

# **Ownership and Collusive Exit: Theory and a Case of Nuclear Phase-out**

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## Abstract

In a declining market each firm hopes others will exit first. Collusive cross-ownership removes this war of attrition: it achieves subgame-perfect collusive exit by giving a stake in the gains that follow from one's exit and by taking a stake in one's continuation gains. We show the result and apply it to the electricity sector where new technologies force incumbents to phase out capacity. An illustrative quantification for the Nordic nuclear industry shows how equity arrangements lead to a highly distorted phase-out, both for the consumer surplus and environment.

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# 1 Introduction

Exit from a declining market is among the prime economic illustrations of *war of attrition*. Exit by one firm increases the profits of the remaining firms, so all firms have incentives to free-ride on the other firms' exit decisions and thereby delay their own exit. This article makes a simple but yet unnoticed observation: cross-ownership arrangements can eliminate the free-riding incentives and, effectively, achieve collusive exit decisions from the market.

The observation is relevant in the electricity sector. Climate and energy policies give rise to a rapidly growing market for renewable energy technologies, putting the demand left for the old technologies on a downward trend and forcing the incumbents to adjust their capacity utilization and, ultimately, exit the market. However, the renewable energy expansion has led to adverse impacts for all incumbent technologies, not only for the intended targets of the policies.<sup>1</sup> Such impacts can follow from flaws in the policy designs but they can follow from voluntary choices as well. When there are a few large players in the market, there is no reason for them to take the policy-driven decline in their residual demand as given: By early closures the industry can influence the demand left for the capacity remaining and thereby implement a noncompetitive capacity phase-out. The possibility of market power in the capacity phase-out has gone unnoticed in the literature on the energy transition.<sup>2</sup>

To provide an illustrative quantification, we look at the dynamic exit decisions of the nuclear power plants in the Nordic electricity market, where the demand for nuclear power generation is declining due to wind power that has increased from a few percentage points to around 10 % of the supply in 2017. Wind power reduces market prices as it replaces higher marginal cost thermal units: the quantification calibrates a reduced-form supply curve for these marginal units to the data on the increased wind generation and the estimated reduction in the price levels. In contrast, nuclear power closures can offset the price decline and, temporarily, even increase the price level.

There is an intricate structure of cross-ownership between the main players in the

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<sup>1</sup>*The Economist* (Oct. 12th 2013) succinctly summarizes the phenomenon in an article titled *How to lose half a trillion euros*: “Renewable, low-carbon energy accounts for an ever-greater share of production. It is helping push wholesale electricity prices down. For established utilities, though, this is a disaster.”

<sup>2</sup>The literature on the energy transition has focused on the system-wide costs that follow when the share of intermittent energy technologies is scaled up. This can present challenges to the current ways of organizing distribution, and production of electricity (see, for example, Ambec and Crampes, 2012; Gowrisankaran, Reynolds and Samano, 2016). Apart from the intermittency problem, it has been long acknowledged that policies encouraging the adoption of new technologies through subsidies systematically lower the final consumer price under reasonable assumptions (for example, Fischer, 2010; Böhringer and Rosendahl, 2010; Fridolfsson and Tangerås, 2013).

Nordic nuclear industry. We compute the exit game outcomes for the existing ownership structure and for several counterfactual situations. The annual cost of procuring wholesale electricity from this market for the consumers is ca. 13 billion euros per year in the coming decade. Removing the cross-ownership entirely forces the nuclear units to play the war of attrition game where almost all units remain running, which reduces the annual procurement cost to 8 billion. We evaluate the inefficient phase-out increases annual emissions by 37 MtCO<sub>2</sub>, corresponding roughly to 40% of the current industrial emissions in the Nordic region.

The quantification is an illustration – it is not an empirical assessment – but the quantitative importance of the theory observation seems robust. Understanding why the industry is currently undergoing a period of activity in rearranging ownership (see Section 2) should be of importance to the competition and environmental policy authorities. First, the results add the exit distortion to the complex short-term distortions caused by renewable energy policies.<sup>3</sup> Second, they point out the need to pay attention to market power in the transition towards clean energy in deregulated electricity markets. The exit from the market is a market performance issue that has not been previously covered.<sup>4</sup> In contrast, a great deal of focus has been put on the performance of electricity markets where incumbents utilize *a given installed capacity* inherited from the regulated past (for example, Borenstein, Bushnell and Wolak, 2002; Fabra and Toro, 2005; Puller, 2007 and Hortaçsu and Puller, 2008).<sup>5</sup> The exit distortions illustrated by the Nordic nuclear industry seem relevant more generally.<sup>6</sup>

Conceptually, Ghemawat and Nalebuff (1985) were among the first to study lumpy exits such as those of nuclear units. In a perfect information oligopoly, with a declining demand and small inter-firm cost differences, they found that in equilibrium firms exit the market in the order of their size; the largest firm exits first at the time when its profit margin turns negative. Although the result on the size and exit order is not robust to the single-plant firm assumption (Whinston, 1988) or to the symmetry of cost (Reynolds, 1988), the war of attrition between the firms has not been overruled by subsequent extensions. It is here the cross-ownership changes the basic logic of exit: the firms can

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<sup>3</sup>For example, the empirical articles by Cullen (2013), Kaffine, McBee and Lieskovsky (2013), Novan (2015) look at the complex impacts of renewables on the generators.

<sup>4</sup>Lundin (2017) also studies joint ownership of nuclear in the Nordics but from a different perspective: does the ownership structure have an impact on maintenance decisions?

<sup>5</sup>In addition, a versatile set of aspects of competition have been looked at, including complex bidding behavior in spot markets (e.g., Reguant, 2014), the impact of contracting on competition (e.g., Green and Le Coq, 2010), vertical structure and competition (Bushnell, Mansur and Saravia, 2008), and also cross-ownership (Amundsen and Bergman, 2002).

<sup>6</sup>For example, there are three companies that own the most US reactors as of 2009 (Davis and Wolfram, 2012).

achieve the fully collusive closure path by an appropriate exchange of shares. This is somewhat different from oligopolistic markets in general where bargaining to collude is difficult by standard free-riding arguments; these difficulties apply to cross-ownership deals as well (Reitman, 1994). In a declining market, the last remaining firms have an incentive to negotiate over the total surplus in the end game. We characterize the division of stakes that implements full collusion as a subgame-perfect outcome. First, the closing firm must have a stake in the gains that follow from the closure. Second, the continuing firm must have a stake in the closing firm to ensure that, in the continuation game following bargaining, the other firm finds the closure to be the subgame optimal action: the closure should increase the value of the firm’s holdings.

In general, our results contribute the literature addressing the question “Why do firms have interest in each others’ equity?” The question has been long puzzling researchers, and there are several potential answers to it. Ghosh and Morita (2017) find that in strategic alliances partial ownerships can induce a firm with superior technological expertise to transfer its knowledge to its competing alliance partner. Knowledge transfers may also partially explain why firms in the nuclear industry ended up making cross-ownership deals, although the very recent changes of shares likely have other motivations. Cross-ownership can reduce the degree of competition (Reynolds and Snapp, 1986), facilitate tacit collusion (Malueg, 1992; Gilo, Moshe and Spiegel, 2006), and even deter entry (Li, Ma and Zeng, 2015). This article adds the exit dynamics as a potential explanation, and also illustrates the potential quantitative meaning of the mechanism. We are not aware of previous conceptual works or quantitative analysis of cross-ownership and exit; there are few recent quantitative or empirical articles on exit in general (Takahashi, 2015; Nishiwaki, 2016).

The article unfolds as follows. To give full attention to our main motivating case, we describe the Nordic nuclear industry in Section 2. The model of exit and cross-ownership in Section 3 identifies the mechanism that is quantified in Section 4.

## 2 The Nordic nuclear industry

The size of Nordic market for electricity is around 400 TWh annually. With market prices ranging from 20 to 50 €/MWh, the value of trade has been 8–20 billion euros per year. Total demand has been remarkably stable over the past two decades, but the increase in renewable wind power generation is starting to have an impact on the supply side. Wind has already replaced a fraction of the highest marginal cost generation, leading to lower prices, other things equal. Table 1 provides a summary of current mean annual

generation volumes in the region by generation type and owner.<sup>7</sup>

**Table 1:** Supply by generation type.

	Fortum	Uniper	Vattenfall	<i>Industry</i>	Others	Total
Nuclear, Sweden	13	20	34	67	0	67
Nuclear, Finland	15	0	0	15	20	35
Hydro	22	9	32	63	152	215
Wind	0	0	2	2	33	35
CHP	2	1	6	9	38	47
Thermal	0	0	0	0	12	12
Total	52	29	75	156	256	411

*Notes:* Annual generation in TWh of the main industry players and other producers by generation type. Nuclear volumes split for Swedish and Finnish assets. Figures compiled from 2014–2016 reports by the companies, and include some assumptions by the authors (in particular we include in the Finnish nuclear volumes Olkiluoto 3 project that is not yet online).

