions with different energy systems that trade with each other.

[7] The model draws on Skaar and Sørgard (2006).

[8] The model could be enriched by adding some intermittent power in region H and some hydropower in region

There are transmission lines for electricity that allow for trade between the two regions, but we assume that F is much larger than H, such that trade between the two regions has no impact on the price in F. Total production in F is exogenous and variable, depending on wind conditions. In particular, we assume that the two periods in the model are defined by the wind conditions in F, with less wind in period 1 than in period 2. Due to storage inability, this means that the price in F is higher in the first period than in the second. More specifically, we let the (exogenous) prices in region F be given by $\overline{p}$ in the first period and $\underline{p}$ in the second, where $\overline{p} \gg \underline{p}$.

In region H, on the other hand, we assume that the total capacity for hydropower production over the two periods (and thus per unit of time) is exogenously given by K.[9] This capacity can be costlessly distributed between the two periods, and we assume that all capacity is used (i.e., there is no waste of water).[10] The hydropower in H is assumed to be produced by one dominant firm and a competitive fringe consisting of a large number of small price-taking firms. We assume that the total production capacity of the fringe is a share β of the total domestic production capacity. The parameter β can thus be interpreted as a measure of the degree of competition in region H. The remaining production capacity, $(1-\beta)K$, is controlled by the dominant firm which strategically chooses how to allocate this capacity between the two periods. We let quantity (per unit of time) supplied by the dominant firm in period i be given by y_i. For simplicity, we assume that variable production costs are zero. In Figure 1 we have illustrated the model, with a space and a time dimension. The producers in region H can reallocate production over time through storage (shown with the dotted line), while in both time periods energy can either be exported or imported between the two regions through transmission lines (shown with

F. However, as long as there is more flexibility in H than in F, in terms of shifting production between time periods, this would not change the main mechanisms in our analysis.

[9] It is well known that hydropower capacity crucially depends on the weather, with limited capacity in a dry year with little rainfall and large capacity in a rainy year. The variation in capacity from year to year is not an issue we address in the present paper. For an analysis of inflow uncertainty, see for example Garcia et al. (2001), Hansen (2009) and Mathiesen et al. (2011).

[10] This assumption is common in the literature and made by Crampes and Moreaux (2001), Johnsen (2001), Bushnell (2003), Skaar and Sørgard (2006), Førsund (2007), Hansen (2009) and Mathiesen et al. (2011), among others.

solid lines).

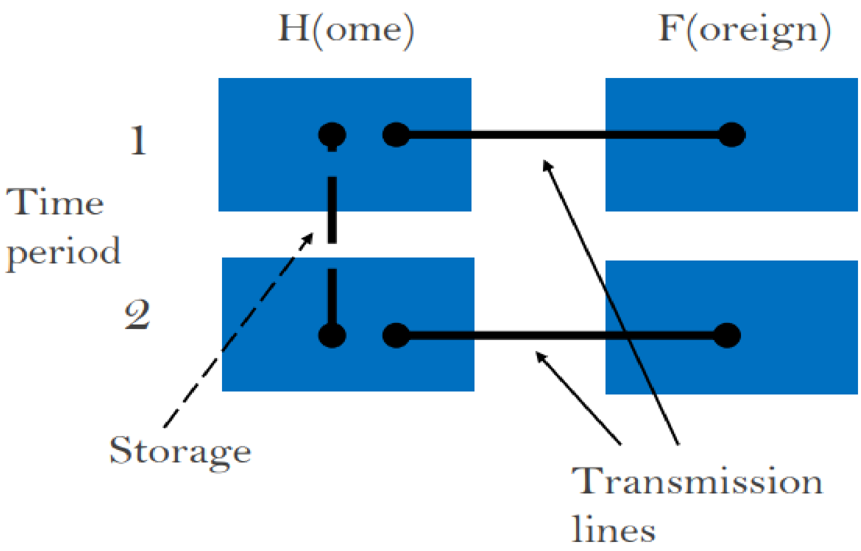

Figure 2: Illustration of two-period model with trade between regions

The price in period i in region H is assumed to be given by the inverse demand function

$$p_i = a - bq_i, \tag{1}$$

where a and b are two positive parameters and q_i is total energy supplied to region H per unit of time in period i. This energy can either be domestically produced or imported from F. In line with the institutional setting in electricity markets, we assume that firms sell in their home market and receive the same (domestic) price per unit of electricity regardless of whether this unit is exported or not. In case of a price difference between H and F, a regulator makes sure that production is reallocated from the low-price region to the high-price region until transmission capacity is fully utilised or prices in the two regions are identical. We will consider equilibria in which (q_1, q_2) is such that $p_1 \leq \overline{p}$ and $p_2 \geq \underline{p}$, implying that region H exports to region F (at price p_1) in period 1 and imports from region F (at price p_2) in period 2.

We let the transmission capacity per unit of time be given by T, whereas actual transmission per unit of time in period i is $t_i \leq T$. If transmission at full capacity ($t_i = T$) is not enough to eliminate the price difference between the regions, the resulting transmission bottleneck generates congestion revenues equal to the price difference times the traded volume. For example, if $\overline{p} > p_1$ for $t_1 = T$, the congestion revenues in the first period are given by $\alpha(\overline{p} - p_1)T$. In each period where a transmission bottleneck occurs, we assume that the regulators in the two regions split the resulting congestion revenues such that a share θ accrues to region H while region F receives the remaining share.

3 Equilibrium outcomes

We look for candidate equilibria in which the domestic price is higher in the first than in the second period, which is the intuitively plausible outcome given our period definitions. If $p_1 > p_2$, the price-taking firms in the fringe maximise their profits by selling all their capacity in the first period. The residual demand is met by the dominant firm. Thus, we look for a subgame perfect Nash equilibrium in which the dominant firm chooses the profit-maximising allocation (y_1, y_2) subject to (i) a total capacity constraint and (ii) the residual demand functions resulting from profit-maximising production allocations by the price-taking firms in the fringe.

We start out by deriving the optimal solution under the assumption that transmission bottlenecks occur in both periods, before considering the case in which a bottleneck occurs only in the first period. Finally, we provide a full characterisation of the subgame perfect Nash equilibrium when taking into account that bottlenecks are endogenously generated (or removed) by the strategic behaviour of the dominant firm.

3.1 Bottlenecks in both periods

Suppose that actual transmission is at full capacity in both periods, such that $t_1 = t_2 = T$. In other words, region H exports at full capacity in the first period and imports at full capacity in the second. In the first period, total supply to region H per unit of time is given by[11]

$$q_1 = \frac{\beta K}{\alpha} + y_1 - T, \tag{2}$$

whereas total supply to region H in the second period is

$$q_2 = y_2 + T. \tag{3}$$

[11] The first term in (2) is the supply per unit of time from the competitive fringe. Since the total capacity controlled by the fringe is βK and the first period has a duration of α, the supply per unit of time is $\beta K/\alpha$.

