IFN Working Paper No. 892, 2011

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June 29, 2013

Abstract

We propose nuclear capacity auctions as a means to improve the incentives for investing in nuclear power. In particular, capacity auctions open the market for large-scale entry by outside firms. Requiring licensees to sell a share of capacity as virtual power plant contracts increases auction efficiency by mitigating incumbent producers' incentive to bid for market power. Our motivating example is Sweden's recent decision to allow new nuclear power to replace old reactors.

Keywords: Capacity auctions; investments; market power; nuclear power; virtual power plants.
JEL Codes: D44; L12; Q48.

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1. Introduction

The decision of the Swedish Parliament in 2010 to open up for new nuclear power marks a u-turn in the country's nuclear policy. The previous 30 years the official policy had been full abandonment. The reactors were to be phased out as fast as the energy system permitted, bearing in mind the consequences for employment and economic welfare. The fundamental role played by nuclear power – it accounts for some 45% of Swedish annual production – can help explain why only two out of twelve reactors have been decommissioned.

Profitable investment requires electricity prices substantially and consistently above marginal nuclear production cost owing to the capital costs of new nuclear power. The economic viability of new nuclear power therefore has been questioned (e.g. Davis, 2012), not least owing to renewable electricity support schemes which have driven down electricity wholesale prices in Sweden and other markets. The Fukushima melt down has brought renewed attention to the dangers of nuclear power.

In light of the nuclear policy reversal and the uncertain future of nuclear power, the main questions are: how much new nuclear power should there be? How will investment, if socially desirable, come about?[1] In a liberalized electricity market, producers invest in capacity if and only if privately profitable. But incumbent owners of Swedish nuclear power may have insufficient investment incentives. Three of the largest power companies in the market, E.ON, Fortum and Vattenfall, share the ownership of all three Swedish nuclear plants and jointly decide about investment. Because of their size, every new reactor lowers market prices. Market concentration implies a risk that investors internalize a large share of the subsequent profit loss on current production resulting from the new reactors. Exercise of such long-run market power leads to underinvestment and excessive electricity prices.

One solution to underinvestment would be to induce the correct amount of investment by an appropriately chosen menu of taxes, subsidies and coercion. An obvious problem is that policy makers lack information about the appropriate level of investment. A second drawback is a political inability to commit to long-term support schemes, which increases the political

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[1] Framing our analysis in the legal context of new nuclear power in Sweden is mainly for illustration. Many of the world's nuclear plants will retire between 2035 and 2050 (Joskow and Parsons, 2012). With the long lead times in planning and construction, how to secure the desired level of investment is a problem nuclear countries like France, the UK and the U.S. need to address in the near future.

risk of the investment. Against this background, market based investments governed by market prices appear particularly appealing. In fact, the inability to centrally plan the socially optimal capacities was one of the main reasons behind Swedish deregulation.

Long-run market power is usually curtailed by imports or by new producers entering the market. But import capacity is limited by bottlenecks in the transmission network. And entry barriers are significant, as incumbent producers in practice control nuclear investments even under the new Swedish legislation: at most ten new reactors can be built, one for each of the reactors currently in operation; a new reactor cannot be set into operation until an old one permanently shuts down; and all new reactors must be located at the three current nuclear sites owned by the incumbent nuclear producers.

We propose nuclear capacity auctions as the key to unlocking the market for nuclear investment. In a nuclear capacity auction, the seller, say a government agency, auctions off a license to build and operate a nuclear reactor. The winner commits to constructing and operating the reactor according to specifications. Compared to a situation where nuclear investment is delegated to incumbents, the auction mitigates long-run market power by introducing competition in the investment stage. Thereby the license may be allocated to a more efficient bidder - either in terms of lower investment costs or because the bidder expects to be able to produce more efficiently than its competitors. The bids also reveal information about the economic viability of nuclear power. In particular, the license remains unsold and no new nuclear power is built if bids are too low (they could even be negative).

An auction is likely to produce a more efficient result the larger the set of bidders because the expected minimum investment cost is lower and bidding competition is fiercer, the more bidders are active in the auction. And the mere threat of entry mitigates incumbents' incentives to bid for market power. Still, producers usually fail to account for the investment's effect on consumer surplus. A bidding consortium of producers and industrial consumers would partly align consumer and producer interests in the bidding process. Thus we recommend to encourage as many bidders as possible to participate in the auction, not only entrants but also incumbents and energy intensive industry, in bidding consortia for nuclear capacity.[2] Joint ownership by incumbent producers exacerbates underinvestment because the

[2] The pro-competitive effects of bidder participation are well-known and hold under general circumstances; see e.g. Milgrom (2004). More generally, our analysis and recommendations lean on a large body of literature on optimal auction design (e.g. Klemperer, 2004, Milgrom 2004). Many of the design issues pertaining for example

opportunity cost of new nuclear power increases. We thus also recommend to avoid the participation of more than one incumbent producer in each bidding consortium, if possible.

Incumbent producers may be willing to pay a premium on the license for the opportunity to exercise short run market power. Incumbents bidding for short term market power distort the auction. The standard remedy is to modify the auction (e.g. Jehiel et al., 1996). We propose a more practical solution: require the licensees to sell a significant share of their capacity as virtual power plant (VPP) contracts. A VPP contract is an option which gives the holder the right to purchase the contracted amount of electricity from the producer at marginal production cost. VPP contracts effectively delegate the production decision to the buyers of the contracts and thereby mitigate short-term market power and the incentives to bid for it.[3]

The profitability of nuclear investment depends not only on market conditions, but also on current and expected taxes. One problem is that policy makers have an incentive to increase taxes once the plant is in operation and investment costs are sunk. Swedish authorities have for instance increased the tax on installed nuclear capacity several times over the years. A novel finding is that investors may protect themselves against tax expropriation by selling long term supply contracts at nuclear marginal production cost *prior* to setting the plant into operation. Long term contracts help investors secure financing of the power plant and simultaneously reduce operating profit susceptible to expropriation.