Nuclear power accounts for roughly a quarter of the power generated in the Nordics. In 2015, there were ten nuclear units in Sweden and four units in Finland. The Swedish units are the ones relevant for strategic closures, as Finnish nuclear ownership structure is somewhat distinct.<sup>8</sup> The ten Swedish units are located in Forsmark, Ringhals, and Oskarshamn sites. Each plant site is operated by a separate limited liability company, all of which are jointly owned by some or all of Fortum, Uniper, and Vattenfall.<sup>9</sup> Figure 1 shows the ownership structure.

Two firms, Uniper and Vattenfall, control through majority shares the Swedish nuclear assets. Fortum is a minority owner but in late 2017 Fortum launched a takeover bid over Uniper with a purchase of a 47 per cent stake in the firm, the fate of which in the Spring 2018 is still uncertain. We refer to these three main players commonly as the *Industry*. Also, besides their nuclear assets, the three industry players control around one third of the generation in the Nordic market with additional holdings in hydropower, wind power, combined heat and power generation (CHP) and conventional thermal power. The other generators include mainly Norwegian hydro power producers, municipal and industrial CHP plant owners in Denmark and Finland and smaller utilities.

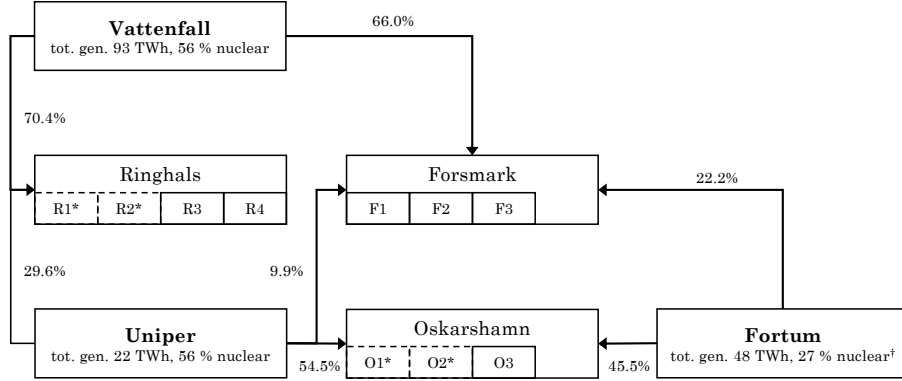
These peculiar cross-ownership arrangements are a result of early joint ventures at the time of construction, later industry consolidation, and, somewhat surprisingly, a political intervention. Uniper ended up as a shareholder in Ringhals as a result of the Swedish

<sup>7</sup>We describe the market development in detail in Section 4.

<sup>8</sup>The units in Finland, excluding two relatively small units owned by Fortum, are owned by co-operatives where the set of partners includes municipalities, consuming industries, and electricity generators. Given the specific ownership structure, the Finnish units are less relevant for the analysis of strategic closure decisions.

<sup>9</sup>Other companies have a 2 % minority share of Forsmark.

**Figure 1:** Cross-ownership of Swedish nuclear assets.



\* Closures announced in 2015.

† Share of nuclear assets in Sweden.

*Notes:* Ownership structure of the Swedish nuclear units R1–R4 in Ringhals, F1–F3 in Forsmark, and O1–O3 in Oskarshamn. The main owners are Vattenfall, Uniper and Fortum.

Government’s decision to force a closure of an older nuclear site in the late 1990s and offer as a compensation a stake in Ringhals, owned fully by the state owned Vattenfall at the time.<sup>10</sup> Since then the ownership structure has been relatively stable until the current market decline, when the industry is seeking to reorganize the ownership.

### 3 Model

**Two-stage illustration.** To illustrate how cross ownership arises in connection with exit, consider two firms,  $(i, j)$ , playing a two-stage game:

1. With probability  $\gamma$  firm  $i$  gets to make a take-it-or-leave offer on cross-ownership  $\alpha \in [0, 1]$  and  $\beta \in [0, 1]$  to firm  $j$ , and with  $1 - \gamma$  firm  $j$  makes the offer<sup>11</sup>;
2. Firms  $(i, j)$  make production decisions.

Shares are claims on profits: firm  $i$ ’s total profit is  $(1 - \beta)\pi^i + \alpha\pi^j$  for given shares and profits  $(\pi^i, \pi^j)$  from the production stage;  $j$ ’s profit is  $\beta\pi^i + (1 - \alpha)\pi^j$ . Firms  $i$  and  $j$  have capacities  $K > k$ , respectively. Throughout, we maintain the convention that

<sup>10</sup>This historical cross-ownership has attracted attention both in the academia (e.g. Amundsen and Bergman, 2002), and with the competition authorities. The Swedish Competition Authority launched an investigation into the cross-ownership structures in 2006. As a result, they did not pursue legal action against the ownership arrangements, but recommended the Swedish Government to initiate actions to dissolve cross-ownerships (Source: Swedish Competition Authority, Dnr 500/2008). The Government followed up with a facilitation of voluntary negotiations between the companies, which in the end did not result in an agreement.

<sup>11</sup>Probabilities represent the bargaining powers of the firms (see Osborne and Rubinstein, 1990)



		Firm $j$	
		$k = 0$	$k = 1$
Firm $i$	$K = 2$	45, 0	20, 10
	$K = 0$	0, 0	0, 90

**Table 2:** No cross-ownership,  $\beta = \alpha = 0$ .

		Firm $j$	
		$k = 0$	$k = 1$
Firm $i$	$K = 2$	40, 5	20, 10
	$K = 0$	0, 0	20, 70

**Table 3:** Cross-ownership,  $\alpha = 2/9, \beta = 1/9$ .

firm  $i$  has the larger capacity.<sup>12</sup> We make the strong assumption that outputs equal the respective capacities as long as the capacities are not retired; it is not feasible to produce at some rate less than the capacity.<sup>13</sup> Marginal cost is constant  $c > 0$  for both firms, and inverse demand  $p(Q)$  is a function of total quantity supplied  $Q$ , with  $p'(Q) < 0$ . Profits are given by function  $\pi^i = \pi(K, k) = (p(k + K) - c)K$ , and similarly  $\pi^j = \pi(k, K)$ . Margins are assumed to be positive but close to zero when both capacities are active,  $p(k + K) - c = \rho > 0$ , where  $\rho$  is small in the following precise sense:

$$\pi(K, 0) > \rho(k + K) \text{ and } \pi(k, 0) > \rho(k + K).$$

Total profits thus increase by closing one of the firms; if firms could jointly decide, they would choose the closure that contributes more to the joint profits. Tables 2 - 3 illustrate how exactly the cross-ownership achieves the collusive outcome. On the left, the equilibrium is that both units run in the production stage; firms would achieve 90 in total by closing the bigger plant. On the right, share  $\alpha$  gives the bigger firm a stake in the post closure gains but there is a need for ownership also in the other direction: the closing firm must give away at least  $1/9$  of its continuation profits, otherwise it will not actually close and thus comply with the plan.

The illustration suggests that the value of the holdings of the closing firm is important for incentives. Given some stakes  $(\alpha, \beta)$ , consider the change in the value of holdings for firm  $j$  if it closes  $k$ :

$$\Delta^j(\alpha, \beta) = \beta \left( \pi(K, 0) - \pi(K, k) \right) - (1 - \alpha) \pi(k, K).$$

Firm  $j$  wants to close if  $\Delta^j(\alpha, \beta) > 0$  which holds for any stake in the continuing firm,  $\beta$ , if its remaining stake in its own plant,  $1 - \alpha$ , is sufficiently low. Similarly, firm  $i$  wants to close if

$$\Delta^i(\alpha, \beta) = \alpha \left( \pi(k, 0) - \pi(k, K) \right) - (1 - \beta) \pi(K, k)$$

is strictly positive which, for some stake  $\alpha$  in the continuing firm, can be ensured by the stake given to the other firm,  $\beta$ .

<sup>12</sup>In the dynamic extension, this asymmetry leads to a unique equilibrium.

<sup>13</sup>Arguably, the nuclear industry is not a poor candidate for illustrating this property.