The total capacity constraint is then given by

$$K = \alpha (q_1 + T) + (1 - \alpha) y_2, \tag{4}$$

which implies

$$y_2 = \frac{(1 - \beta) K - \alpha y_1}{1 - \alpha}. \tag{5}$$

The dominant firm chooses y_1 to maximise

$$\pi = \alpha p_1 y_1 + (1 - \alpha) p_2 y_2, \tag{6}$$

subject to (5) and **(1)**. The first-order condition for an interior solution to this problem can be written as

$$\frac{\partial \pi}{\partial y_1} = \alpha \left[\frac{\partial p_1}{\partial q_1} y_1 + p_1 - \left(\frac{\partial p_2}{\partial q_2} y_2 + p_2 \right) \right] = 0, \tag{7}$$

This condition essentially states that the dominant firm's profits are maximised for an allocation of production where the marginal revenue is equal in both periods, which is a well-known property under monopoly or market power more generally. Using (1) and (5), the profit-maximising solution is explicitly given by[12]

$$y_1^{BB} = \begin{cases} \frac{a-\overline{p}}{b} + T - \frac{\beta K}{\alpha} & if \quad K \leq K_1 \\ K + (1-\alpha) T - \frac{(1+\alpha)}{2\alpha} \beta K & if \quad K > K_1 \end{cases}, \tag{8}$$

where

$$K_1 := \frac{2\alpha (a - \overline{p} + \alpha b T)}{(2\alpha + (1 - \alpha) \beta) b}. \tag{9}$$

By substituting (8) into (5), we find the second-period domestic supply to be given by

$$y_2^{BB} = \begin{cases} \frac{(K-\alpha T)b - \alpha(a-\overline{p})}{(1-\alpha)b} & if \quad K \leq K_1 \\ K - \frac{\beta}{2} K - \alpha T & if \quad K > K_1 \end{cases}. \tag{10}$$

This yields the following domestic prices in the two periods:

$$p_1^{BB} = \begin{cases} \overline{p} & if \quad K \leq K_1 \\ a + \alpha b T - \frac{2\alpha + (1-\alpha)\beta}{2\alpha} b K & if \quad K > K_1 \end{cases}, \tag{11}$$

[12] We use superscript BB to indicate equilibrium values in the candidate equilibrium with transmission bottlenecks in both periods.

$$p_2^{BB} = \begin{cases} \frac{1}{1-\alpha}\left(a - \alpha\overline{p} - bK + (2\alpha - 1)\, bT\right) & if \quad K \leq K_1 \\ a - b\left(\left(1 - \frac{\beta}{2}\right)K + (1-\alpha)\, T\right) & if \quad K > K_1 \end{cases}. \tag{12}$$

From (7) we know that the dominant firm wants to allocate its capacity such that the marginal revenue is equal across the two periods. However, since domestic prices correlate negatively with total production capacity, an interior solution to the firm's optimisation problem is not feasible if this capacity is sufficiently low. In this case, if $K \leq K_1$, the optimal choice of the dominant firm is to choose a first-period supply such that the domestic price is just low enough to induce exports in this period; i.e., $p_1 = \overline{p}$.

With the above derived prices, the profits of the dominant firm are given by

$$\pi^{BB} = \begin{cases} \frac{((1+\alpha)a-(2\alpha+(1-\alpha)\beta)\overline{p}-b(K+(1-3\alpha)T))bK-\alpha(a-\overline{p}+bT)(a-\overline{p}+(2\alpha-1)bT)}{(1-\alpha)b} & if \quad K \leq K_1 \\ \frac{(1-\alpha)\beta^2 bK^2+4\alpha(K(1-\beta)(a-bK)+((\alpha(2-\beta)-1)K+\alpha(1-\alpha)T)bT)}{4\alpha} & if \quad K > K_1 \end{cases}. \tag{13}$$

3.2 Bottleneck only in the first period

Suppose instead that domestic production is so high that the second-period bottleneck is removed; i.e., $p_2 = \underline{p}$ for $t_2 < T$. Thus, the domestic production capacity is such that there are maximum exports in period 1, but only a fraction (if any) of the import capacity is used in period 2. In this case, first-period total supply in region H is still given by (2), and the total capacity constraint is given by (4)-(5). The problem of the dominant firm can now be expressed as

$$\max_{y_1} \pi = \alpha p_1 y_1 + (1-\alpha)\, \underline{p} y_2, \tag{14}$$

subject to (5) and $t_2 \geq 0$. The first-order condition for an interior solution to this problem is given by

$$\frac{\partial \pi}{\partial y_1} = \alpha \left[\frac{\partial p_1}{\partial q_1} y_1 + p_1 - \underline{p}\right] = 0. \tag{15}$$

As in the previous case, profits are maximised for an allocation where the marginal revenue is equal in both periods. The difference is that the dominant firm is now a price taker in the second period, which means that the marginal revenue is constant and equal to the foreign price in this period. Using (1), this yields the following explicit solution:[13]

$$y_1^B = \begin{cases} \frac{a-\underline{p}+bT}{2b} - \frac{\beta}{2\alpha}K & if \quad K \leq K_2 \\ \frac{(1-\beta)}{\alpha}K - \frac{(1-\alpha)\left(a-\underline{p}\right)}{\alpha b} & if \quad K > K_2 \end{cases}, \tag{16}$$

where

$$K_2 := \frac{(2-\alpha)\left(a-\underline{p}\right) + \alpha bT}{(2-\beta)\, b}. \tag{17}$$

The first-period supply function is discontinuous at $K = K_2$ because of the constraint $t_2 \geq 0$. For $K \leq K_2$, the domestic capacity is not high enough to keep the second-period price at $\underline{p}$ without imports. However, if $K > K_2$, the equilibrium is a corner solution without imports, where the dominant firm produces just enough in the second period to keep the price at $\underline{p}$, while the remaining capacity is supplied in the first period where it can be sold at a higher price. Using (16) in (2) and (1), this price is given by

$$p_1^B = \begin{cases} \frac{a+\underline{p}+bT}{2} - \frac{b}{2\alpha}\beta K & if \quad K \leq K_2 \\ \frac{a-(1-\alpha)\underline{p}-(K-\alpha T)b}{\alpha} & if \quad K > K_2 \end{cases}. \tag{18}$$

From (5) and (16), the second-period supply from the dominant firm is given by

$$y_2^B = \begin{cases} \frac{(2-\beta)bK-\alpha\left(a-\underline{p}+bT\right)}{2(1-\alpha)b} & if \quad K \leq K_2 \\ \frac{1}{b}\left(a-\underline{p}\right) & if \quad K > K_2 \end{cases}, \tag{19}$$

and total supply (including imports) in the second period is given by

$$q_2^B = y_2^B + t_2^B. \tag{20}$$

The amount of imports that yields a second-period price equal to $\underline{p}$ is found by substituting (19) and (20) into (1), setting $p_2^B = \underline{p}$ and solving for t_2, which yields

$$t_2^B = \begin{cases} \frac{(2-\alpha)\left(a-\underline{p}\right)-(2-\beta)bK+\alpha bT}{2(1-\alpha)b} & if \quad K \leq K_2 \\ 0 & if \quad K > K_2 \end{cases}. \tag{21}$$

[13] We use superscript B to indicate equilibrium values in the candidate equilibrium with a transmission bottleneck only in the first period.

Finally, the profits of the dominant firm are given by

$$\pi^B = \begin{cases} \frac{\alpha^2\left(a-\underline{p}\right)^2+2\alpha^2\left(a-\underline{p}\right)bT+(\beta K-\alpha T)^2b^2-2\alpha\left(\beta a-(2-\beta)\underline{p}\right)bK}{4\alpha b} & if \qquad K \leq K_2 \\ \frac{((2-\alpha-\beta)K-\alpha(1-\alpha)T)b\left(a-\underline{p}\right)-(1-\alpha)\left(a-\underline{p}\right)^2+(1-\beta)\left(\alpha\underline{p}-(K-\alpha T)b\right)bK}{\alpha b} & if \qquad K > K_2 \end{cases}. \tag{22}$$

If we compare the profits earned by the dominant firm in each of the two candidate equilibria, with and without a transmission bottleneck in the second period, i.e., a comparison of (13) and (22), we find that

$$\pi^{BB} > (<)\, \pi^B \quad if \quad K < (>)\, \widehat{K}, \tag{23}$$

where

$$\widehat{K} := \frac{a-\underline{p}+(2\alpha-1)\,bT+\sqrt{1-\alpha}\left(a-\underline{p}-bT\right)}{(2-\beta)\,b} \tag{24}$$

Thus, if the total capacity is sufficiently high, the dominant firm has an incentive to induce an outcome that removes the bottleneck in the second period. This incentive will be further explained and discussed below.