2. Nuclear power in the Nordic countries

Sweden is part of the integrated Nordic electricity market together with Denmark, Finland and Norway.[4] Bottlenecks in the transmission grid regularly divide the Nordic market into *price areas*. Over the last years, Finland and Sweden usually have formed a joint price area against the other markets. Nuclear power accounts for roughly 20 per cent of installed capacity in the Finnish-Swedish price area, hydro power and thermal capacity other than nuclear account for nearly 40 per cent each. There are also small shares of wind power (NordREG, 2012).

Table 1 identifies the main owners of the five nuclear plants currently operating in the Nordic market, along with the net capacity of each plant (the number of reactors is in parenthesis). All three Swedish plants are owned jointly by two or more large generation companies. This

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to spectrum auctions - how to attract bidders, how to avoid collusion – are relevant also to nuclear capacity auctions. The possibility to attract large industrial consumers as bidders is specific to capacity auctions, however.

[3] Ausubel and Cramton (2010b) discuss VPP auctions at length without relating them to capacity auctions.

[4] The Nordic market is also interconnected with Estonia, Germany, Poland, Russia and The Netherlands.

is not the case in Finland, where Fortum owns Loviisa on its own and Olkiluoto jointly with the energy intensive industry: Pohjolan Voima is controlled by the pulp and paper manufacturers United Paper Mills and Stora Enso.

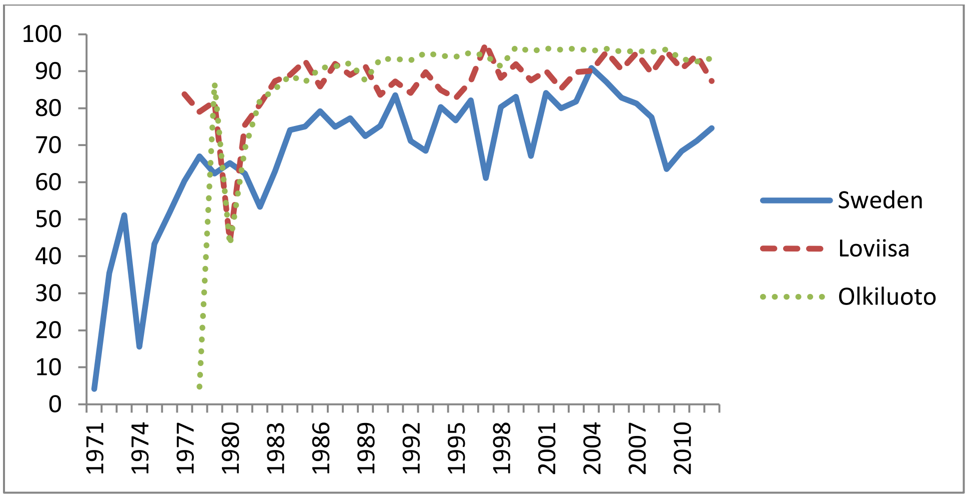
Table 1: Ownership shares of Nordic nuclear power

	Sweden			Finland	
	Forsmark	Oskarshamn	Ringhals	Loviisa	Olkiluoto
E.ON	10	55	30	-	-
Fortum	22	45	-	100	27
Vattenfall	66	-	70	-	-
Pohjolan Voima	-	-	-	-	57
Capacity - MWe	3138 (3)	2311 (3)	3702 (4)	1156 (2)	1540 (2)

Source: The websites of the respective nuclear plants.

The two reactors at the Barsebäck plant were shut down 1999 and 2009 as a consequence of the Swedish decision to abandon nuclear power. Finland has remained generally positive to nuclear power and has instead decided to expand nuclear production. A third reactor is under construction at the Olkiluoto site, and the Finnish government has recently authorized the construction of two new reactors. Estimates of the remaining lifespan of the above reactors range between 40 and 60 years. Several of them therefore are likely to be phased out by 2030.

Figure 1: Nuclear capacity utilization Sweden versus Finland 1971-2012



Source: IAE- PRIS database. Data from the closed Swedish plant Barsebäck are excluded.

Operating performance displays significant variation between the different plants. Figure 1 reports annual capacity utilization of the ten active Swedish reactors compared to the two

Finnish plants. The volatility over the first years stems from the fact that most reactors were phased-in during that period. Swedish nuclear power has systematically underperformed relative to the two Finnish plants, and predates market liberalization in 1996. From 1981 and onwards, annual capacity utilization in the Swedish plants on average was 16.68 percentage points lower than in Olkiluoto. This amounts to a full reactor of the size currently under construction at Olkiluoto, assuming a capacity utilization of 87 per cent. Note also that Olkiluoto has outperformed Loviisa for most of the period since 1981. The average difference in capacity utilization is 3.38 percentage points.