**Proposition 1** *The subgame-perfect equilibrium equity shares achieve the first-best for the two firms:*

(i) *If  $\pi(K, 0) - \pi(k, 0) > 0$ ,  $j$  closes  $k$ . The stakes are, with probability  $\gamma$ ,*

$$\beta^i = \frac{\pi(k, K)}{\pi(K, 0)} \text{ and } \alpha^i \text{ so that } \Delta^j(\alpha^i, \beta^i) > 0,$$

*and, with probability  $1 - \gamma$ ,*

$$\beta^j = 1 - \frac{\pi(K, k)}{\pi(K, 0)} \text{ and } \alpha^j \text{ so that } \Delta^j(\alpha^j, \beta^j) > 0.$$

(ii) *If  $\pi(k, 0) - \pi(K, 0) > 0$ ,  $i$  closes  $K$ . The stakes are, with probability  $\gamma$ ,*

$$\alpha^i = 1 - \frac{\pi(k, K)}{\pi(k, 0)} \text{ and } \beta^i \text{ so that } \Delta^i(\alpha^i, \beta^i) > 0,$$

*and, with probability  $1 - \gamma$ ,*

$$\alpha^j = \frac{\pi(K, k)}{\pi(k, 0)} \text{ and } \beta^j \text{ so that } \Delta^i(\alpha^j, \beta^j) > 0,$$

**Proof.** Assume that the collusive outcome is  $k = 0$ , and consider firm  $i$  in the position to offer an exchange of shares to  $j$ . The offer should satisfy two things:  $j$  should receive at least the payoff it gets by full rejection, which equals  $\pi(k, K)$  because neither firm closes conditional on entering the second stage without cross ownership, and, additionally,  $j$  should find it optimal to close in the second stage after accepting the offer. Thus,

$$\beta^i \pi(K, 0) = \pi(k, K) > \beta^i \pi(K, k) + (1 - \alpha^i) \pi(k, K)$$

where the equality is the indifference between “accepting and closing” and “rejecting”. The inequality ensures that  $j$  does not continue in the second stage. Rearranging and using  $\beta^i$ , we observe that for  $\alpha^i$  to satisfy the second stage incentives, it must lie in the interval

$$\frac{\pi(K, k)}{\pi(K, 0)} < \alpha^i < 1$$

so that the need for cross-ownership is strict. The incentive constraint for  $j$  can be rewritten as  $\Delta^j(\alpha^i, \beta^i) > 0$  so that  $j$  closes to increase the value of its holdings. If  $j$  is in the position to offer, which happens with probability  $1 - \gamma$ , continuing firm  $i$  receives  $\beta^j$ ,

$$(1 - \beta^j) \pi(K, 0) = \pi(K, k)$$

and to satisfy the second stage incentives, that is, to make sure that firm  $j$  actually closes after completing the deal, we have

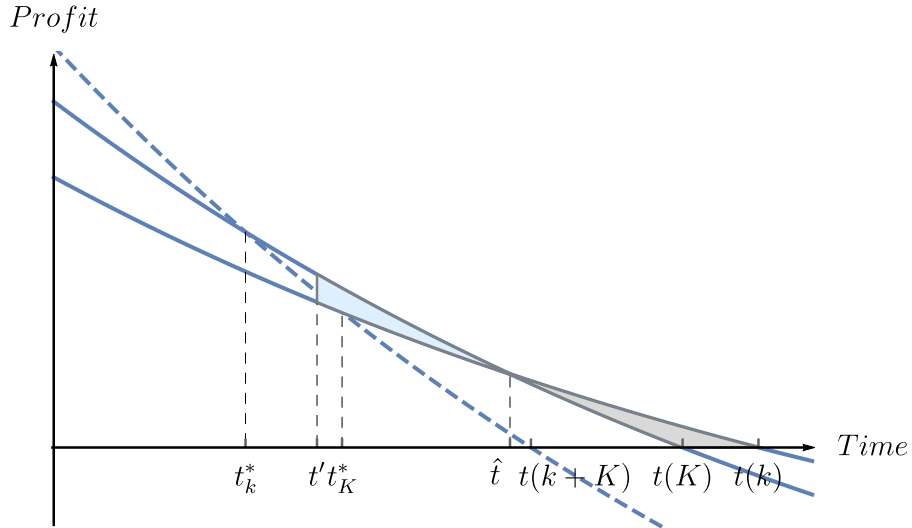
$$\beta^j \pi(K, 0) > \beta^j \pi(K, k) + (1 - \alpha^j) \pi(k, K) \Rightarrow \Delta^j(\alpha^j, \beta^j) > 0.$$

The equilibrium shares follow from these conditions, including the second-stage incentive constraint for  $j$ . However, partial ownership can be enough for incentives in this case ( $\beta^j > 0, \alpha^j = 0$ ): if profit margin is close to zero,  $\rho \approx 0$ , the value increase of the continuing firm always dominates in the incentives,  $\Delta^j(0, \beta^j) > 0$ .

If the full collusion requires the closure of the larger firm, item (ii) in the Proposition, the results are mirror images of the previous case. ■

Expected shares represent the bargaining powers of the firms (see Osborne and Rubinstein, 1990), but one could follow a variety of ways to model the bargaining. The lesson from the illustration is that firms coming close to exit have incentives to negotiate to internalize the closure externalities. In contrast, the collusive outcome is difficult to implement when the market is big enough to accommodate several firms, as the standard free-riding arguments can erode the incentives to negotiate cross-ownership (see, for example, Reitman, 1994).

**Figure 2:** Flow profits over time.



Notes: Flow profits as functions of time. Firm  $j$  profits survives positive longer if alone in the market,  $\pi_t^j = \pi(k, 0, t) = 0$  at  $t = t(k)$ ; for firm  $i$  we have  $\pi_t^i = \pi(0, k, t) = 0$  at  $t = t(K)$ . Joint profit is the dashed curve with  $\pi(K, k, t) + \pi(k, K, t) = 0$  at  $t = t(k + K)$ .

**Dynamics of exit.** How did firms end up being close to exiting from the market? Can cross ownership internalize closure externalities in a truly dynamic setup? To model a declining market and closures made over time, we introduce one change to the primitives above: inverse demand is a function of time  $t$  so that  $p_t(Q)$  is strictly monotonically

decreasing in  $t$ . Profits for  $(i, j)$  are  $\pi_t^i = \pi(K, k, t) = (p_t(k + K) - c)K$  and  $\pi_t^j = \pi(k, K, t) = (p_t(k + K) - c)k$  so we can structure the development of profit flows by assumptions on function  $\pi(\cdot)$ . Denoting partial derivatives by numbered subscripts, we assume:

**Assumption 1** *Flow profits decline in time, are strictly concave in the firm's own capacity, and the marginal value of the own capacity declines with time:*

$$\pi_3(\cdot) < 0, \pi_{22}(\cdot) < 0, \pi_{23}(\cdot) < 0.$$

The assumptions imply “single crossing” of profit flows when firms are alone in the market, as in Fig. 2. The game starts at some  $t_0$ , and we consider variations in  $t_0$  to incorporate the level of the initial demand as a precondition for the equilibrium outcome. For  $t_0$  sufficiently low, demand is high so that keeping both plants active gives positive flow profits,  $\pi(K, k, t) + \pi(k, K, t) > 0$ , higher than from any single plant. For  $t_0$  larger than  $t = t(k)$ , even the small firm is too big to remain in the market  $\pi_t^j = \pi(k, 0, t(k)) = 0$ .

In this exit game, firms choose the closure dates of the plants non-cooperatively, given some fixed shares  $(\alpha, \beta)$ . As a benchmark, consider first equilibrium exit when there are no ownership arrangements, as in Ghemawat and Nalebuff (1985):

**Proposition 2** *(Ghemawat & Nalebuff). If  $\alpha = \beta = 0$ , there is unique subgame-perfect equilibrium (SPE) where firms exit in their size order: larger capacity firm is the first to exit, at time where  $p_t(k + K) = c$ ; smaller capacity firm exits when  $p_t(k) = c$ .*

In Fig. 2, larger firm exits at time  $t(k + K)$  and the smaller at  $t(k)$ . It is useful to outline the proof for the arguments that follow.