3.3 The subgame perfect Nash equilibrium

In order to derive and characterise the subgame perfect Nash equilibrium, we first make the following three assumptions regarding parameter values:

$$\frac{\alpha\,(2-\beta)\left(a+\underline{p}\right)-\beta\left(\sqrt{1-\alpha}+1\right)\left(a-\underline{p}-bT\right)+\alpha\,(2-3\beta)\,bT}{2\alpha\,(2-\beta)} < \overline{p} < a+(2\alpha-1)\,bT, \tag{25}$$

$$a-bT-\frac{4\alpha\,(1-\beta)\,bT}{\left(1+\sqrt{1-\alpha}\right)\beta} < \underline{p} < a-bT, \tag{26}$$

$$\beta < \alpha\frac{a-\underline{p}+bT}{a-\underline{p}+\alpha bT}. \tag{27}$$

The conditions in (25)-(26) basically require that the foreign price in the first period is sufficiently high (but not too high), while the foreign price in the second period is sufficiently low (but not too low). The interpretation of the upper bound on $\underline{p}$ is that it is not possible to bring the second-period price in region H down to the foreign price level by relying only on imports, which is a relatively mild assumption. Finally, the condition in (27) requires that the dominant firm's share of the total capacity is not too small, which is a reasonable assumption in an analysis focusing on the effects of market power and strategic behaviour in energy markets.

Our first proposition gives a complete characterisation of the subgame perfect Nash equilibrium:[14]

Proposition 1 *Given that the parameter conditions in (25)-(27) hold, the subgame perfect Nash equilibrium outcome is characterised by the following regimes:*

Regime 1a *If* $\underline{K} < K \leq K_1$ *, there are transmission bottlenecks in both periods and the equilibrium prices are characterised by* $\underline{p} < p_2^{BB} < p_1^{BB} = \overline{p}$*.*

Regime 1b *If* $K_1 < K < \widehat{K}$*, there are transmission bottlenecks in both periods and the equilibrium prices are characterised by* $\underline{p} < p_2^{BB} < p_1^{BB} < \overline{p}$*.*

Regime 2a *If* $\widehat{K} \leq K < K_2$*, there is a transmission bottleneck only in the first period and the equilibrium prices are characterised by* $\underline{p} = p_2^B < p_1^B < \overline{p}$ *with positive imports in the second period.*

Regime 2b *If* $K_2 \leq K < \overline{K}$*, there is a transmission bottleneck only in the first period and the equilibrium prices are characterised by* $\underline{p} = p_2^B < p_1^B < \overline{p}$ *with no imports in the second period.*

The proposition characterises the subgame perfect Nash equilibrium for the entire interval of production capacities where the price is higher in the first than in the second period, ranging from the lower bound $\underline{K}$, for which equilibrium prices are $\overline{p}$ in both periods, to the upper bound $\overline{K}$, for which equilibrium prices are $\underline{p}$ in both periods.[15]

Notice that the positive price difference between the first and second period, which occurs in all regimes, is caused by the dominant firm's market power. The opportunity to export in the first period makes the residual demand less price elastic in this period, all else equal. This implies that, for equal prices in the two periods, the dominant firm's marginal revenue is lower in the first period than in the second. The dominant firm has therefore an incentive to reallocate production towards the second period in order to increase the first-period price and thereby increase its export revenues. This incentive is also at the core of the qualitatively most important regime change in Proposition 1, from Regime 1 to 2, which implies that the

[14] The proof of this and all subsequent propositions are given in the Appendix.

[15] If $K < \underline{K}$, the domestic capacity is so low that region H imports from region F in both periods, whereas if $K > \overline{K}$, the domestic capacity is so high that H exports to F in both periods. Explicit expressions for $\underline{K}$ and $\overline{K}$ are given in the proof of Proposition 1 in the Appendix.

transmission bottleneck in the second period is endogenously removed due to the strategic behaviour of the dominant firm. This will be more carefully discussed in the subsequent section when analysing the effects of higher domestic production capacity.

4 Price effects of increased production and transmission capacities

In this section we analyse how the equilibrium prices in region H are affected by changes in domestic production capacity, and by changes in the transmission capacity between the two regions.

4.1 Domestic production capacity

Proposition 1 shows that, not surprisingly, total production capacity in region H plays a crucial role in determining the equilibrium outcome. The next proposition details how an increase in total capacity affects domestic prices in equilibrium:

Proposition 2 *(i) Within each of the regimes defined by Proposition 1, an increase in total domestic production capacity leads to a lower average price. (ii) In a neighbourhood of $\widehat{K}$, an increase in production capacity from below to above $\widehat{K}$ leads to a higher (lower) price in the first (second) period and a higher average price.*

Within each regime, a higher domestic production capacity has the intuitive and expected effects of leading to lower average prices. In Regime 1a, the dominant firm's supply in the first period is constrained by the export condition $p_1 \leq \overline{p}$. Higher production capacity will therefore be allocated towards the second period, leading to a lower price in this period. In Regime 1b, on the other hand, the optimal allocation of the dominant firm is an interior solution with $\underline{p} < p_2 < p_1 < \overline{p}$. In order to keep the marginal revenue equal in the two periods, a capacity increase will lead to higher domestic supply, and thus lower prices, in both periods.

Higher capacity will also lead to a lower first-period price in Regime 2, but notice that in Regime 2a, this effect depends crucially on the existence of a competitive fringe. In the absence of such a fringe, the entire capacity increase would have been allocated to the second period, since the marginal revenue in this period is constant (and equal to $\underline{p}$). Thus, a capacity increase would just imply a replacement of imports with higher domestic supply in the second period, leaving the first-period price unchanged. However, in the presence of a competitive fringe that sells all its capacity in the first period, a higher total capacity will also reduce the first-period price, since the fringe by assumption controls a share β of the capacity increase.[16] In Regime 2b, however, where all additional capacity beyond K_2 is sold in the first period, both by the fringe and by the dominant firm, the first-period price, and thus the average price, decreases monotonically in K regardless of the existence of a competitive fringe.

The second part of Proposition 2 is less obvious and shows that, within a certain interval of K, higher production capacity can paradoxically lead to a higher average price in region H. In order to understand this result, consider the trade-off that the dominant firm is faced with when deciding on the optimal allocation of supply between the two periods. As long as $p_1 < \overline{p}$ and $p_2 > \underline{p}$, by moving one unit of supply from the first to the second period, the firm can obtain a higher price for all inframarginal units in the first period at the expense of a lower price for all units sold in the second. In an interior solution, this trade-off is optimally balanced for a supply allocation where the marginal revenue is the same in both periods. However, suppose that this allocation is such that p_2 is exactly equal to $\underline{p}$. In this case, if the dominant firm shifts one additional unit of supply from the first to the second period, this unit would just replace one imported unit in the second period without lowering the price. Thus, by shifting production from the first to the second period, it would be possible for the dominant firm to obtain a higher price in the first period without suffering a lower price in the second, which would clearly be profitable. In more technical terms, this means that there is a discrete positive jump in the dominant firm's second-period marginal revenue when p_2 approaches $\underline{p}$ from above. By continuity, this implies in turn that if a candidate optimal allocation in Regime 1 yields a second-period price that is sufficiently close to $\underline{p}$, it is more profitable for the dominant firm to induce Regime 2 by reallocating production towards the second period in a way which causes the second-period price to drop to $\underline{p}$, with a corresponding positive price jump in the first period. Since the second-period price is decreasing in K in Regime 1, the incentive for such a regime shift will occur once the total capacity reaches a threshold level, given by $\widehat{K}$. This regime shift does not only lead to a higher price dispersion between the periods, but in the neighbourhood of $\widehat{K}$ it will also lead to an increase in the average price in region H.

[16] From (18), it is easily verified that

$$\frac{\partial p_1^B}{\partial K} = -\frac{\beta b}{2\alpha} < (=)\, 0 \text{ if } \beta > (=)\, 0.$$

In Figure 3 we illustrate how the equilibrium prices in Region H in period 1 and 2 depend on total production capacity in this region for a particular parametric example in which $\overline{p} = 8$, $\underline{p} = 3$, $a = 10$, $T = 3$, $b = 1$, $\beta = 1/4$ and $\alpha = 1/2$. In this example, $\underline{K} = 2$, $K_1 \approx 3.11$, $\widehat{K} \approx 5.62$, $K_2 \approx 6.86$ and $\overline{K} = 8.5$. The figure confirms the analytical results stated in Proposition 1 and 2. Any parameter configuration which satisfies the parameter conditions given by (25)-(27) would yield a qualitatively similar picture.