3. Incumbents' incentives for investing in nuclear power

Our analysis rests upon the assumption of profit maximizing firms. Management therefore exercises market power to its full extent within the company's legal boundaries. Nuclear power represents the archetypical base load generation: operating costs are relatively low and consist mainly of fuel costs, maintenance and nuclear waste management. Capital costs, most notably associated with construction and decommission, represent the major portion of the levelized cost of nuclear power.[5] Because electricity prices usually exceed nuclear marginal cost and nuclear power often represents a minor source of total production capacity, one would expect the exercise of short-term market power, whereby nuclear production is reduced momentarily to raise the price of electricity, to be infrequent. Consistent with this view, Davis and Wolfram (2012) find high capacity utilization in U.S. nuclear power plants operating in deregulated wholesale electricity markets.[6]

Market power concerns are prevalent in the *long run* when owners must decide how much to invest in new production capacity. In a competitive market, all firms take the price as given and increase capacity until the cost of producing one additional unit of the good – *the long-run marginal cost* – equals the price. A firm exercising market power instead accounts for the price drop following capacity expansion. The value of incremental capacity – *the long-run marginal revenue* – therefore is lower than the price. Exploitation of long-run market power thus leads to underinvestment. In a long-run competitive market, market power is mitigated by entry or by imports. Public opposition to nuclear power and to the exploitation of unexplored river basins have provided entry barriers to the development of new nuclear and

[5] Du and Parsons (2009) estimate operating costs of new US nuclear power to be 1.8 ₵/kWh, while the capital cost estimate is in the range 4.8-6.6 ₵/kWh. Nuclear taxes further inhibit the profitability of investment and are likely to change over time. We consider the implications of tax uncertainty for nuclear investment in Section 4.3.
[6] This finding does not imply that short term market power never is a concern; see Section 4.2 for a discussion.

large scale hydro production in Sweden. And import competition is limited by the capacity of the international transmission interconnections under monopoly control of Svenska Kraftnät, the Swedish Transmission System Operator. Entry barriers suggest strong possibilities for exercising long-run market power in the Swedish electricity market. Hence, we assume that incumbents possess and exercise long-run market power in their investment decision throughout the paper.[7] Our purpose is to study how a nuclear capacity auction may facilitate investment by reducing entry barriers.

Figure 2: Nuclear investment incentives

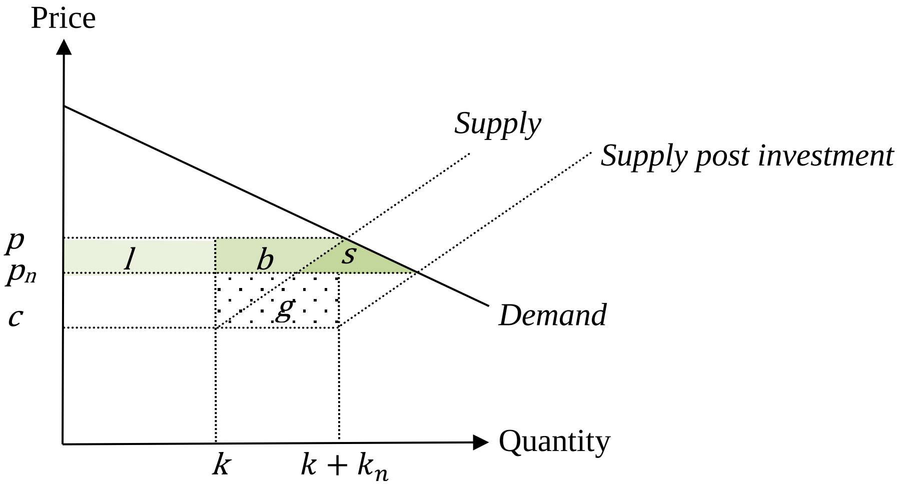


Figure 2 illustrates in a parsimonious model the trade-off between price and capacity in the incumbent's decision to invest in new nuclear power. The demand and supply schedules are for a representative year. The incumbent owns a generation portfolio, for example old nuclear plants, producing base-load electricity at constant marginal cost c up to the capacity k. Additional consumption is covered by increasingly costly peak-load production. Supply equals the marginal cost curve if the market is competitive in the short run. The market-clearing price equals p. The yearly operating profit of the generation portfolio is $(p - c)k$.

[7] Empirical research on long-run market power in electricity markets is scarce, not least on the Nordic market. One explanation could be measurement problems. Typical measures are based on the wedge between price and marginal cost. To estimate long-run marginal cost, one has to estimate the competitive returns to capital. Estimates based upon historical data are of limited value, either because historical returns reflect market power or because they reflect regulatory policy when estimated on pre-liberalization data. The typical approach, and the one adopted by studies estimating investment costs, uses an arbitrary rate of return, say 10 per cent. Whether this rate of return appropriately reflects risk is unknown. Political entry barriers limiting large scale hydro and nuclear investments have increased capital returns in the Swedish market, thereby exacerbating the problem of estimating market power.

Consider the decision to increase capacity by a modern reactor of capacity k_n. Supply shifts outward, the price falls to p_n and operating profit becomes $(p_n - c)(k + k_n)$. The dotted area $g = (p_n - c)k_n$ represents the profit gain from additional capacity, the light shaded area $l = (p - p_n)k$ the profit loss the incumbent suffers on installed capacity due to the lower electricity price. Nuclear reactors have a technical lifetime of 50 years or more. Let G be the expected net present value (ENPV) of g, and L the ENPV of l. The investment is profitable if the ENPV of the net profit increase covers the investment cost: $G - L \geq F_I$. The investment has consequences beyond the profitability of nuclear power. The price reduction from p to p_n inflicts a loss on yearly peak-load production equal to the darker area b with an ENPV of B, while consumer surplus increases by $l + b + s$ with an ENPV of $L + B + S$.