**Proof.** Let  $\Delta > 0$  be the (small) length of the time period so that decisions are made at  $0, \Delta, 2\Delta, \dots$  and actions are frozen between any two decision points. Thus, if firm  $i$  chooses not to close at some time point, it must remain active for the coming interval of time  $\Delta$  and can reconsider closing after  $\Delta$  has lapsed. Consider some time point  $t - \Delta$  from interval  $[t(K), t(k))$  in Fig. 2. Suppose that both firms are still active at time  $t - \Delta$ . Given the payoffs show in Fig. 2, after  $\Delta$ , we arrive at  $t$ , still in  $[t(K), t(k))$ , and then  $K$  will be closed: its flow profits are negative even when alone in the market. But capacity  $k$  is still profitable at any such  $t$ . Looking at decisions at time  $t - \Delta$ , firm  $j$  earns the total profit

$$w_{t-\Delta}^j = \pi_{t-\Delta}^j \Delta + \exp(-r\Delta)v_t^j$$

by remaining active where  $r > 0$  is the discount rate and  $v_t^j > 0$  is the total profit from operating alone from time  $t$  to  $t(k)$ . Importantly, when  $\Delta \rightarrow 0$ , the flow profit over one

$\Delta$  becomes inconsequential and  $v_t^j > 0$  is exactly defined, with appropriate correction for discounting, by the size of the positive area under flow profit curve  $\pi(k, K, t)$  over the remaining time interval of activity.<sup>14</sup> Thus, although  $j$  makes a loss when  $K > 0$  over  $\Delta$ , total profit is strictly positive,  $w_{t-\Delta}^j > 0$ , for small  $\Delta$ . In contrast, for firm  $i$ ,

$$w_{t-\Delta}^i = \pi_{t-\Delta}^i \Delta + 0 < 0$$

because there is no continuation payoff and both firms make a loss in interval  $[t - \Delta, t)$ . Firm  $i$  thus optimally shuts down already at  $t - \Delta$  from interval  $[t(K), t(k))$ , and, in fact, by backwards induction, this argument for  $j$ 's continuation and  $i$ 's closure can be extended to interval  $[t(k + K), t(k))$ , where  $t(k + K)$  is the time at which margins turn negative if both remain active. ■

Turn now to shares  $(\alpha, \beta)$  that implement the collusive outcome in the dynamic exit game. We must first characterize the collusive outcome – which firm should be closed first? This turns out to depend on the market size.

**Definition 1** *Initial market size is critically low if a two-plant monopoly optimally closes first the larger plant. In a non-critically low market, the optimal first closure is the smaller plant.*

This market definition is linked to the payoff primitives as follows.<sup>15</sup> Suppose the monopoly is forced to close one plant at the outset  $t_0$  – which plant will be closed? It will compare the areas under the flow profits  $\pi(K, 0, t)$  and  $\pi(0, k, t)$  over the respective life times of the plants. Clearly, closing  $k$  can dominate only if initial time  $t_0$  is low enough so the bigger plant has time to benefit from its profit advantage in  $[t_0, \hat{t})$ , given that this plant will have profit disadvantage after time point  $\hat{t}$ . See Fig. 2 for  $\hat{t}$ .

From this comparison the monopoly knows which plant to close if it has to close one plant: small one if  $t_0 < t'$ , and big one if  $t_0 > t'$  in Fig. 2.<sup>16</sup> But the full choice set includes also the option to continue with both plants, which is optimal if  $t_0 < t_k^*$  or if  $t' < t_0 < t_K^*$ . In the former case, two plant flow profit  $\pi(K, k, t) + \pi(k, K, t)$  exceeds the individual profits flows until time  $t_k^*$  where  $k$  is closed. In the latter, there is not enough time to accumulate profits with  $K$  so it must be closed but this happens only when  $\pi(K, k, t) + \pi(k, K, t)$  declines to  $\pi(k, 0, t)$  which happens at time  $t_K^*$ .

We can now describe the shares that implement the collusive outcome. The shares can be thought of as arising from one-shot bargaining at time  $t_0$ , where the closing

<sup>14</sup>Discounting could be removed from the analysis without affecting the substance matter. Then, the continuation payoff is precisely the area under the flow profit curve.

<sup>15</sup>The two-plant optimum has been characterized by Whinston (1988).

<sup>16</sup>Note that  $t'$  depends on the discount rate: for a larger discount rate, the lower is the initial level of demand that still justifies continuation with the bigger plant.

firm is given incentives to comply with the collusive plan. For shorthand, let  $\delta(t) = \exp(-r(t - t_0))$ . As in two stages, the closing firm needs to consider if the closure improves the flow value of its holdings,

$$\Delta^j(t, \alpha, \beta) = \beta(\pi(K, 0, t) - \pi(K, k, t)) - (1 - \alpha)\pi(k, K, t),$$

which gives, for  $j$  and some shares  $(\alpha, \beta)$ , the change in flow value following from closing  $k$ . Similarly, firm  $i$  can evaluate the flow gain from closing  $K$ :

$$\Delta^i(t, \alpha, \beta) = \alpha(\pi(k, 0, t) - \pi(k, K, t)) - (1 - \beta)\pi(K, k, t)$$

Gains from closures,  $\Delta^j(t, \alpha, \beta)$  and  $\Delta^i(t, \alpha, \beta)$ , can be made strictly positive by strict cross-ownership, as in two stages.

**Theorem 1** *The subgame-perfect equilibrium achieves the first-best for the two firms in the dynamic exit game:*

- (i) *Consider a critically low market, both firms active and profitable. Collusive immediate closure of plant  $K$  can be implemented by fixed profit shares*

$$\alpha = \frac{\int_{t_0}^{t(k+K)} \pi(K, k, t)\delta(t)dt}{\int_{t_0}^{t(k)} \pi(k, 0, t)\delta(t)dt} < 1$$

*and any  $\beta$  satisfying*

$$\Delta^i(t_0, \alpha, \beta) \geq 0$$

- (ii) *In a non-critically low market, collusive immediate closure of smaller plant  $k$  can be implemented by fixed profit shares*

$$\beta = \frac{\int_{t_0}^{t(k+K)} \pi(k, K, t)\delta(t)dt + \int_{t(k+K)}^{t(k)} \pi(k, 0, t)\delta(t)dt}{\int_{t_0}^{t(K)} \pi(K, 0, t)\delta(t)dt} < 1$$

*and any  $\alpha$  satisfying*

$$\Delta^j(t_0, \alpha, \beta) \geq 0.$$

**Proof.** Item (i). As the conjectured closure is collusive and immediate, the total maximum payoff is achieved by running only firm  $j$  from time  $t_0$  to  $t(k)$ :

$$\int_{t_0}^{t(k)} \pi(k, 0, t)\delta(t)dt.$$

Firm  $i$ 's outside option is to reject and obtain payoff

$$\int_{t_0}^{t(k+K)} \pi(K, k, t) \delta(t) dt$$

following the path identified in Proposition 2. Share  $\alpha$  gives firm  $i$  exactly this outside option payoff as a fraction of the collusive total payoff, where the outside option is given by the exit game without cross-ownership. Share  $\beta$  incentivizes firm  $i$  actually to close after the ownership arrangement; alternatively,  $i$  can take the shares and continue playing the exit game. We construct the payoff for  $i$  in this exit game and show that it closes immediately if  $\Delta^i(t_0, \alpha, \beta) \geq 0$ . The present-value total payoff for firm  $i$  from an outcome path, where firm  $i$  closes at some  $T^i \geq t_0$  before firm  $j$  that closes at some  $T^j$ , is

$$\int_{t_0}^{T^i} \left( (1 - \beta)\pi(K, k, t) + \alpha\pi(k, K, t) \right) \delta(t) dt + \int_{T^i}^{T^j} \alpha\pi(k, 0, t) \delta(t) dt.$$

Write the last integral as

$$Z(t) = \int_t^{T^j} \alpha\pi(k, 0, \tau) \delta(\tau) d\tau$$

so that  $Z(T^i) = Z(t_0) + \int_{t_0}^{T^i} Z'(t) dt$  and thus the payoff becomes

$$Z(t_0) + \int_{t_0}^{T^i} \left( (1 - \beta)\pi(K, k, t) + \alpha\pi(k, K, t) - \alpha\pi(k, 0, t) \right) \delta(t) dt$$

where  $Z(t_0)$  is the total profit that would follow from closing  $K$  at time zero. The term inside the integral is by now familiar, so we can write the total profit as:

$$Z(t_0) - \int_{t_0}^{T^i} \Delta^i(t, \alpha, \beta) \delta(t) dt$$

If firm  $i$  closes first in equilibrium, the term inside the last integral must turn positive at the closure time,  $t = T^i$ , or it is positive at the outset and then the closure is immediate. But, by construction, there exists  $\beta$  such that  $\Delta^i(t_0, \alpha, \beta) \geq 0$ . Also, Assumption 1 implies

$$\frac{\partial \Delta^i(t, \alpha, \beta)}{\partial t} > 0.$$

Thus, there exists  $\beta$  such that  $i$ 's best response is to close at  $t_0$  given that  $j$  continues. And, trivially,  $j$ 's best response is to continue.

Item (ii). Recall that the closure is collusive and immediate, which requires that only firm  $i$  runs from time  $t_0$  to  $t(K)$ . Share  $\beta$  in the Proposition gives firm  $i$  the outside option payoff from the exit game without cross-ownership. For  $\alpha$ , we must consider the

exit game with the proposed shares  $(\alpha, \beta)$ , and show that  $j$ 's best response is to close at  $t_0$ , and then  $i$ 's best response is to continue. We omit the formal steps as they are mirror images of those for  $i$  above. ■

Obviously the same outcome can be achieved by giving the closing firm even more of the total surplus, reflecting another division of bargaining powers, although then one must make an upward adjustment in the ownership in the other direction as well. Moreover, for example, the minimal share  $\alpha$  in the Proposition, declines to zero with the initial market size as  $t_0$  approaches  $t(k + K)$ . Intuitively, in such a situation, firm  $i$  closes anyways almost immediately, and thus the need to compensate disappears as well.