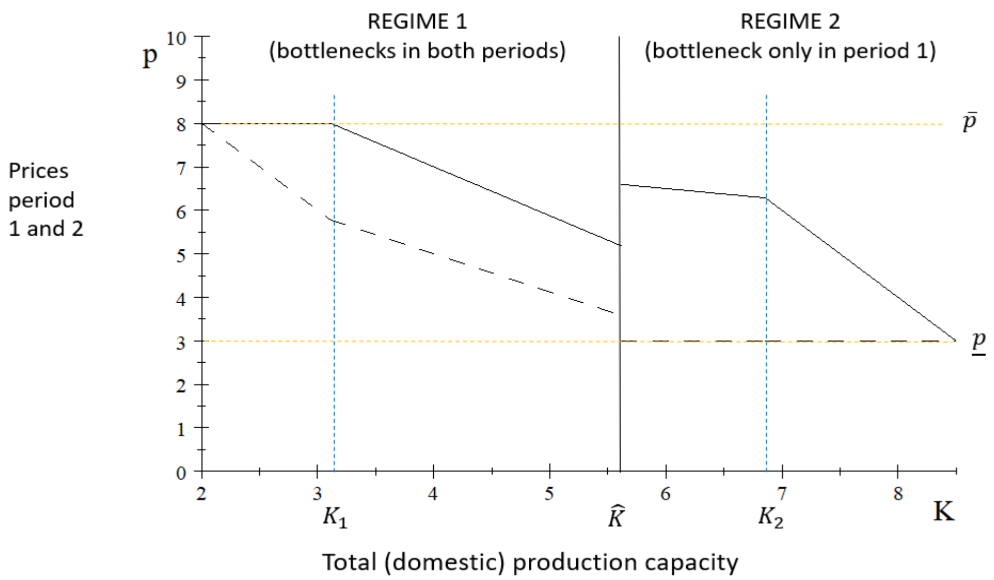

Figure 3: Equilibrium prices in 1st period (solid line) and 2nd period (dashed line) depending on total production capacity in Region H

4.2 Transmission capacity

Suppose that new transmission lines are built between H and F which increase the amount of energy that can be transmitted between the regions per unit of time. The next proposition summarises how the equilibrium prices in region H are affected by such an investment.

Proposition 3 *An increase in the transmission capacity has the following effects:*

(i) In Regime 1a, the first-period price remains constant while the second-period price, and thus the average price, goes up (down) if $\alpha > (<)\, 1/2$.

(ii) In Regime 1b, the first-period price goes up and the second-period price goes down, while the average price goes up (down) if $\alpha > (<)\, 1/2$.

(iii) In Regime 2, the second-period price remains constant while the first-period price, and

thus the average price, goes up.

(iv) The scope for transmission bottlenecks to occur in both periods increases (decreases) if $\alpha > (<)\, 3/4$.

When the transmission lines are used at full capacity in both periods (i.e., Regime 1), a marginal increase in the transmission capacity leads to higher exports in the first period and higher imports in the second. The increased export capacity in the first period implies that the dominant firm is able to transfer some extra units of output from the second to the first period, where these units can be sold at a higher price. In Regime 1a, the optimal amount of production shifted is the one that keeps the first-period price at $\overline{p}$, and this amount depends in turn on the relative duration of the two periods. If $\alpha > 1/2$, implying that region H is a net exporter, the amount of production that needs to be shifted in order to keep the first-period price at $\overline{p}$ is larger then the second-period increase in imports, leading to an overall increase in the second-period price. The opposite is true if region H is a net importer ($\alpha < 1/2$).

In Regime 1b, however, the dominant firm's incentives are slightly different. A higher export capacity implies that the dominant firm faces a less price-elastic first-period demand, and since this regime is characterised by an interior solution in both periods (i.e., $\underline{p} < p_2 < p_1 < \overline{p}$), the dominant firm has an incentive to obtain a higher first-period price by replacing some domestic supply with exports. This is achieved by shifting an amount of production from the second to the first period that is smaller than the increase in the transmission capacity. In this regime, an increase in the transmission capacity will therefore lead to a higher first-period price and a lower second-period price. The relative strength of the two counteracting price responses depends again on the relative duration of the two periods. If $\alpha > (<)\, 1/2$, the first-period price increase is larger (smaller) than the second-period price decrease, leading to a higher (lower) average price in region H.

In Regime 2a, the dominant firm has once more an incentive to obtain a higher first-period price in response to the less elastic first-period demand resulting from increased export capacity. As in Regime 1b, the firm will therefore shift production from the second to the first period in a quantity that is lower than the increase in the exported volume. However, in Regime 2 there is no second-period price effect since there is no transmission bottleneck in this period. In Regime 2a, the amount of production shifted by the dominant firm will be exactly replaced by higher imports, keeping the second-period price at $\underline{p}$. In Regime 2b, on the other hand, there is no import and therefore no reallocation of production between periods in response to a higher transmission capacity. This will make the first-period price increase even stronger, since a larger share of the total first-period supply is exported without any compensating reallocation of production from the second to the first period. Thus, in Regime 2, an increase in the transmission capacity will lead to an unambiguous increase in the average price in region H due to a higher first-period price. Overall, we can conclude that increased transmission capacity will lead to a higher average price in region H if one of the following two conditions is met: (i) the region is a net exporter ($\alpha > 1/2$) or (ii) the total domestic production capacity is sufficiently high ($K > \widehat{K}$).

The above discussion explains how equilibrium prices depend on the transmission capacity within each equilibrium regime, but the transmission capacity also influences the production capacity thresholds that define the different regimes. In particular, a higher transmission capacity increases (reduces) the regime threshold $\widehat{K}$, and thus reduces (increases) the parameter set for which Regime 2 is an equilibrium outcome, if α is sufficiently high (low). This can be explained as follows. Recall that the dominant firm's incentive for inducing a regime change from Regime 1 to Regime 2 is related to the first-period price increase obtained by shifting production from the first to the second period. Thus, the strength of this incentive depends on the resulting magnitude of the first-period price increase, which is given by $p_1^B - p_1^{BB}$ evaluated at $K = \widehat{K}$. We already know that both p_1^B and p_1^{BB} are increasing in T. However, since a higher p_1^{BB} can only be obtained at the cost of a lower p_2^{BB}, while a higher p_1^B can be obtained by replacing imports with domestic supply in the second period without affecting the second-period price, the effect of higher transmission capacity on the optimal first-period price in Regime 1 depends on the relative durations of the two periods, while the corresponding effect on the optimal first-period price in Regime 2 does not. More specifically, whereas the magnitude of $\partial p_1^{BB}/\partial T > 0$ is monotonically increasing in α, the magnitude of $\partial p_1^B/\partial T$ does not depend on α. Consequently, if α is sufficiently small, higher transmission capacity will magnify the first-period price increase ($p_1^B - p_1^{BB}$) that can be obtained by inducing a shift from Regime 1 to Regime 2.

The dominant firm will therefore have an incentive to induce this regime shift at a lower production capacity threshold (i.e,. $\partial \widehat{K}/\partial T < 0$). On the other hand, if α is sufficiently large, higher transmission capacity will *reduce* the the magnitude of $p_1^B - p_1^{BB}$, thus making the dominant firm *less* inclined to induce the regime shift, which implies that $\partial \widehat{K}/\partial T > 0$.[17] In

[17] Although the effect of T on the price difference $p_1^B - p_1^{BB}$ is the main factor determining the dominant firm's incentive for inducing a shift from Regime 1 to Regime 2, there are also other factors at play, which implies that the threshold level of α that determines the sign of $\partial \left(p_1^B - p_1^{BB}\right)/\partial T$ does not perfectly coincide with the

this case, higher transmission capacity will have the arguably paradoxical effect of *increasing* the scope for transmission bottlenecks to occur in both periods.

5 Price effects of increased domestic competition

In this section we ask how the equilibrium prices are affected by the degree of competition in region H, interpreted as the relative size of the competitive fringe. We start out by considering the effects of a marginal increase in the degree of competition within the parameter set defined by (25)-(27), before presenting the extreme case of a perfectly competitive supply of energy in region H.