The net welfare effect of the investment equals the net increase in consumer surplus, S, plus the increase in nuclear operating profit, G, less the investment cost, F_I. The terms $L + B$ represent pure redistribution from producers to consumers and have no welfare effect. Market power leads to underinvestment because incumbents fail to internalize the positive effect, S, on consumers, but account for the redistributive effect, L. In particular, investments by the incumbent are socially desirable, but privately unprofitable if

$$G - L < F_I < G + S. \qquad (1)$$

Underinvestment is more severe the larger the incumbent's generation portfolio, as L increases. Joint ownership of the nuclear plants by the three largest electricity producers in Sweden further exacerbates underinvestment because all owners are likely to internalize profit losses on their generation portfolio.

To illustrate the magnitudes involved, consider a hypothetical investment by Vattenfall in a reactor of the same type as Olkiluoto 3. With an installed capacity of 1600MWe, the reactor's yearly output is $k_n = 12.6$ TWh at 90 per cent capacity utilization. If operating profit is 30 Euro per MWh, net of taxes, then $g = 378$ million Euro. With an expected life span of 60 years and a real discount rate of 5 per cent, the ENPV of the reactor is approximately $G = 7.2$ billion Euro (bEUR). To estimate the associated loss, L, on installed capacity, let current hydro capacity (or upgrades of it) remain operational for the life span of the new reactor, with annual production of 33 TWh – Vattenfall's hydro output in 2012. Assume that the new reactor becomes operational in 2026, and that 5 out of Vattenfall's 7 Swedish nuclear reactors operate for ten additional years, with a yearly output of 35.5 TWh.[8] If the Swedish wholesale price of electricity drops by 1.25 Euro per MWh subsequent to investment, then Vattenfall's annual loss on installed capacity will be 85.6 mEUR during the first ten years and 41.3 mEUR the fifty subsequent years. This yields a discounted loss of $L = 1.1$ bEUR, or 15 percent of the investment value.[9]

In a market with free entry, an entrant planning a nuclear facility with capacity k_n would internalize the increase, G, in producer surplus, still would not care about the consumer gain S, but neither the profit loss L. Entry is profitable if G is large enough to cover the entrant's investment cost: $G > F_E$. Note also that the mere threat of entry could be enough to induce investment. By investing k_n in additional capacity, the incumbent recovers G and does not only suffer the loss L. Under the assumption that capital costs are the same for the entrant and the incumbent in the numerical example, entry would generate socially optimal investment for capital costs in the range 6.1 to 7.2 bEUR. The relevance of these numbers are illustrated by the large investment cost uncertainties. The recent cost estimate for Olkiluoto 3 of 8.5 bEUR is largely due to delays and cost overruns. The original contract was for 3.2 bEUR.[10]

Entry generates potential welfare gains other than mitigating long-run market power. In a competitive market, entry occurs and is successful if and only if entrants are more efficient than the incumbents, either in terms of lower investment costs ($F_E < F_I$) or because they produce more efficiently. The low capacity utilization in Swedish nuclear power plants (see Figure 1) also suggests a potential for improved productive efficiency through entry.

The Swedish Parliamentary decision in 2010 to allow the replacement of the old reactors by new ones does little to reduce entry barriers. There are firm restrictions on the number of new reactors, the locations and when they are allowed to be put into operation. Effectively, nuclear investment still remains in the hands of E.ON, Fortum and Vattenfall. We propose nuclear capacity auctions as a key to unlocking the market.

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[8] Vattenfall estimates that Ringhals 1 and 2 will be decommissioned after 50 years of operation, that is in 2026. The other 5 reactors are younger, and Vattenfall estimates their life span to 60 years. (Source: Press release on May 22, 2013 retrieved from Vattenfall's website.) If the latter estimate is correct, then the younger reactors will operate for at least 10 years beyond 2026. Vattenfall's total nuclear output in 2012 was 43.5 TWh, out of which Ringhals 1 and 2 contributed about 8 TWh. Assuming that the yearly expected production in the other reactors is the same as in 2012 gives residual nuclear production of 35.5 TWh per year.

[9] 12.61 TWh amounts to an 18 per cent increase in Vattenfall's production relative to 2012, excluding the output in Ringhals 1 and 2. The assumed price drop is 2.5 per cent and implies that Vattenfalls's residual demand curve has a price elasticity above 7. Total demand elasticities are usually estimated well below 1. The assumed price drop thus presumes that the supply of Vattenfall's competitors is very elastic.

[10] www.world-nuclear.org/info/Country-Profiles/Countries-A-F/Finland/, June 28, 2013.

4. A nuclear capacity auction

A nuclear capacity auction sells the license to build and operate a nuclear reactor at a specific site to one of several bidders. Consider a set of J potential entrants bidding for the license to replace an old reactor with a modern one, assuming the old reactor is decommissioned by the time the new one starts operating. Assume that all investors would run the new reactor competitively. Operating costs depend primarily on fuel costs, which are fairly stable and predictable. Hence, we assume that the ENPV of operating profit, G, is known and the same for all bidders. The viability of new nuclear power depends crucially upon capital costs. These costs have escalated over time, partly due to stricter safety standards but also because the costs of large scale engineering projects have increased substantially. The ability to complete a project in time and at required specifications is crucial and probably varies across bidders. We therefore assume that bidder $j \in J$ has investment cost F_j and values the license at $G - F_j$. A purpose of the auction is to elicit information about investment costs.[11]

We use the Vickrey auction to illustrate the economics of the nuclear capacity auction. In a Vickrey auction, the license is sold if and only if at least one bid exceeds a threshold, the *reserve price*. The license goes to the highest bidder at the price of the second highest bid or the reserve price, whichever the highest. Bidding the true valuation is a dominating strategy in the Vickrey auction. Consequently, the license goes to the entrant with the lowest investment cost, F_E, if sold. The auction selects the most efficient bidder but is not necessarily optimal as entrants do not account for the increase in consumer surplus, S, arising from increased production. A negative reserve price, $b^* = -S$, ensures however that the investment is undertaken if and only if socially desirable as $G - F_E \geq b^* \Leftrightarrow G + S \geq F_E$.