## 4 Nordic Nuclear Power Phase-out

### Setting

We now solve numerically an exit game in the Nordic nuclear industry with cross-ownerships. We use a stylized model of the industry and the electricity market which captures the key dynamics relevant for the exposition of the impacts of ownership. To quantify the profits of the plants we need a relationship between the market price and the quantity produced with different technologies. When nuclear power units close, all else equal, the market price increases because there is substitution towards higher marginal costs technologies.<sup>17</sup> When wind power expands, all else equal, the market price decreases because wind replaces the higher marginal costs technologies. We calibrate such a price-quantity relationship to capture the approximate change in the observed annual price levels and wind power expansion.<sup>18</sup> It is important to interpret the precise results of the quantification with caution; it illustrates the mechanism with ballpark numbers but leaves the empirical assessment open for future work.

**Market.** From Table 1, the total production is close to 400 TWh annually. We assume that this amount will be demanded also in the future; the demand has remained stable and inelastic over time, if one accounts for the natural variation in temperatures. There are arguments for increased demand over time (everything from data centers to an uptake in electric vehicles and overall electrification), but also factors that could reduce demand over time (main drivers are the restructuring of the economy away from energy intensive

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<sup>17</sup>This is as in Davis and Hausman (2016) who provide an empirical breakdown of the implications of a single plant closure in California: the closure increased generation by higher marginal cost natural gas.

<sup>18</sup>The numbers used in the current article are self-contained but we have a supporting estimation of the price-quantity relationship on a more granular level in Liski and Vehviläinen (2018).



industries and increases in energy efficiency).

The supply comes from several technologies characterized by technical details that are important in the short-term analyses but less relevant here because of the abundant hydro resources and the long-term nature of the analysis. Around half of the supply comes from hydro resources that provide a counterbalance for the intermittent wind power; therefore scaling up the share of renewable technologies has not proven difficult in the Nordic electricity system. Nuclear covers one quarter of supply and the remainder has historically been procured from various sources of conventional thermal power<sup>19</sup>. In the past decade, wind power generation has increased from a few percentage points to the current around 10 % of the market. Subsidized entry of low marginal cost wind has almost one-to-one replaced generation from the fleet of thermal units (see Liski and Vehviläinen, 2018).

The market price of electricity must cover the marginal costs of the running plants. Thermal power units have the highest marginal cost, and thus they are typically the marginal running units. When wind power replaces thermal units, the market prices tend to decline. In 2009, wind output was around 10 TWh and the annual market price was 36 €/MWh. By 2017 the amount of wind had increased to 40 TWh and the market price was 27 €/MWh.<sup>20</sup> Because demand is assumed to be inelastic, it is the thermal supply curve that gives us the prices associated with the quantities produced. We use a semi-log functional form to capture the increasing marginal cost of generation<sup>21</sup>:

$$\ln p_t = 3.7 + .013q_t,$$

where  $p_t$  is the annual price and  $q_t$  denotes the annual thermal power generation in TWh. Now, an increase in wind reduces the amount of thermal,  $q_t$ , and a decrease in nuclear increases  $q_t$ . With a wind level of 10 TWh annually, the calibrated supply function gives a price of 36 €/MWh and with 40 TWh the price is 24 €/MWh<sup>22</sup>.

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<sup>19</sup>Mainly coal- and biofuel-fired thermal plants and combined heat and power, CHP.

<sup>20</sup>Measured in 2010 euros. The years have been chosen because the other key covariates, input fuel prices and hydrological conditions, were close to each other. Annual prices are strongly dependent on the Nordic temperatures and hydrological conditions but long-term forward prices are less dependent on such idiosyncratic variation, although they also depend on the fuel prices. The fall in the forward prices is more or less of the same magnitude as the fall in the spot prices above.

<sup>21</sup>Inelastic demand and semi-log functional form are common in the electricity market analysis, see for example Bushnell, Mansur and Saravia (2008). Parameter values are calibrated to the market data above; Liski and Vehviläinen (2018) describe the full data set and provide an IV estimation in a much richer empirical setting that results with similar parameter values.

<sup>22</sup>Because part of nuclear capacity was already phased out in 2017, the actual price is slightly above the calibration here. Implicitly, fixing the supply curve as above fixes all other variation such as variations in input prices, hydrological conditions, and temperature, to roughly their historical mean values.

The Nordic climate and energy policies aim to increase the share of renewables in the market, with the projected increases mostly in wind power generation.<sup>23</sup> By 2020 wind power generation is expected to rise to around 50 TWh annually, representing 13 % of the market.<sup>24</sup> All Nordic countries have plans to continue with renewable subsidies beyond 2020. Although estimates on the amount of new wind are bound to be uncertain, we take an additional 50 TWh more wind by 2050 as our baseline case.<sup>25</sup> The mean annual generation of the Swedish nuclear units has been 67 TWh annually, more than enough to offset the current wind power expansion but less than the assumed total wind of 100 TWh in 2050.

**Players.** In Table 4, we list all Swedish nuclear units in 2015, their historical mean annual productions, announced closure dates and marginal costs. Of the initial ten units, four have been announced to be closed. Our base case analysis focuses on the remaining six units on three plant sites (Forsmark 1, 2 and 3; Oskarshamn 3; and Ringhals 3 and 4).

**Table 4:** Swedish nuclear power units.

Unit	Abbr.	Generation TWh/year	Announced closure	Marginal cost €/MWh	Ownership		
					Fortum	Uniper	Vattenfall
Forsmark 1	F1	7.23	–	19.5	22.2%	9.9%	66.0%
Forsmark 2	F2	8.11	–	17.6	22.2%	9.9%	66.0%
Forsmark 3	F3	8.72	–	16.5	22.2%	9.9%	66.0%
Oskarshamn 1	O1	2.55	2017	29.5	45.5%	54.5%	–
Oskarshamn 2	O2	4.16	2015	25.3	45.5%	54.5%	–
Oskarshamn 3	O3	9.92	–	19.1	45.5%	54.5%	–
Ringhals 1	R1	5.33	2020	26.9	–	29.6%	70.4%
Ringhals 2	R2	4.78	2019	27.3	–	29.6%	70.4%
Ringhals 3	R3	7.29	–	18.8	–	29.6%	70.4%
Ringhals 4	R4	8.18	–	18.6	–	29.6%	70.4%

*Notes:* The table lists the Swedish nuclear units as of 2015. The energy produced is obtained from the plant capacity and historical availability factors. Marginal costs include all required investment to continue operating the plants post 2020, and are measured in 2015 euros (Source: Energikommisionen M 2015:01 and assumptions by the authors to the additional investment costs for the plants O1, O2, R1, and R2 that are announced to be closed should they have continued to operate. Government regulations imposed new safety related costs to all nuclear plants post 2020.).

The two players with assumed decision rights on closures are the majority owners,

<sup>23</sup>Source: Climate and energy policies in the Nordic countries, see Appendix A.

<sup>24</sup>Wind power generation about 40 TWh in 2017, and 50 TWh in 2020 corresponds roughly to the projects already in the pipeline.

<sup>25</sup>The effects of this relatively small increase will be substantial on the margin. Already around 50 TWh of wind, the amount expected in 2020, is sufficient to render most of the price responsive thermal generation, the capacity with highest marginal costs, in the Nordic region idle.

Vattenfall and Uniper<sup>26</sup>. Overall, Vattenfall is the larger player with multiple plants in its control and no minority shares: it owns a majority in both Forsmark (66.0% and Ringhals 70.4%) and does not own any shares in Oskarshamn. Uniper is the smaller player with a majority share in Oskarshamn (54.5%). Uniper also has minority shares in Ringhals (29.6%) and Forsmark (9.9%). The third major owner, Fortum, has no majority holdings in the Swedish nuclear plants but a stake in Forsmark (22.2%) and Oskarshamn (45.5%). These observed actual cross-ownerships are used in our base case analysis.

**Simulations.** All equilibrium outcomes, and the optimal strategies for the monopolist and the social planner are solved numerically with backward induction in discrete time. The end time of the game is well-defined if we have a sufficient entry of new wind. Consider that only a single plant is in operation: This single plant will exit when the payoffs of the plant will become negative, that is, when prices match marginal costs. The latest of such times gives us the precise end time needed for the backward induction.<sup>27</sup>

Working backwards, at each time stage the “instantaneous” payoffs during the discrete time period for both players are calculated in all states, i.e. all the combinations of running plants, and combined with the payoffs of the unique continuation games from those states. After the payoffs are determined, we obtain all pure strategy equilibria. With a sufficiently small discretization interval, there is a unique subgame-perfect pure strategy equilibrium.<sup>28</sup>

## Results

**Base game.** We consider (i) a competitive (subgame-perfect) counterfactual where each of the units would operate on its own, (ii) a competitive (subgame-perfect) outcome with the observed cross-ownership, (iii) the monopolistic strategy to illustrate the fully collusive outcome, and (iv) the social planner’s optimal policy.