5.1 A larger competitive fringe

Suppose that the relative size of the competitive fringe increases. How does this affect equilibrium prices? The next proposition summarises the answer to this question.

Proposition 4 *A higher degree of domestic competition has the following effects:*

(i) In Regime 1a and 2b, prices in both periods remain constant.

(ii) In Regime 1b, the first-period (second-period) price goes down (up), while the average price remains constant.

(iii) In Regime 2a, the second-period price remains constant while the first-period price, and thus the average price, goes down.

(iv) The scope for transmission bottlenecks to occur in both periods increases.

In Regime 1a, the equilibrium prices do not depend on the degree of domestic competition. Since the first-period price is constant (and equal to $\overline{p}$) in this regime, a larger competitive fringe will just replace the dominant firm's first-period production without affecting the firm's incentives for second-period supply, thus leaving the second-period price unaffected. In Regime 1b, however, prices in both periods depend on the degree of competition. Since the fringe supplies all its capacity in the first period, a larger fringe leads to a higher relative supply in the first period, all else equal, which reduces the price in the first period and increases the price in the second. However, the amount of production shifted from the second to the first period is such that the average price is unaffected also in this regime. Thus, as long as there are transmission

threshold level of α that determines the sign of $\partial\widehat{K}/\partial T$.

bottlenecks in both periods, increased domestic competition has, perhaps surprisingly, no effect on the average price. This is also true in Regime 2b, with no second-period imports, since in this regime all capacity beyond what is needed to keep the second-period price at $\underline{p}$ is used in the first period, regardless of the relative size of the competitive fringe. It is only in Regime 2a, where one bottleneck is removed *and* region H relies on imports to keep the second-period price at $\underline{p}$, that increased competition reduces the average price. In this regime, a larger competitive fringe implies that a larger share of the total capacity is used in the first period. This is possible since the production shifted away from the second period will be exactly replaced by higher imports, thus leaving the second-period price unaffected while the first-period price is reduced.

Finally, stronger domestic competition will also increase the regime threshold $\widehat{K}$, thus reducing the parameter space for which Regime 2 is an equilibrium outcome. When the relative size of the competitive fringe increases, the first-period price reduction in Regime 2a is larger than the corresponding price reduction in Regime 1b, which implies that the first-period price increase obtained by inducing a shift from Regime 1 to Regime 2 is reduced. In turn, this reduces the dominant firm's incentive to induce such a shift, all else equal, and therefore increases the threshold value of K above which Regime 2 is an equilibrium outcome. Thus, and perhaps surprisingly, more competition increases the scope for transmission bottlenecks to occur in both periods.

5.2 Perfect competition

Proposition 4 shows the price effects of increased competition within the parameter set for which the equilibrium is defined by the four regimes characterised by Proposition 1. This parameter set is given by (25)-(27) and does not include the case where the relative size of the competitive fringe becomes very large. Thus, in order to complete the picture, consider the special case of $\beta = 1$, where energy supply in region H is perfectly competitive. In this case, any price difference between the periods will cause production to be reallocated towards the period with the higher price, implying that equilibrium prices will be equal across the two periods. Thus, the equilibrium is characterised by $q_1 = q_2$. Let domestic supply in period i be given by x_i. If there are bottlenecks in both periods (i.e., if $\underline{p} < p_1 = p_2 < \overline{p}$), we have $q_1 = x_1$ and $q_2 = x_2 + T$, which implies that $x_1 = x_2 + T$ in equilibrium. Using the total capacity constraint, which in this case is given by $K = \alpha (x_1 + T) + (1 - \alpha) x_2$, the equilibrium domestic production allocation across the two periods is given by

$$x_1 = K - (2\alpha - 1)\,T \tag{28}$$

and

$$x_2 = K - 2\alpha T. \tag{29}$$

The resulting price is given by (1) as long as K is such that $p_1 = p_2 \geq \underline{p}$. Otherwise, for sufficiently high values of K, a larger share of domestic production will be sold in the second period, replacing imports, so that is price in each period is kept at $p_1 = p_2 = \underline{p}$. More explicitly, the equilibrium prices under a perfectly competitive supply of energy in region H are given by

$$p_1 = p_2 = \begin{cases} a - bK + (2\alpha - 1)\,bT & if \quad \underline{K} \leq K < K^c \\ \underline{p} & if \quad K^c \leq K < \overline{K} \end{cases}, \tag{30}$$

where

$$K^c := \frac{a - \underline{p}}{b} + (2\alpha - 1)\,T. \tag{31}$$

Compared with the equilibrium given by Proposition 1, perfect competition reduces the number equilibrium regimes to two. For $K < K^c$, the equilibrium price (which is the same in both periods) is monotonically decreasing in K until it reaches $\underline{p}$ at $K = K^c$. In the interval $K^c \leq K < \overline{K}$, the equilibrium is a corner solution where higher production capacity implies that second-period imports are replaced by domestic production, without any price effects, until domestic demand is fully met by domestic supply (i.e., $t_2 = 0$) at $K = \overline{K}$. Thus, unlike the case of a sufficiently large dominant firm, higher production capacity can never lead to higher domestic prices under perfect competition. In Figure 4, the competitive equilibrium ($\beta = 1$) is illustrated for the same parametric example as in Figure 3, alongside the previously shown equilibrium with a large dominant firm ($\beta = 1/4$).

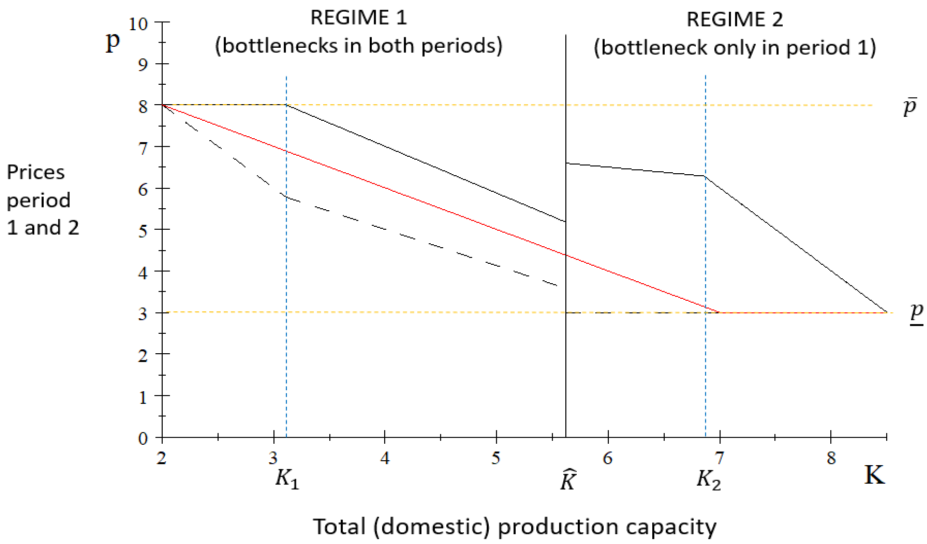

Figure 4: Equilibrium prices under market power (black curves; $\beta = 1/4$) and perfect competition (red curve; $\beta = 1$) depending on production capacity

6 Market power and domestic welfare

The analysis in the previous sections has shown that the presence of domestic market power leads to non-trivial and sometimes arguably unexpected price effects of network integration. A pertinent normative question is then whether such market power is detrimental or beneficial for the domestic region. Will more competition in the domestic region increase the gains from trade and have a positive impact on domestic welfare? In this section we show that this is far from guaranteed.