The above auction is socially optimal (in a partial equilibrium sense) and illustrates how a nuclear capacity auction can improve welfare relative to a policy delegating the responsibility of building and operating new nuclear power to an incumbent. One problem is that b^* is unobservable to the seller, not least because the reserve price must be evaluated at the post-investment price, p_n.[12] Another drawback is that the auction may generate very low revenues (as in the spectrum auctions in New Zealand). In fact, the investment could even be

[11] As there are as many as ten licenses up for sale, the seller conceivably could sell multiple licenses in the same auction and even bundle them together. Given the economic magnitudes and uncertainties involved, the bidding process probably reveals important information about the profitability of nuclear investment. Owing to this price discovery process, we envision sequential auctions of single licenses to be the most practical. But we acknowledge that it could be optimal to bundle site-specific licenses if they display complementarities.

[12] The reserve price could of course build on an estimate of S.

subsidized as $b^* < 0$. Swedish law, however, precludes subsidies to nuclear power and therefore we simply assume that the reserve price is zero.

The Vickrey auction with zero reserve price produces the social optimum if the investment is privately profitable, $F_E \leq G$, or socially unprofitable, $F_E > G + S$. Entrants' previous experience in building and operating modern reactors yields a competitive advantage, a factor which may be particularly important for Sweden where two of the current owners have no such experience. But it is also conceivable that incumbents have lower capital costs than the other bidders ($F_I < F_E$) because of scale returns to operating multiple reactors on a single site, or superior knowledge about site specific constraints, local regulations and overall market conditions.[13] Let therefore the incumbent participate in the auction. Also assume that the incumbent knows whether $G > F_E$ (or infers so upon observing that entrants are preparing bids). Provided $G > F_E$, the incumbent's relevant alternative to winning the license is that the entrant does so, and therefore the incumbent bids $G - F_I$ and wins the license if and only if $F_I < F_E$. (If $G < F_E$, the incumbent's investment incentives are the same as in the previous section. In this case the capacity auction has no welfare effect besides the cost of setting it up). Underinvestment occurs from a welfare viewpoint if and only if

$$G < \min\{F_E; \mathrm{F_I}\} < G + S. \qquad (2)$$

The auction improves welfare compared to the default situation in (1) where the incumbent controls the investment. The incumbent no longer internalizes the pure redistribution loss L because of the threat of entry. And the expected minimum investment cost is lower and bidding competition fiercer, the larger the set of bidders.

The fact that no bidders internalize the consumer surplus increase S remains problematic. Encouraging energy intensive industries to participate in bidding consortia could mitigate underinvestment. Energy intensive industries are valuable owners of nuclear power plants as they internalize consumer surplus, not only operating profit. The least-cost entrant values the investment at $G - F_E + \alpha(L + B + S)$, where α depends on consumer ownership share, the perceived probability that the nuclear power plant is not built and electricity demand. If all bidders have formed symmetric bidder consortia, then the reactor is built by the least-cost

[13] A comparison between U.S. and French nuclear power shows that construction costs were smaller in France where reactor designs were more standardized, nuclear sites had multiple reactors and were operated by a single owner (Grubler, 2010). This evidence suggests a cost advantage of operating multiple reactors on a single site.

consortium if $\min\{F_E; \mathrm{F_I}\} \leq G + \alpha(L + B + S)$. Private and social preferences are aligned in this (very) parametric case if $\alpha = S/(L + B + S) \in (0,1)$. The value of including industrial consumers, measured by α, increases when the investment's net effect on consumer surplus, S, is stronger. As an added benefit, expected auction revenues are higher as valuations increase when bidders internalize the consumer surplus. And the high capacity utilization in Olkiluoto relative to Loviisa, see Figure 1, suggests a potential for improved productive efficiency through consumer ownership.

Recommendation 1: Encourage as many serious bidders as possible to participate in the nuclear capacity auction: incumbents, entrant utilities and energy intensive industries.

A serious bidder is an investor, or consortium of investors, with project proposals that meet relevant safety standards and with a credible commitment to safely dispose of radioactive waste. Investors must also have the financial resources to build the new reactor, operate (or subcontract) it according to market regulations and decommission it in a proper manner. A fairly large number of utilities worldwide have established track records for the safe and efficient operation of nuclear power plants. In Europe, these include EDF, Electrabel (GDF-Suez) and RWE. The energy intensive industry sometimes holds ownership shares as in Olkiluoto. A consortium of large Swedish industrial consumers, Industrikraft i Sverige AB, has stated an interest in investing in new nuclear power plants in Sweden.

Project preparation is expensive and time consuming. Reducing project costs increase the attractiveness of the auction, the number of bidders, and thereby auction performance. To minimize bidder costs, investors should be subject to a transparent approval process prior to their acceptance. The rules of the auction should be clear and communicated well in advance. All aspects of project planning related to grid investment should be carried out by the system operator, which also avoids costly duplication.[14] A significant part of project planning falls upon the nuclear power plant manufacturers who could be involved in several consortia. The project risk facing the individual manufacturer might be substantially smaller than the risk taken by individual bidding consortia, which serves to reduce participation costs further.