The competitive outcome proceeds as in Ghemawat and Nalebuff (1985) multiplant case. The war of attrition leads to the largest unit (O3) closing first and then the other

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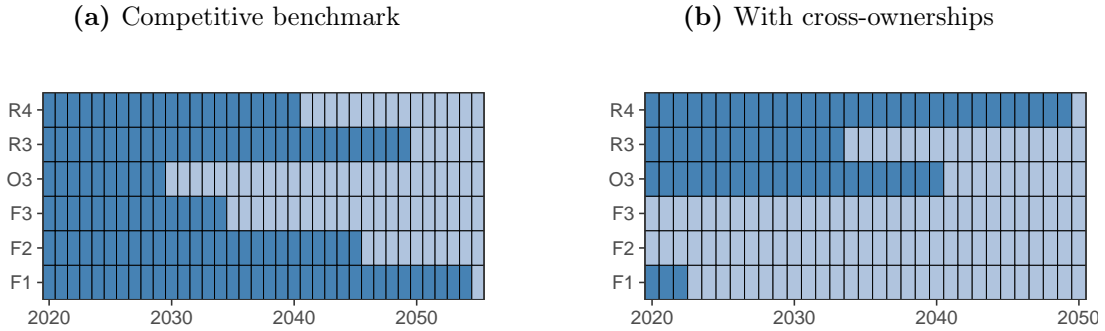
<sup>26</sup>The public reports on the closures of O1, O2, R1 and R2 support the assumption that the majority owners can force the closure decisions. According to media reports the minority owners opposed closures. Somewhat confusingly Fortum signaled willingness to continue with O1 and O2, but Uniper forced the decision. At the same time Vattenfall forced the closure of R1 and R2 despite the objections of Uniper.

<sup>27</sup>If each player has capacity that can run profitably at the end of the simulation period, there is no guarantee for a unique pure strategy equilibrium. We do not enforce technical closure limits, but the closure times from simulations are in line with the current view on the operating lifetimes of the plants.

<sup>28</sup>The discrete time is an issue for uniqueness; see in Whinston (1988). We check for the uniqueness of the resulting equilibria, and if necessary use a more granular calculation. For details, we refer to our code, available online through the link in the Appendix A.

plants in the size order until the smallest unit (F1) closes last.<sup>29</sup> See Fig. 3, panel (a).

**Figure 3:** Impact of ownership structure to the closure decisions over time.



Notes: The operational state of the nuclear units. Codes F1–F3 are the units in Forsmark and R3–R4 in Ringhals, operated by the larger firm Vattenfall. O3 is located in Oskarshamn and is operated by the smaller firm Uniper. Darker color represents a running plant.

Figure 3, panel (b), demonstrates the impact of the ownership structure to firms' closure decisions. When we account for the current cross-ownerships, several effects distort the phase-outs away from the competitive path in panel (a). First, it immediately pays off to close some capacity at the start of the game in 2020. Vattenfall is initially the larger player, it has the majority in F1–F3 and R3–R4, and Uniper only in O3. The mechanism is as in Whinston (1988): the larger player can internalize a part of the effects of the closures, and it's larger exposure also enables the smaller player to force earlier closures. As the market decline continues, further capacity reduction will take place. Again, Vattenfall is the one to close until only two units remain. The end game is as in Ghemawat and Nalebuff (1985): the largest unit (owned by Uniper) closes, and finally the last unit (owned by Vattenfall) closes. Cross-ownerships affects Uniper's exit decision: Uniper benefits from its closure through ownership in Vattenfall's plants. As a result, the closure of O3 takes place earlier than if Uniper would not have a stake in the other plants. Finally, ownership stakes affect also the order of closure for Vattenfall. Uniper's share in Ringhals is higher than in Forsmark. By keeping a Ringhals unit running last, Vattenfall can get Uniper to close O3 earlier, which in turn leads to higher industry payoffs<sup>30</sup>.

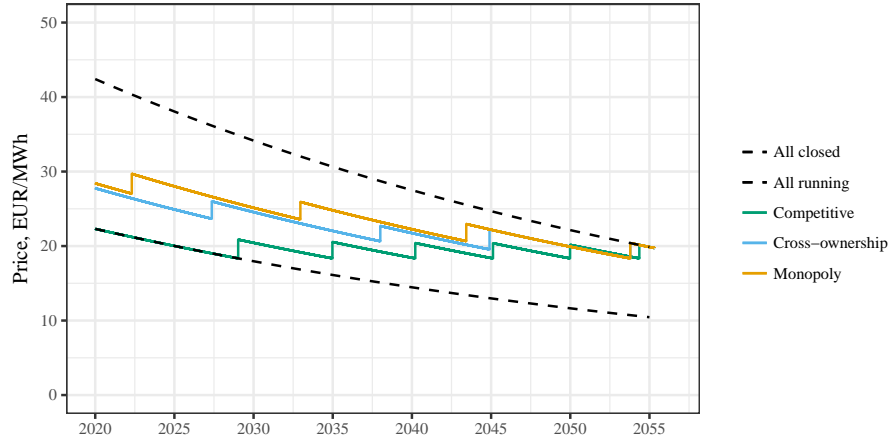
The gains to the industry come at the cost of higher prices for the consumers. Increase in wind will push down the prices longer-term regardless of the measures taken by the incumbents. An upper limit for prices is given if all nuclear units are closed and a lower limit with all units running. Strategies taken by the players will put prices between

<sup>29</sup>These simulations are done with homogenous costs for the plants. Accounting for the reported cost differences results in the larger and more modern plants to stay longer, see Appendix B.

<sup>30</sup>Vattenfall is close to indifferent here: it owns a larger share of R4 than of F3 because there are also other owners in F3.

these extremes, as depicted in Figure 4. We provide two reference points: a competitive path where single nuclear unit owners would all compete with each other and the fully collusive price path of the monopolist. With the observed cross-ownerships, the industry comes close to the collusive price path.

**Figure 4:** Simulated prices.



Notes: Prices from simulation over time. Competitive solution is where each unit is owned by a single owner with no other interest in the market. Fully collusive price path is the one of the monopolist's. Upper and lower boundaries are given by all nuclear units closed and running, respectively.

Table 5 summarizes the mean annual payoffs over 2020–2029 period for each player, and other key statistics. In the competitive war of attrition between single owners, the mean industry payoff is around 94 MEUR per year. With the cross-ownerships, the mean industry payoffs increase to 221 MEUR per year, close to the fully collusive outcome. Though the absolute differences are small to the nuclear industry, the changes translate to much larger differences in the costs for consumers. Given the equilibrium market prices, the mean annual market value of electricity varies between 8 billion euro and 15 billion euro per year. In the competitive outcome, the equilibrium closure path would lead to cost of 8 billion euro per year to the consumers. With cross-ownerships the cost rises to 10 billion euro per year.

The reduction of nuclear power output leads to an increase in emissions if thermal power is required to balance the system after nuclear exits. The mean generation of the six units included in the game has been around 50 TWh per year. The capacity closures reduce this output swiftly and significantly. Mean annual nuclear output over the 2020–2029 period decline slightly to 49 TWh per year in the competitive outcome, but drop to 31 TWh per year if the cross-ownerships are accounted for, and to 25 TWh per year for the monopolist. Corresponding annual emissions are calculated against the situation where all six units would still be running. If all nuclear units close and equivalent amount

**Table 5:** Results of the six plant game with only the nuclear assets.

	Market price €/MWh	Payoff				Trade value M€/a	Nuclear output TWh/a	Carbon emissions MtCO <sub>2</sub> /a
		Uniper M€/a	Fortum M€/a	Vattenfall M€/a	Industry M€/a			
All running	20.1	17	21	46	84	7,989	49.4	0
Competitive	20.3	18	23	52	94	8,088	48.5	0.9
Cross-ownership	25.6	41	76	104	221	10,183	30.7	17.8
Monopoly	27.4	20	51	158	228	10,932	25.2	22.9
All closed	38.1	0	0	0	0	15,195	0	46.8

Notes: Mean values for 2020–2029. Payoffs of the industry players include revenue from sales of their nuclear output at market prices and running costs of nuclear plants. Trade value is the total market revenue (cost) of suppliers (consumers). Carbon emissions are calculated from the reduction of nuclear output with the assumed substitution to coal fired thermal.

is generated with an average coal-fired thermal power<sup>31</sup>, emissions increase by 47 MtCO<sub>2</sub> per year. In the competitive outcome the emission increase is less than one MtCO<sub>2</sub>, whereas the cross-ownership and monopoly outcomes lead to 17–23 MtCO<sub>2</sub> increases, corresponding roughly to a quarter of the current industrial emissions in the region<sup>32</sup>.