We take a utilitarian approach by assuming that domestic welfare is simply given by the total surplus accruing to domestic agents, and is thus the sum of consumers' surplus, producers' surplus and congestion revenues. In Regime k, domestic welfare per unit of time in period 1 is then given by

$$W_1^k = \frac{\left(a - p_1^k\right)^2}{2b} + p_1^k \left(\frac{a - p_1^k}{b} + T\right) + \theta \left(\overline{p} - p_1^k\right) T, \tag{32}$$

where the first term is consumers' surplus, the second term is producers' surplus, and the third term is the domestic region's share of the congestion revenues.[18] Similarly, domestic welfare

[18] Notice that, in equilibrium, all the transmission capacity is used for export (in period 1) in all regimes; i.e.,.

per unit of time in period 2 is given by

$$W_2^k = \frac{\left(a - p_2^k\right)^2}{2b} + p_2^k \left(\frac{a - p_1^k}{b} - t_2^k \right) + \theta \left(p_2^k - \underline{p} \right) t_2^k, \tag{33}$$

where $t_2^{BB} = T$ and $t_2^B < T$. Total domestic welfare in Regime k over the two periods is then given by

$$W^k = \alpha W_1^k + (1 - \alpha) W_2^k. \tag{34}$$

The next proposition summarises the relationship between market power and welfare in the domestic region:

Proposition 5 *(i) In Regime 1a and 2b, increased competition has no effect on consumers' surplus, producers' surplus and congestion revenues, and has therefore no effect on domestic welfare.*

(ii) In Regime 1b, increased competition leads to a reduction in both consumers' and producers' surplus, but congestion revenues increase. The overall effect on domestic welfare is always negative as long as the domestic region does not receive a disproportionately large share of the congestion revenues.

(iii) In Regime 2a, increased competition leads to an increase in consumers' surplus, a reduction in producers' surplus, and an increase in congestion revenues. The overall effect on domestic welfare is generally ambiguous, but a marginal increase in domestic competition has always a positive effect on welfare if the degree of competition is sufficiently low to begin with.

The results stated in the above proposition reveal that, for a sizeable subset of the parameters defined by (25)-(27), the effect of increased competition on domestic welfare is either zero or negative. The most striking results arguably appear in Regime 1b, where increased competition not only reduces producers' surplus but is also detrimental to consumers. In this regime, which is characterised by $K_1 < K < \widehat{K}$, increased competition reduces the first period price and increases the second-period price in a way that leaves the average price unaffected (cf. Proposition 4). Since the domestic region exports in the first period and imports in the second, the price reduction in the first period has a larger impact on profits than the price increase in the second period. Thus, increased competition leads to a reduction in producers' surplus because of the first-period loss in export revenues. On top of that, consumers' surplus also goes

$t_1^k = T$ for $k = B$ and $k = BB$.

down, even though the average price remains at the same level. The reason is that consumers' surplus is convexly decreasing in the price level, which implies that the price increase in the low-price period has a larger impact (in absolute terms) on consumers' surplus than the price reduction in the high-price period.[19] Thus, in Regime 1b, market power is beneficial for both producers and consumers in the domestic region.

On the other hand, a smaller intertemporal price difference leads to higher congestion revenues. Whether this is enough to compensate for the loss in consumers' and producers' surplus depends on the share of the congestion revenues that accrues to the domestic region. In the extreme case of $\theta = 1$, any loss in net export revenues due to a smaller intertemporal price difference is fully compensated by an increase in congestion revenues. In other words, with $\theta = 1$ the entire surplus from trade is always appropriated by the domestic region regardless of the intertemporal domestic price difference. In this case, domestic welfare is maximised when the total surplus from domestic sales is maximised, which requires equal prices across the two periods. This implies in turn that more competition, which leads to a lower intertemporal price difference, is welfare enhancing. However, for $\theta < 1$ the loss in net export revenues due to a smaller intertemporal price difference is not fully compensated by an increase in congestion revenues, and if θ is below a certain threshold level, the increase in congestion revenues is smaller than the combined reduction in consumers' and producers' surplus. Notice that this threshold level of θ is strictly above one half, which implies that increased competition in Regime 1b leads to lower domestic welfare unless the domestic region receives a disproportionately large share of the congestion revenues.

A welfare gain from increased competition is also absent in Region 1a ($\underline{K} < K \leq K_1$) and in Region 2b ($K_2 \leq K < \overline{K}$). In these cases, equilibrium prices do not depend on the degree of competition in either period, as shown by Proposition 4 and explained in Section 5.1, which in turn implies that neither consumers' nor producers' surplus is affected by the degree of competition, and congestion revenues are also left unchanged.

The only remaining case in which increased competition is potentially beneficial in terms of domestic welfare is when domestic production capacity is characterised by $\widehat{K} \leq K < K_2$, i.e., in Regime 2a. From Proposition 4 we know that the only effect of increased competition in this

[19] This result generalises beyond linear demand. For a general inverse demand function $p(Q)$, the loss in consumer surplus due to a marginal price increase is larger when the initial price is lower if

$$p''(Q)\,Q + p'(Q) < 0,$$

which holds for concave, linear and 'not-too-convex' demand functions.

regime is a reduction in the first-period price. This price drop has the straightforward implication that consumers' surplus goes up, producers' surplus go down, while congestion revenues increase (because of a higher price difference between the regions in the high-price period). The overall welfare effect is therefore *a priori* indeterminate and can be either positive or negative depending on specific parameter values. If the degree of competition is initially sufficiently low, a marginal increase in competition is always welfare improving, since the corresponding reduction in producers' surplus in this case is very small.[20] Thus, welfare is never maximised in the presence of a domestic monopolist. In fact, it can be shown that domestic welfare is concave in the degree of competition, which suggests that welfare is maximised when the producers have some, but not too much, market power.[21]

7 Concluding remarks

We have shown that a dominant hydropower producer that trades with a region with intermittent power production can use its flexibility to exploit market power. The main mechanism is that the hydropower producer can reallocate production between different time periods, thereby creating intertemporal price differences. Paradoxically, a producer with sufficient market power can find it profitable to remove bottlenecks in some situations and create an integrated market. In such situations, increased domestic production capacity may actually lead to higher average prices in the domestic market. On the other hand, bottlenecks might also be strategically induced by the dominant producer in response to increased transmission capacity, which is another paradoxical result emanating from our analysis.

Although there are clearly gains from trade between regions with storable (hydropower) and intermittent (wind power) energy sources, the way these gains are extracted and distributed depends crucially on the presence of market power in the hydropower region. For an intermediate range of domestic production capacity (Regime 1b and 2a in our model), increased market power in the hydropower region leads to larger intertemporal price differences in that region with a

[20] A domestic monopolist would optimally induce an intertemporal price difference that maximises domestic profits. By the Envelope Theorem, the effect of a marginal change in this price difference would then be zero for $\beta \to 0$.

[21] Domestic welfare, denoted by W, is given by the sum of (A35), (A36) and (A37) in the Appendix. Using the equilibrium prices reported in Section 3, we derive

$$\frac{\partial^2 W}{\partial \beta^2} = -\frac{bK^2}{4\alpha} < 0 \text{ if } \widehat{K} \leq K < K_2.$$

higher price in the period with exports and a lower price in the period with imports. Due to this the prices in the hydropower region differ less from the prices in the region with intermittent power, and the bottleneck revenues are reduced. It results in larger net export revenues for the hydropower region. An upshot of such strategic intertemporal reallocation of production is that it harms the region with intermittent power and therefore introduces a *beggar-thy-neighbour* element to the way market power is exploited in this setting. Perhaps more surprisingly, the presence of market power in the hydropower region is not necessarily harmful for the consumers in this region. On the contrary, we show that increased domestic competition in many cases has either no effect or a negative effect on consumers' surplus, which in turn implies that total welfare in the hydropower region tends often to be positively correlated with the degree of market power.

We have motivated our modelling with the existence of a dominant hydropower producer in one region, a producer with flexibility to reallocate water over time through reservoirs, and we have shown that such a dominant firm's strategic behaviour depends crucially on the domestic production capacity. In a hydropower system it is well known that total energy production is determined by the inflow of water, and thereby by the amount of rain and snow during a year. High (low) domestic capacity can then be interpreted as a wet (dry) year with high (low) inflow of water. From a consumer perspective, one might expect that we should be especially concerned about market power in a dry year, with restricted capacity due to low inflow. However, we find that consumers are not harmed by market power if the domestic production capacity is sufficiently low. On the contrary, we find that consumers are harmed by market power only if the capacity is sufficiently high, such that the dominant firm finds it profitable to strategically remove a bottleneck and dump production in an integrated market with a low price, thereby inducing a higher domestic price in the period with a high price abroad. In this case (Regime 2a in our model), more market power leads to a higher price in the high-price period without affecting the price in the low-price period, thus leading to a reduction in consumers' surplus. Thus, another somewhat paradoxical conclusion from our analysis is that one should perhaps be more concerned about market power in a wet year than in a dry year.