Joint ownership of production capacity implies that owners would like to internalize parts of profit loss B on other production in the investment decision; see Figure 2. Incumbents fail to

[14] Svenska Kraftnät has started to investigate the transmission requirements for new reactors in Sweden.

internalize this loss for the same reason they fail to internalize L if entrants participate in the auction. But if incumbents are the only participants, then joint ownership is likely to reduce auction efficiency through collusive bidding. In fact, the need for replacing the old reactors creates an opportunity to dissolve the current ownership structure in the Swedish nuclear plants. As an added benefit, this would increase competition in the auction by adding several incumbents to the stock of bidders.

Recommendation 2: Ideally, each bidding consortium should contain at most one incumbent producer as a major stakeholder.

Producers may prefer joint ownership of nuclear reactors for reasons other than internalization of profit losses. It can represent a risk-sharing mechanism in case of accidents or unexpected break-downs. But other solutions, such as nuclear pools wherein a larger set of producers shoulder the financial burden of nuclear disaster, appear superior in handling risks. Another motivation can be the magnitude of the investment. But in a global market, there is no reason why capital necessarily should be raised jointly by incumbents. A counterexample is China Guangdong Nuclear Power Company which has expressed an interest in a minority stake in EDF's planned nuclear reactors in the U.K. Joint ownership with the industry represents another attractive possibility. Either way, reactors are built without the involvement of multiple large incumbent producers, one of them being the Olkiluoto plant in Finland.

The outcome of the nuclear capacity auction may imply that entrant(s) operate some reactors at a site while the incumbent operates others. Mixed operation should not cause substantial problems under normal operating conditions as transmission would be optimized to handle full capacity utilization of all reactors. Transmission bottlenecks may call for a coordinated down regulation at a site. But a market mechanism, the real time market, is in place to handle interruptions efficiently. Another concern might be that multiple owners find it difficult to cooperate on sharing onsite safety equipment. But it would be in the long-term interest of owners to ensure a safe operation of all reactors because all of them are stuck in the same boat. Reactor-specific operating responsibilities may even provide a benchmark against which to compare individual reactor performance.

Construction delays are common, not least for innovative reactor designs.[15] In light of these uncertainties, reactor replacement should be spread over time to minimize shortage risk and excessive prices. Coordinating the substitution of old reactors for new ones is facilitated if reactors are owned by incumbent producers. Also, delays would be less of a problem in an integrated market as the production in one reactor then plays less of a role for total supply.

An old reactor's remaining life time is uncertain and continued operation may be possible when the new reactor is built. An incumbent can inflict a serious loss on entrants by maintaining operations in an old plant, because the Swedish legislation forbids a new reactor to be put into operation until an old one shuts down. Continued production is credible because the opportunity cost to the incumbent is zero. Strategic deferral undermines the auction as no rational entrant would bid anything under those circumstances. The legal requirement that all new reactors must be built at a current site probably implies that they represent *essential facilities* under Swedish competition policy. Hence, current owners could be legally forced to relinquish control of their sites in exchange for a reasonable compensation. Ideally, the compensation should be based upon the ENPV of continued operation. Applying this criterion is difficult as the incumbent presumably has incentives to exaggerate the value of continued production so as to extract rents from the entrant or to deter entry. In practice, excessive compensation may well be less of a problem. Most of the reactors will probably be close to the end of their expected life time when they are up for replacement and therefore the value of continued production ought to be low.

4.1. Safety considerations

As the nuclear accidents in Three Mile Island, Tchernobyl and Fukushima have reminded us, safety is fundamental to the socio-economic viability of nuclear power. Projects should be required to meet strict safety regulations before being allowed to enter into the auction. In practice, there will only be a handful of relevant designs to consider because manufacturers develop standardized reactors as a response to global safety requirements and R&D costs. Cutting safety corners comes at considerable financial risk as regulators could introduce new regulations or delay construction. The closure of the Shoreham nuclear power plant in 1989, which was ready to but never allowed to produce electricity, shows that regulators can even terminate projects if safety concerns become serious enough.

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[15] An illustrative case in point is the new generation III+ reactor at Olkiluoto. It was originally scheduled to start operation in May 2009, but could be delayed until 2016 by the owner's latest assessment (www.tvo.fi/news/32, retrieved June 20, 2013).

Swedish power plants pay a production tax and plant specific fees to cover nuclear waste storage costs. The Swedish Parliament is processing a law which will demand full liability for all costs arising from nuclear accidents. A substantial part of expected environmental cost thus should be internalized in operating and capital costs. Nuclear safety depends on crucially upon management. Hausman (2013) investigates the effect of deregulation in the U.S on nuclear safety and finds an economically (although not always statistically) significant reduction in safety incidents. As deregulation had a positive impact on nuclear capacity utilization (Davis and Wolfram, 2012), these results suggest that safety and nuclear operating performance are complements. Competition to build new nuclear power could thus improve safety insofar as bidding competition selects the most efficient producers.

4.2. Short-term market power

A fundamental problem is that incumbent producers have an incentive to underinvest in new nuclear power to maintain profitability on their remaining production portfolio. Entrants would profit from a larger investment because they do not suffer any profit loss on installed capacity. Incumbents thus prefer to enter the nuclear capacity auction with a relatively small project. But small projects run a risk of being outperformed by larger projects in the auction.[16] Projecting a reactor of the same size as the competitors could be the only option for an incumbent to preempt entry. As the winning incumbent then would possess a reactor of excessive size for its own purposes, it has an incentive to raise profits by reducing output *ex post*, i.e. exercise short-term market power. Also, investment is based on expected, and not realized outcomes. Demand fluctuations, transmission bottlenecks and hydro inflow regularly create conditions under which it would be optimal to exercise nuclear market power. We now analyze the consequences of short-term market power for nuclear capacity auctions.[17]