**Extended game with a full portfolio of assets.** The key players own other assets than stand to gain from nuclear closure decisions. Although the industry’s total hydro capacity benefitting from the nuclear unit closures (63 TWh/year of actual generation) is almost as big as the nuclear capacity itself (67 TWh/year of actual generation), the shares in these benefitting assets are unevenly distributed: Fortum and Vattenfall have the biggest strategic incentive for closures with both having around 40 TWh/year of other generation<sup>33</sup>. Table 6 illustrates the market outcomes with revenues from hydro assets included in the decision making and with heterogenous costs for the nuclear units (see Appendix B). The collusive path is clear, a monopolist would close all nuclear units immediately. In the equilibrium paths only the nuclear unit O3 owned by Uniper would remain in operation, and it closes sooner when cross-ownerships are accounted for.

With current observed cross-nuclear and cross-asset ownerships, the mean annual market value in equilibrium closure path is 13 billion euro. If each nuclear plant would be owned and operated only by their current majority owner, and these would not have other vested interests in the market, the mean market annual value is reduced to 8 billion euro. The environmental impacts are also significant, the cross-ownerships result in 37 MtCO<sub>2</sub> per year higher emissions, or around 40 % of the total industrial emissions in the

<sup>31</sup>We use efficiency of 36% with coal emission of 341 g/kWh, corresponding to an older coal fired condensing plant or in the low end for the oil shale generation in the neighbouring region.

<sup>32</sup>Source: European Environmental Agency, Emissions within EU ETS, excl. aviation, 2017.

<sup>33</sup>Fortum’s ownership in the Finnish nuclear units included.

**Table 6:** Results of the six plant game with hydro assets.

	Market price €/MWh	Profit				Trade value M€/a	Nuclear output TWh/a	Carbon emissions MtCO <sub>2</sub> /a
		Uniper M€/a	Fortum M€/a	Vattenfall M€/a	Industry M€/a			
All running	20.1	348	148	539	1,035	7,990	49.5	0
Competitive	20.1	348	148	539	1,035	7,990	49.5	0
Cross-ownership	33.5	693	326	924	1,944	13,357	9.9	37.4
Monopoly	38.1	729	288	1,074	2,091	15,196	0	46.8
All closed	38.1	729	288	1,074	2,091	15,196	0	46.8

Notes: Mean values for 2020–2029. Payoffs of the industry players include revenue from the sales of their nuclear and hydro generation at market prices, and their running costs. Trade value is the total revenue (cost) of suppliers (consumers). Carbon emissions are calculated from the reduction of nuclear output with the assumed substitution to coal fired thermal.

region.

We also note that a social planner would likely keep the nuclear plants running, even if emission externalities are ignored, because of the large market impacts<sup>34</sup>. In Table 6 the difference in total cost to the consumers is around 5 billion euros whereas the loss to industry profits is around 1 billion.

**Sensitivities.** In the base case exposition above we use homogenous marginal costs for the nuclear units. The equilibrium argument and backward induction logic stay valid even if the costs are heterogenous. If marginal costs are sufficiently different, the order of closures is affected but still there is a unique ordering for the closures (as in see Reynolds, 1988). We run the simulation with cost data from the engineering estimates published by the Swedish Government, see Table 4.<sup>35</sup> With variations in costs, the main change compared to the base case come as the cheaper units in Forsmark replace the costlier units in Ringhals. However, our main results with respect to the impact of cross-ownership remain robust (see Appendix B). The quantity and timing of the total capacity phase-out does not change much, although the roles of different units on the equilibrium path change.

Various drivers may affect the overall pace of closures. Higher than anticipated demand may intencivize the nuclear units to stay longer, whereas lower demand can lead

<sup>34</sup>As a small caveat we note that a fully efficient outcome would need to take a position on the related investment costs of alternative generation, which we believe warrants its own study. The direct welfare losses from increased cost of generation are around the same magnitude as the nuclear industry payoffs.

<sup>35</sup>The cost data had been collected in 2015 by the Government as a basis for energy and climate policy update. At the time, nuclear generation was actually targeted with a specific and sizable tax of around 5–7 EUR/MWh or 20–30 % of the total marginal costs. Vattenfall, the main industry player, threatened the Government with total closure of their fleet if the tax was not removed. The tax was removed.

to even earlier exist. Similarly, entry or exit of other supply or additional transmission links to other regions may lead to price developments that deviate from our base case simulation. We remain mindful for all these possibilities but the magnitudes are likely to remain marginal compared to the supply effects caused by the large expected wind increases and the potential of nuclear exits. In our simulations the effects of slower or faster decline in the residual demand will affect the timing of closures, but will not change the main effect: with cross-ownerships the exits occur earlier. Appendix B provides an example of the changes in the outcomes if the calibrated supply curve is adjusted.

On 20 September 2017 Fortum announced its intention to launch a public takeover offer of Uniper. If successful, the bid would reduce the number of major owners in the Swedish nuclear industry from three to two. As already noted by Whinston (1988), in some circumstances a merger could actually turn out to be socially beneficial if the equilibrium outcome is shifted from a more collusive outcome to a more competitive one as a result. On the basis of our simulations, in Appendix B, this does not seem to be the case in the analysis including the full portfolio assets before and after the merger. On its own, Uniper is relatively more dependent on the quantities produced by its nuclear units; it runs the units longer compared to how the merged company would run the same assets. Accounting for the merger, the simulation suggest the full closure of all nuclear almost immediately.

Finally, the four closure decisions already taken by the firms in 2015 naturally lead to the following question: Can the model replicate the order and magnitude of the observed closures? To address the question, we need to calibrate the model parameters to correspond to the market conditions prior to the closures, which requires a more detailed set of cost covariates for thermal power than what we have used so far in the analysis. This analysis is available on request. The results indicate that the actual closures are somewhere between the competitive and cross-ownership outcomes of the simulation.

## 5 Concluding Remarks

We developed a simple theory of collusive ownership and exit from a declining market, building on strong assumptions on capacity utilization and common knowledge of private costs and market fundamentals. The assumptions on the information structure are critical in war of attrition games, and our results hinge on these as well. Cross-ownership is likely to play a role for alternative information structures: in alliances firms can share private information on costs and potentially their private signals on the market fundamentals, in the spirit of Ghosh and Morita (2017).

For the energy market application, it would be important to introduce uncertainties



common to all players regarding the market development, similarly as in Murto (2004). Fuel and emissions prices are characterized by persistent uncertainties that impact the marginal costs of the alternatives to nuclear, thus making the value of nuclear units persistently uncertain. There is a novel twist to the relationship between renewables, nuclear, and the fuel prices: the entry of renewables tends to disconnect the market from persistent fuel price uncertainties (less thermal power generation implies lower pass-through of fuel costs), and the closure of nuclear works in the opposite direction.

It is important to interpret the precise quantitative results with caution but we still believe the analysis delivers a strong policy conclusion. First, cross-ownership should be dissolved, or closures should be regulated. Second, once the incentives for early closures are removed, there is a case for running some units even when they run a deficit: The consumer surplus covers the losses. In our calculations, the losses of the nuclear industry amount to less than 60 million euro annually whereas the consumers benefit by factor 10 more (see Table 5, rows “all running” and “competitive”). Additionally, the subsidized life-times contribute significantly to emissions reductions.<sup>36</sup>

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<sup>36</sup>Note that the threat of expedited nuclear phase-out has already led to removal of nuclear specific taxes in Sweden and subsidies to nuclear in several U.S. states.

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## Appendix A Data

Data used together with the code for replicating the results can be downloaded from: [https://www.dropbox.com/sh/qjr0y4j9oyfs570/AAA28DpATzIEqZal0XLFxZ5\\_a?dl=0](https://www.dropbox.com/sh/qjr0y4j9oyfs570/AAA28DpATzIEqZal0XLFxZ5_a?dl=0)

**Data sources.** We use the following national energy policy documents (latest at the time of writing) as the basis of the long term estimates on wind power addition.