An alternative to reservoirs in a hydropower system is batteries or the production of hydrogen. Although such technologies are not economically feasible at the moment, our model illustrates the potential challenges if such a technology becomes important in some regions. In fact, what we have analysed is the case where a dominant firm with flexibility in its production controls both storage and production, and we have shown that this can lead to price distortions through the creation of intertemporal price differences. Our analysis therefore points to a possible market failure arising from combined control of storage and production, which raises the question of whether we should impose structural measures where storage is disentangled from production. According to Fabra (2021), this is an area with limited research, and we leave this issue for future research.

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Appendix

Proof of Proposition 1

In Regime 1a, the candidate equilibrium is derived under the assumption of the following price ranking:

$$\overline{p} \geq p_2^{BB} \geq \underline{p}. \tag{A1}$$

Using (12), it is straightforward to show that this assumption holds if

$$\underline{K} \leq K \leq \widetilde{K}, \tag{A2}$$

where

$$\underline{K} := \frac{a - \overline{p}}{b} + (2\alpha - 1)\, T, \tag{A3}$$

and

$$\widetilde{K} := \frac{a - \left(\alpha \overline{p} + (1-\alpha)\, \underline{p}\right)}{b} + (2\alpha - 1)\, T. \tag{A4}$$

In Regime 1b, the candidate equilibrium is derived under the condition

$$\overline{p} \geq p_1^{BB} \geq p_2^{BB} \geq \underline{p}, \tag{A5}$$

which, using (11)-(12), requires

$$K' \leq K \leq \min\left\{K'', K'''\right\}, \tag{A6}$$

where

$$K' := \frac{2\alpha\,(a - \overline{p} + \alpha b T)}{(2\alpha + (1-\alpha)\,\beta)\, b}, \tag{A7}$$

$$K'' := \frac{2\alpha T}{\beta} \tag{A8}$$

and

$$K''' := \frac{2\left(a - \underline{p} - (1-\alpha)\, bT\right)}{(2-\beta)\, b}. \tag{A9}$$

In Regime 2a, the candidate equilibrium is derived under the condition

$$\overline{p} \geq p_1^{BB} \geq \underline{p}, \tag{A10}$$

which, using (11), requires

$$K_B' \leq K \leq K_B'', \tag{A11}$$

where

$$K_B' := \frac{\alpha \left(a + \underline{p} - 2\overline{p} + bT\right)}{\beta b} \tag{A12}$$

and

$$K_B'' := \frac{\alpha \left(a - \underline{p} + bT\right)}{\beta b}. \tag{A13}$$

Furthermore, we require the following condition to be met:

$$0 \leq t_2 \leq T. \tag{A14}$$

Using (21), this requires

$$K_T \leq K \leq K_T', \tag{A15}$$

where

$$K_T := \frac{(2-\alpha)\left(a - \underline{p}\right) - (2 - 3\alpha)\, bT}{(2-\beta)\, b} \tag{A16}$$

and

$$K_T' := \frac{(2-\alpha)\left(a - \underline{p}\right) + \alpha bT}{(2-\beta)\, b}. \tag{A17}$$

Finally, in Regime 2b, the candidate equilibrium is derived under the condition $p_1^B \geq \underline{p}$, which from (18) requires

$$K \leq \overline{K} := \frac{a - \underline{p}}{b} + \alpha T. \tag{A18}$$

Given all the above stated conditions, along with the analysis in Section 3, the subgame perfect equilibrium outcome presented in Proposition 1 exists if

$$0 \leq \underline{K} \leq K_2 \leq \widetilde{K}, \tag{A19}$$

$$\max\left\{K_2, K_B', K_T\right\} \leq \widehat{K} \leq \min\left\{K'', K''', K_T'\right\} \tag{A20}$$

and

$$K'_T \leq \min\left\{K''_B, \overline{K}\right\}. \tag{A21}$$

It is relatively straightforward to show that $\underline{K} > 0$ if

$$\overline{p} < a + (2\alpha - 1)\, bT, \tag{A22}$$

and that $K_2 > \underline{K}$, $\min\left\{\widehat{K}, \widetilde{K}\right\} > K_2$ and $\widehat{K} > \max\left\{K'_B, K_T\right\}$ if

$$\overline{p} > \frac{\alpha\,(2-\beta)\left(a+\underline{p}\right) - \beta\left(\sqrt{1-\alpha}+1\right)\left(a-\underline{p}-Tb\right) + Tb\alpha\,(2-3\beta)}{2\alpha\,(2-\beta)}. \tag{A23}$$

Furthermore, $\min\left\{K''', K'_T\right\} > \widehat{K} > K_T$ if

$$\underline{p} < a - bT \tag{A24}$$

and $K'' > \widehat{K}$ if

$$\underline{p} > a - bT - \frac{4\alpha\,(1-\beta)\, bT}{\beta\left(1+\sqrt{1-\alpha}\right)}. \tag{A25}$$

Finally, it is also easily verified that $\min\left\{K''_B, \overline{K}\right\} > K'_T$ if

$$\beta < \alpha\frac{a-\underline{p}+bT}{a-\underline{p}+\alpha bT}. \tag{A26}$$

Thus, the conditions in (A19)-(A21) hold if all the conditions in (A22)-(A26) hold, thus proving the existence of the equilibrium characterised in Proposition 1.

Proof of Proposition 2

(i) From the relevant equilibrium expressions, it is straightforward to verify that $\partial p_1^{BB}/\partial K = 0$ and $\partial p_2^{BB}/\partial K < 0$ in Regime 1a, that $\partial p_1^{BB}/\partial K < 0$ and $\partial p_2^{BB}/\partial K < 0$ in Regime 1b, and that $\partial p_1^{B}/\partial K < 0$ and $\partial p_2^{B}/\partial K = 0$ in Regime 2. If follows automatically that the average price is decreasing in K in each regime.

(ii) Using (11)-(12) and (18), the price effects of an increase in K from marginally below to marginally above $\widehat{K}$ are given by

$$\lim_{K\to\widehat{K}^+} p_1^{B} - \lim_{K\to\widehat{K}^-} p_1^{BB} = \frac{1}{2}\sqrt{1-\alpha}\left(a-\underline{p}-bT\right) > 0 \tag{A27}$$

and

$$\underline{p} - \lim_{K \to \widehat{K}^-} p_2^{BB} = -\frac{1}{2}\left(1 - \sqrt{1-\alpha}\right)\left(a - \underline{p} - bT\right) < 0. \tag{A28}$$

The corresponding effect on the average price is then simply given by

$$\begin{aligned} &\alpha\left(\lim_{K \to \widehat{K}^+} p_1^B - \lim_{K \to \widehat{K}^-} p_1^{BB}\right) + (1-\alpha)\left(\underline{p} - \lim_{K \to \widehat{K}^-} p_2^{BB}\right) \\ = \; &\frac{1}{2}\left(\alpha + \sqrt{1-\alpha} - 1\right)\left(a - \underline{p} - bT\right) > 0. \end{aligned} \tag{A29}$$

By continuity, the signs of (A27)-(A29) remain the same also if we consider a discrete increase in K from below (but sufficiently close to) $\widehat{K}$ to above (but sufficiently close to) $\widehat{K}$.