It may sound counterintuitive to exploit market power by withholding nuclear production. But some producers have no other option. Vattenfall mainly keeps hydro, nuclear and wind power in its Nordic portfolio. Wind power has a lower marginal cost than nuclear power, and spilling water is illegal. Nuclear withholding occasionally *is* the cheapest way of exploiting market power. Plants typically shut down for maintenance and reloading in off-peak periods. Rather

[16] In general, the auction would select between differentiated projects. Asker and Cantillon (2008) show that scoring auctions typically outperform alternative auction formats. In a scoring auction, the seller scores each project based on a ranking of the different attributes and awards the license to the bidder with the highest score relative to the price. A higher reactor capacity is an attribute which should increase the score of the project.
[17] Obviously, the concerns and remedies we identify in this section apply to all kinds of capacity auctions, and are relevant also for capacity auctions of peak demand generation currently under discussion in Europe.

than starting a nuclear reactor and shutting down other production, it is cost efficient to *prolong* maintenance stops. This is particularly profitable in a hydro-nuclear power system because storage effectively allows the owner to transfer nuclear market power from off-peak to peak demand. Finally, nuclear market power is difficult to detect. Standard measures rely on differences between price and marginal cost. But nuclear power is base-load and usually priced above short-term marginal cost at competitive equilibrium. Also, it is easy to mask capacity withholding as something else, for example safety concerns.

Assume that an incumbent owns two reactors with joint capacity $k_1 + k_2$. Reactor 2 is up for replacement by one with capacity $k_n > k_2$. Market performance depends on whether the license is acquired by the incumbent or an entrant. For the reasons discussed above, assume that replacement capacity is so high that the incumbent would exercise market power. Let $\pi^m = (p^m - c)q^m$ be the incumbent's annual operating profit, where q^m is output, p^m the electricity price, and c marginal production cost, which for simplicity is the same in reactor 1 and the new one. Competition ensues if an entrant wins the license. Aggregate nuclear production is higher, $q^d > q^m$, the electricity price lower, $p^d < q^m$, and industry profit lower, $\pi^d = (p^d - c)q^d < \pi^m$, under duopoly. Each duopolist earns $\pi^d/2$ by assumption.

Let operating profit be sufficient to cover the entrant's levelized capital cost: $\pi^d/2 > f_E$. The incumbent's corresponding valuation of the license is $\pi^m - f_I - \pi^d/2$ because entry is the relevant alternative to winning the auction. The auction awards the license to the bidder with the highest valuation, so the incumbent wins if and only if

$$\underbrace{\pi^m - \pi^d}_{Market\ power} + \underbrace{f_E - f_I}_{Cost\ advantage} > 0. \qquad (3)$$

The first term in (3) represents the value of market power. It could be so high that the incumbent wins the license even if at a cost disadvantage in building the new facility. Nuclear power is monopolized instead of exposed to competition, and it is more costly than necessary to build the new plant. We propose virtual power plant contracts as a solution to this problem.

Suppose the licensor requires whomever wins the license to sell the full capacity k_n as virtual power plant (VPP) contracts.[18] A VPP contract is a call option which gives the holder the

[18] VPP contracts were first used in France in 2001 when the dominant producer EDF was forced to sell nuclear capacity in this manner. In the Nordic market, the Danish producer DONG regularly auctions off 600 MWe in the price area Denmark West where it holds a dominant position; see www.nordpoolspot.com/TAS/VPP-

right to purchase the contracted amount of electricity from the producer at strike price c. If the entire capacity k_n is sold as VPPs and exercised, then total nuclear production increases to $q^v > q^d > q^m$, and the price falls to $p^v < p^d < p^m$ because competing production is reduced less than one-for-one. This happens independently of who actually owns the new reactor.

An incumbent who wins the license retains the operating profit $\pi_1^v = (p^v - c)q_1^v$ in reactor 1, where q_1^v is equilibrium production at p^v. The profit from selling VPPs is $\pi_2^v = (p^v - c)k_n$ because the value of a single option with strike price c is $p^v - c$. An incumbent who loses the auction to an entrant earns π_1^v. The incumbent's valuation of the license becomes $\pi_1^v + \pi_2^v - f_I - \pi_1^v = \pi_2^v - f_I$. The entrant's valuation is the profit of selling the k_n VPP contracts less the investment cost: $\pi_2^v - f_E$. The incumbent wins the auction if and only if

$$\pi_2^v - f_I > \pi_2^v - f_E \Leftrightarrow \underbrace{f_E - f_I}_{Cost\ advantage} > 0.$$

VPP contracts for the full capacity of the new reactor have eliminated the value of market power present in (3). VPP holders de facto determine production in the new facility. A small buyer without market power exercises the option if the expected price of electricity is higher than the strike price c. Hence, there is no market power to bid for.

Recommendation 5: Require owners of new nuclear capacity to sell a substantial share of their capacity as virtual power plant contracts.

Bidding for market power vanishes when options are exercised non-strategically and all new capacity k_n is contracted. A competitive VPP market appears reasonable because entry costs are small and buyers can contract on small volumes. The set of potential bidders is large: VPPs present an opportunity for new producers to gain a foothold in the market and for large industrial consumers to hedge electricity consumption. In practice, the contract volume is likely to be below the full capacity. If so, the incumbent may exercise market power on the share which is not sold as VPPs. Some buyers may also be able to amass a significant share of contracts if the market is thin. Incumbent producers in particular may pay a premium for VPP contracts to preserve market power and should probably not be permitted to participate.