1. DENMARK: The Danish Government

- Energy – for a green Denmark, 2018. <http://en.efkm.dk/>

2. FINLAND: Ministry of Economic Affairs and Employment

- Valtioneuvoston selonteko kansallisesta energia- ja ilmastostrategiasta vuoteen 2030, 2017 (*in Finnish*). <http://tem.fi/>

3. NORWAY: The Norwegian Government

- Kraft til endring - energipolitikken mot 2030, Meld. St. 25, 2016 (*in Norwegian*). <https://www.regjeringen.no>

4. SWEDEN: The Swedish Government and Energikommisionen

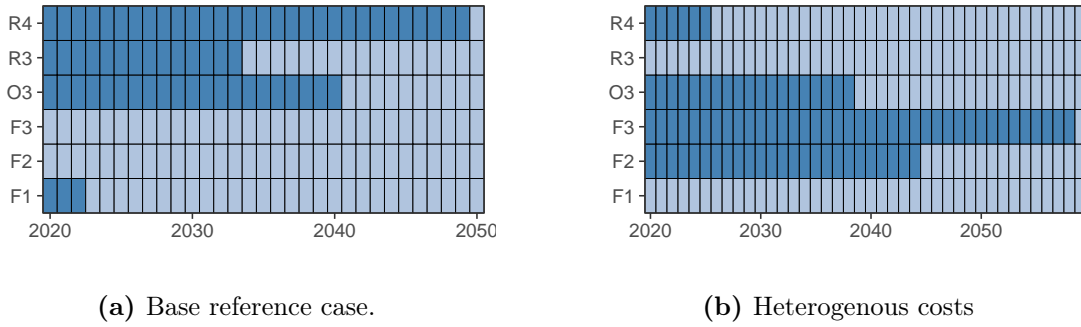
- Ramöverenskommelse mellan Socialdemokraterna, Moderaterna, Miljöpartiet de gröna, Centerpartiet och Kristdemokraterna, 2016 (*in Swedish*). <https://www.regeringen.se/>
- Kraftsamling för framtidens energi, SOU 2017:2, 2017 (*in Swedish*).
- Promemoria om de ekonomiska förutsättningarna för befintlig svensk elproduktion, M2015:01, 2016 (*in Swedish*). <http://www.energi Kommissionen.se>

**Key additional assumptions.** Real interest rate in all simulations is 3 %. All monetary items are reported in 2010 euros. The engineering cost estimates for Swedish nuclear are included in the documents published by the government. We add the estimated safety related investment cost (5 EUR/MWh) to the marginal costs for the Swedish nuclear plants that have already been announced to close (O1, O2, R1, and R2).

# Appendix B Supplementary simulations

## Heterogeneous costs

Heterogenous marginal costs for nuclear are set on the basis of the engineering estimates published by the Swedish government (Energikommissionen, Promemoria om de ekonomiska förutsättningarna för befintlig svensk elproduktion, M2015:01, 2016).



**Figure B1:** Impact of assumptions on costs to the closure decisions over time. Darker color represents a running plant.

**Table B1:** Base reference case.

	Market price €/MWh	Payoff				Trade value M€/a	Nuclear output TWh/a	Carbon emissions MtCO <sub>2</sub> /a
		Uniper	Fortum	Vattenfall	Industry			
		M€/a	M€/a	M€/a	M€/a			
All running	20.1	17	21	46	84	7,989	49.4	0
Competitive	20.3	18	23	52	94	8,088	48.5	0.9
Cross-ownership	25.6	41	76	104	221	10,183	30.7	17.8
Monopoly	27.4	20	51	158	228	10,932	25.2	22.9
All closed	38.1	0	0	0	0	15,195	0	46.8

**Table B2:** Heterogenous cots.

	Market price €/MWh	Payoff				Trade value M€/a	Nuclear output TWh/a	Carbon emissions MtCO <sub>2</sub> /a
		Uniper	Fortum	Vattenfall	Industry			
		M€/a	M€/a	M€/a	M€/a			
All running	20.1	17	17	51	85	7,990	49.5	0
Competitive	20.1	17	17	51	85	7,990	49.5	0
Cross-ownership	25.3	59	57	114	230	10,068	31.6	16.9
Monopoly	27.6	39	39	168	247	10,978	25	23.2
All closed	38.1	0	0	0	0	15,196	0	46.8

## Sensitivity to supply curve specification

The marginal costs of the price setting thermal plants are varied around the base case mean of 2001–2014 period. The changes correspond roughly to one standard deviation of the observed variation.

**Table B3:** Stronger price impact from wind (increase multiplier by 50 %).

	Market price €/MWh	Payoff				Trade value M€/a	Nuclear output TWh/a	Carbon emissions MtCO <sub>2</sub> /a
		Uniper M€/a	Fortum M€/a	Vattenfall M€/a	Industry M€/a			
All running	14.1	-41	-52	-113	-206	5,634	49.5	0
Competitive	19.9	6	9	32	47	7,945	31.7	16.9
Cross-ownership	24.0	26	51	49	126	9,570	22.1	25.9
Monopoly	27.1	17	26	96	139	10,783	16.1	31.6
All closed	37.1	0	0	0	0	14,777	0	46.8

**Table B4:** Base reference case.

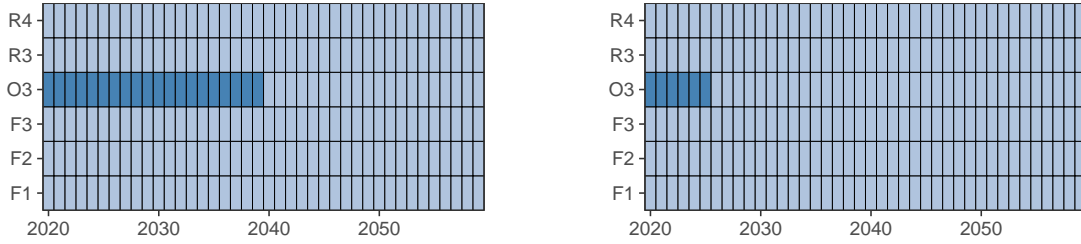
	Market price €/MWh	Payoff				Trade value M€/a	Nuclear output TWh/a	Carbon emissions MtCO <sub>2</sub> /a
		Uniper M€/a	Fortum M€/a	Vattenfall M€/a	Industry M€/a			
All running	20.1	17	21	46	84	7,989	49.4	0
Competitive	20.3	18	23	52	94	8,088	48.5	0.9
Cross-ownership	25.6	41	76	104	221	10,183	30.7	17.8
Monopoly	27.4	20	51	158	228	10,932	25.2	22.9
All closed	38.1	0	0	0	0	15,195	0	46.8

**Table B5:** Lower price impact from wind (decrease multiplier by 50 %).

	Market price €/MWh	Payoff				Trade value M€/a	Nuclear output TWh/a	Carbon emissions MtCO <sub>2</sub> /a
		Uniper M€/a	Fortum M€/a	Vattenfall M€/a	Industry M€/a			
All running	25.3	69	86	187	342	10,090	49.5	0
Competitive	25.3	69	86	187	342	10,090	49.5	0
Cross-ownership	26.5	71	97	190	357	10,553	44.2	5
Monopoly	27.7	49	65	248	362	11,022	39.2	9.7
All closed	38.9	0	0	0	0	15,489	0	46.8

## Merger of Fortum and Uniper

The figures and tables below present the results from simulations where the nuclear costs are set on the basis of the engineering data and hydro assets are included in the decision making. The merger of Fortum and Uniper is done simply by including all Uniper’s assets under Fortum.



(a) Reference with hydro and heterogeneous costs. (b) Merger of Fortum and Uniper.

**Figure B2:** Impact of merger to closures. Darker color represents a running plant.

**Table B6:** Reference case with heterogeneous costs and hydro assets included.

Case	Price EUR/MWh	Fortum MEUR/a	Uniper MEUR/a	Vattenfall MEUR/a	Industry MEUR/a	Market MEUR/a	Nuclear TWh/a	Emissions MtCO <sub>2</sub> /a
All running	20.1	348	148	539	1,035	7,990	49.5	0
Competitive	20.1	348	148	539	1,035	7,990	49.5	0
Cross-ownership	33.5	693	326	924	1,944	13,357	9.9	37.4
Monopoly	38.1	729	288	1,074	2,091	15,196	0	46.8
All closed	38.1	729	288	1,074	2,091	15,196	0	46.8

**Table B7:** Results of the simulation with full merger of Uniper’s assets to Fortum.

Case	Price EUR/MWh	Uniper MEUR/a	Fortum MEUR/a	Vattenfall MEUR/a	Industry MEUR/a	Market MEUR/a	Nuclear TWh/a	Emissions MtCO <sub>2</sub> /a
All running	20.1	0	496	539	1,035	7,990	49.5	0
Competitive	20.1	0	496	539	1,035	7,990	49.5	0
Cross-ownership	35.6	0	1,024	990	2,014	14,168	5.3	41.8
Monopoly	38.1	0	1,017	1,074	2,091	15,196	0	46.8
All closed	38.1	0	1,017	1,074	2,091	15,196	0	46.8







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