Proof of Proposition 3

(i) From (12) we derive

$$\frac{\partial p_2^{BB}}{\partial T} = \frac{(2\alpha - 1)\, b}{1-\alpha} > (<)\, 0 \quad if \quad \alpha > (<)\, \frac{1}{2}, \tag{A30}$$

when evaluated at $K < K_1$ (i.e., in Regime 1a). (ii) From (11)-(12), and evaluated in Regime 1b, it is straightforward to verify that $\partial p_1^{BB}/\partial T > 0$ and $\partial p_2^{BB}/\partial T < 0$, and that

$$\alpha \frac{\partial p_1^{BB}}{\partial T} + (1-\alpha)\frac{\partial p_2^{BB}}{\partial T} = (2\alpha - 1)\, b > (<)\, 0 \quad if \quad \alpha > (<)\, \frac{1}{2}. \tag{A31}$$

(iii) It follows directly from (18) that $\partial p_1^B/\partial T > 0$. Since $p_2^B = \underline{p}$ in Regime 2, the average price is also increasing in T in this period. (iv) From (24) we find that

$$\frac{\partial \widehat{K}}{\partial T} = \frac{2\alpha - \sqrt{1-\alpha} - 1}{2 - \alpha\beta} > (<)\, 0 \quad if \quad \alpha > (<)\, \frac{3}{4}. \tag{A32}$$

Proof of Proposition 4

(i) From (11), (12) and (18) it is straightforward to verify that $\partial p_1^{BB}/\partial\beta = \partial p_2^{BB}/\partial\beta = 0$ in Regime 1a and 2b. (ii) From (11) and (12) it is also straightforward to verify that $\partial p_1^{BB}/\partial\beta < 0$, $\partial p_2^{BB}/\partial\beta > 0$ and

$$\alpha \frac{\partial p_1^{BB}}{\partial \beta} + (1-\alpha)\frac{\partial p_2^{BB}}{\partial \beta} = 0 \tag{A33}$$

in Regime 1b. (iii) It follows directly from (18) that $\partial p_1^B/\partial\beta < 0$ in Regime 2a, which, since $p_2^B = \underline{p}$, also implies that the average price is decreasing in β in this regime. (iv) From (24) we find that

$$\frac{\partial \widehat{K}}{\partial \beta} = \frac{\left(1+\sqrt{1-\alpha}\right)\left(a-\underline{p}-bT\right)+2\alpha bT}{\left(2-\beta\right)^2 b} > 0. \tag{A34}$$

Proof of Proposition 5

Let consumers' surplus, producers' surplus and congestion revenues be denoted by CS, PS and CR, respectively. In the subgame-perfect Nash equilibrium characterised by Proposition 1, these are given by

$$CS = \begin{cases} \alpha\frac{\left(a-p_1^{BB}\right)^2}{2b} + (1-\alpha)\frac{\left(a-p_2^{BB}\right)^2}{2b} & if \quad \underline{K} < K < \widehat{K} \\ \alpha\frac{\left(a-p_1^{B}\right)^2}{2b} + (1-\alpha)\frac{\left(a-\underline{p}\right)^2}{2b} & if \quad \widehat{K} \le K < \overline{K} \end{cases}, \tag{A35}$$

$$PS = \begin{cases} \alpha p_1^{BB}\left(\frac{a-p_1^{BB}}{b}+T\right) + (1-\alpha)\,p_2^{BB}\left(\frac{a-p_2^{BB}}{b}-T\right) & if \quad \underline{K} < K < \widehat{K} \\ \alpha p_1^{B}\left(\frac{a-p_1^{B}}{b}+T\right) + (1-\alpha)\,\underline{p}\left(\frac{a-\underline{p}}{b}-t_2^B\right) & if \quad \widehat{K} \le K < \overline{K} \end{cases} \tag{A36}$$

and

$$CR = \begin{cases} \theta\left[\alpha\left(\overline{p}-p_1^{BB}\right)+(1-\alpha)\left(p_2^{BB}-\underline{p}\right)\right]T & if \quad \underline{K} < K < \widehat{K} \\ \theta\alpha\left(\overline{p}-p_1^{B}\right)T & if \quad \widehat{K} \le K < \overline{K} \end{cases}, \tag{A37}$$

where p_1^{BB}, p_2^{BB}, p_1^B and t_2^B are given by (11), (12), (18) and (21), respectively. Furthermore, let total welfare be defined by $W := CS + PS + CR$.

(i) It is easily confirmed that $\partial CS/\partial\beta = \partial PS/\partial\beta = \partial CR/\partial\beta = 0$ for $\underline{K} < K \le K_1$ and for $K_2 < K < \overline{K}$; i.e., in Regime 1a and in Regime 2b.

(ii) Regime 1b is defined by $K_1 < K < \widehat{K}$. From (A35)-(A37) we derive

$$\frac{\partial CS}{\partial \beta} = -\frac{(1-\alpha)\,bK}{4\alpha}\left(2\alpha T-\beta K\right) < 0 \quad if \quad K_1 < K < \widehat{K}, \tag{A38}$$

$$\frac{\partial PS}{\partial \beta} = -\frac{(1-\alpha)\,\beta bK^2}{2\alpha} < 0 \quad if \quad K_1 < K < \widehat{K}, \tag{A39}$$

$$\frac{\partial CR}{\partial \beta} = (1-\alpha)\,\theta bKT > 0 \quad if \quad K_1 < K < \widehat{K}, \tag{A40}$$

which in turn implies that

$$\frac{\partial W}{\partial \beta} = \frac{(1-\alpha)\,bK}{4\alpha}\left[2\left(2\theta-1\right)\alpha T-\beta K\right]. \tag{A41}$$

The negative sign of (A38) is established by noticing that $2\alpha T > \beta K$ if $K < K''$, where K'' is given by (A8), and that $K'' > \widehat{K}$ is a requirement for equilibrium existence, which implies that $2\alpha T > \beta K$ for all $K_1 < K < \widehat{K}$. The sign of (A41) is given by the sign of the expression in square brackets, which is monotonically increasing in θ. For $\theta = 1$, we see that $\partial W/\partial\beta = -\partial CS/\partial\beta > 0$ for $K_1 < K < \widehat{K}$. On the other hand, if $\theta = 1/2$, then $\partial W/\partial\beta$ is clearly negative. Thus, due to monotonicity, $\partial W/\partial\beta$ is positive (negative) if θ is above (below) a threshold level that lies strictly between 1/2 and 1.

(ii) Regime 2a is defined by $\widehat{K} \leq K < K_2$. From (A35)-(A37) we derive

$$\frac{\partial CS}{\partial\beta} = \frac{K}{4\alpha}\left[\alpha\left(a-\underline{p}\right) + \left(\beta K - \alpha T\right)b\right] > 0 \quad if \quad \widehat{K} \leq K < K_2, \tag{A42}$$

$$\frac{\partial PS}{\partial\beta} = -\frac{\beta b K^2}{2\alpha} < 0 \quad if \quad \widehat{K} \leq K < K_2, \tag{A43}$$

$$\frac{\partial CR}{\partial\beta} = \theta\left(1-\alpha\right)bKT > 0 \quad if \quad \widehat{K} \leq K < K_2, \tag{A44}$$

which implies that

$$\frac{\partial W}{\partial\beta} = \frac{\alpha K}{4}\left[\alpha\left(a-\underline{p}-\left(1-2\theta\right)bT\right) - \beta b K\right]. \tag{A45}$$

The positive sign of (A42) is established by noticing that the expression in square brackets, which determines the sign of (A42), is positive if

$$K > \frac{\alpha}{\beta b}\left(bT - \left(a-\underline{p}\right)\right). \tag{A46}$$

A comparison of (24) and (A46) shows that

$$\widehat{K} - \frac{\alpha}{\beta b}\left(bT - \left(a-\underline{p}\right)\right) = \frac{\left(2\alpha + \beta\left(1-\alpha+\sqrt{1-\alpha}\right)\right)\left(a-\underline{p}-bT\right) + 2\alpha\beta bT}{\beta\left(2-\beta\right)b} > 0. \tag{A47}$$

Thus, the condition in (A46) holds, implying that $\partial CS/\partial\beta > 0$, for all values of K defined by $\widehat{K} \leq K < K_2$. Similarly, the sign of (A45) depends on the sign of the expression in square brackets, which is clearly positive, implying that $\partial W/\partial\beta > 0$, if β is sufficiently small. In general, it is straightforward to confirm by numerical examples that, when imposing the parameter restriction given by (25)-(27) and $\widehat{K} \leq K < K_2$, the sign of $\partial W/\partial\beta$ can be either positive or negative depending on specific parameter values.

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