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auction/. Ausubel and Cramton (2010b) give a detailed account of VPP auctions. They note that VPPs have accounted for small shares of the dominant firms' capacity and suggest that it would be difficult to increase that share. But VPP obligations have so far only been imposed on existing capacity and as such constitute an infringement on property rights. We propose to introduce VPPs ex ante, before property rights are allocated through the nuclear capacity auction. Presumably it would be easier to impose VPPs ex ante than ex post.

In general, VPP contracts reduce the value of bidding for market power and eliminates this motive in the limit when the entire capacity is contracted. In principle, the share of VPP contracts could be allowed to differ between incumbents and entrants. An entrant without market power should not be affected by VPPs. Under perfect competition VPPs simply have no welfare effect besides the cost of setting them up. The licensor should thus decide the share of VPPs primarily with an eye to the incumbent's incentive to exercise market power.

The price reduction triggered by VPPs could be so large as to render investment unprofitable. If $\pi_2^v < f_E < \pi^d/2$, then the incumbent wins the license by default since the entrant does not participate in the auction. If also $\pi^v < f_I$, the incumbent abstains from bidding and monopoly prevails. The entrant would participate absent any VPPs and win the license if also (3) was violated. This drawback with VPPs hinges on the assumption of fixed capacity. In practice, entrants are likely to adapt the size of their project, which would facilitate entry.

A solution where incumbents control all nuclear power but sell capacity under VPP contracts might seem a superior alternative to nuclear capacity auctions. VPPs promote competition by limiting short run market. Under this alternative setup, the incumbent still could exercise long run market power by underinvesting in capacity. And the solution foregoes the possibility of investment by more efficient entrants. We view VPPs and nuclear capacity auctions as complements rather than substitutes.

4.3. Tax expropriation

Swedish nuclear plants are subject to a nuclear tax in addition to the general property tax and a tax on nuclear waste. In 2000, it shifted from a production tax to a tax on installed capacity and has increased on several occasions since then. Consider a nuclear plant operating at full capacity k with constant (short-run) marginal cost c, selling at price $p > c$. Net profit equals operating profit $(p - c)k$ less the capacity tax tk. Capital costs being sunk, the government can expropriate the entire operating profit by raising the nuclear tax *ex post* until $t = p - c$. A private investor anticipating zero operating profit would stay out of the market. But the return on the investment is unaffected by the tax if nuclear power is state-owned. Net nuclear profit equals $(p - c)k - tk$, but is offset by tax revenue tk, so that the state earns $(p - c)k$ in total.

State ownership can be a prerequisite for investment in industries where tax expropriation is expected to constitute a major problem.[19] But diversified ownership is desirable, because it promotes investment and improves competition. Hence, short-run gains of tax expropriation probably are offset by the long-run costs of market concentration and foregone investment. Thus it is in the government's self-interest to promote instruments that reduce expropriation. Long-term supply contracts constitute one such potential instrument.

Suppose private investors, prior to building the power plant, sell long-term supply contracts for x MWh electricity in the form of options with strike price c per MWh. When the plant becomes operational, it makes zero operating profit on the x MWh of energy sold at marginal cost c. The operating profit available for tax expropriation from the nuclear owners thus falls to $(p - c)(k - x)$. In the limit when the supply contracts cover the entire production, $x = k$, no operating profit remains for expropriation. The revenue from selling the supply contracts can be used to finance the construction of the nuclear power plant.

If the state can equally well expropriate contract owners, then long-term supply contracts cannot overcome tax expropriation of nuclear owners. But in many cases, buyers would be energy intensive industries with a desire to hedge their electricity consumption. Insofar as these industries are more prone to move operations abroad, they probably are economically and politically more difficult to expropriate. Moreover, long-term supply contracts are only one of several instruments consumers can use to hedge their electricity consumption. Tax expropriation would be further limited if, for legal reasons, it is difficult to tax discriminate between different financial instruments. In the limit, as tax expropriation of buyers becomes impossible, producers can avoid tax expropriation by selling the entire production up front.

5. Conclusion

We propose nuclear capacity auctions as a means to improve investment incentives. In particular, capacity auctions open the market for large-scale entry by outside firms. While capacity auctions specifically for nuclear power have not been done before, they are not conceptually new. Brazil, Chile, Colombia and New England (Ausubel and Cramton, 2010a; Moreno et al., 2010) auction long-term supply contracts with the purpose of ensuring adequate reserve capacity for periods of scarcity and stimulating investments more generally.

[19] We restrict attention to nuclear capacity taxes. Himpens et al. (2011) analyze commitment problems in relation to nuclear production taxes. They propose nuclear capacity auctions, too, but as a means to raise government revenue beyond what is possible by production taxes alone.

Markets for reserve capacity are under discussion in several European countries. The spot market for electricity alone is thought to provide insufficient investment incentives for reserve capacity because price ceilings or interventions prevent spot prices from reaching the levels necessary to render investment profitable.

Because nuclear marginal production cost is low relative to market prices, and provided nuclear power owners act competitively in the short run, reactors will produce at full capacity most of the time. Thus, new nuclear power would be profitable at prices way below any price ceiling. Instead, investment incentives are distorted because of long-run market power, entry barriers and political risk. This paper has sketched some desirable properties of nuclear capacity auctions. More work needs to be done in pinning down the specific details of the auction design. In our view, a key factor to attract investors is a long run commitment to a nuclear policy which enables entrants, not only incumbents, to profitably invest in nuclear power. Organizing nuclear capacity auctions would contribute to such a commitment.

Acknowledgements

We are grateful to Cedric Argenton, Peter Cramton, Leigh Hancher, Bert Willems, two anonymous reviewers and seminar participants at IFN and TILEC for their comments. This research was financed within the IFN program "The Economics of Electricity Markets".

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