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Optimal regulation of energy network expansion when costs are stochastic☆

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ABSTRACT

We analyze optimal regulation of the gradual investments in energy networks necessary to accommodate the energy transition. We focus on a real option problem where costs of new network technology are stochastic and not observable to the regulator. We solve for the regulatory scheme that optimally balances timely investments with rent extraction in this dynamic agency context. We then apply this methodology to a situation in which investment can be either in traditional network technology, with observable costs, or using an innovative network technology for which there is asymmetric information on costs. The optimal choice trades off the potential benefits of cheaper expansion with the costs of overcoming information frictions.

1. Introduction

The transition to a more environmentally friendly energy market requires large investments, not only by competitive energy producers, but also by monopolistic firms owning and operating power and gas grids. For example, to accommodate large amounts of small-scale renewable electricity production at consumers' homes (such as solar panels, micro-CHPs), system balancing functions may have to be decentralized in smart grids, that require deployment of new technologies. Bertolini et al. (2018), for example, study how smart grids facilitate investment in domestic solar panels, while Sidhu et al. (2018) explore the costs and benefits of introducing energy storage in the grid, allowing better accommodation of distributed generation. Likewise, a choice for carbon capture and storage will require investments in pipeline infrastructures to transport the greenhouse gas from its industrial sources to storage locations. And large scale deployment of electric vehicles necessitates more elaborate infrastructure for roadside charging.

A common characteristic of these new infrastructures is that they are still under development. As in all new technologies, costs for deployment are expected to fall in the longer run as more experience is gained, but their evolution will be

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uncertain in the shorter run (EPRI, 2011; Sidhu et al., 2018). Also, investments in the new energy systems will be made progressively, starting at those locations with high benefits, and expanding as costs are reduced. Optimal investment will occur gradually, taking into account the option value of waiting for improved information on costs. Such investment problems are well described by real options, in particular with ongoing expansion opportunities such as pioneered in e.g. Pindyck (1988).

The speed at which network firms will adopt such new technologies will, however, not only be guided by changing costs and societal benefits. The energy and network owners are natural monopolies, and they are typically regulated by the government. The regulatory frameworks that these firms operate in will determine their allowed revenues, and therefore will also affect their investment behavior (Cambini et al., 2016).

In this paper, we analyze the problem of optimal regulation of long-run infrastructure investment processes in the presence of asymmetric information on costs. To do so, we consider a real option model with continuous investment in a dynamic principal-agent setting. The network firm, who is the agent, privately observes the stochastic investment costs, and decides on its investments. The government regulator, who is the principal, does not observe the stochastic costs, but can observe capacity built by the network. The regulator will determine the allowed revenues (consisting of a set of capacity dependent fees), which will drive the network's investment behavior. We ask what set of fees the regulator should set to elicit social surplus maximizing investment behavior as these unobserved costs fall stochastically.[1]

In the absence of information asymmetry, the real option problem of finding surplus maximizing investment was studied by Pindyck (1988) (see also Dixit and Pindyck, 1994, chapter 11), who showed that capacity should be expanded whenever costs drop below a capacity dependent threshold: the higher capacity, the lower costs need to fall to increase that capacity further. Dobbs (2004) considered the regulatory problem of incentivizing investment by a monopolist using price cap regulation, but did not specify the asymmetry of information that necessitates such regulation. Moretto et al. (2008) investigate how various regulatory schemes compare in real option investment timing. Guthrie (2006) provides a survey of such applications of real options investment in regulation contexts.

Regulation of discrete, lumpy investment was studied from a mechanism design perspective in Broer and Zwart (2013), who assumed static asymmetric information on a constant cost level. There, the stochastic variable, demand, was assumed to be observable by both regulator and the monopolist. An extension to continuous investment in network expansion was considered in Willems and Zwart (2018), who in addition looked at a financing constraint requiring the investments to be paid out of usage fees on an ongoing basis.

Our first contribution here is to address the regulatory problem with *dynamic* asymmetric information: the regulator cannot observe costs which are continuously evolving. We use the framework for dealing with such dynamic adverse selection in continuous-time real options models developed in Arve and Zwart (2016). Related techniques were explored in Bergemann and Strack (2015); Maeland (2006). In previous real options applications, discrete investments were considered. In this paper we demonstrate how the methodology can be expanded to deal with continuous investment models.

We then apply this methodology to study how optimal regulation should drive investment in a greenfield situation, where there is a choice between a traditional technology, with publicly observable costs, and an innovative technology with asymmetric information on stochastic costs. In either case, an initial investment will be made; after that the network will be gradually expanded as costs (which for the innovative technology are unobservable to the regulator) decline further.

The choice between traditional and innovative technology is in part driven by the potential cost and quality benefits of the innovative technology: both initial costs and the real-option value of expansion might be more favorable for the new technology. Information asymmetry, on the other hand, distorts decisions in the direction of the traditional technology, for which the regulator can incentivize investment without the need for paying economic rents to the firm. We find that in the optimal regulation, with asymmetric information, networks with low costs will always be incentivized to pursue the innovative technology, provided that this alternative also dominates without information asymmetry. For higher cost realizations, on the other hand, the information asymmetry makes it harder to outperform the traditional technology. Even if the highest possible cost-level would dominate the traditional technology in a situation without information asymmetry, optimal regulation may call for resorting to investment in traditional technology in those cases instead, to enable the regulator to limit the allowed revenues to the network.

In the following, we will first introduce the model. In section 3 we solve the model in the first-best real option situation, along the lines of Pindyck (1988). Then we turn to the effects of information asymmetry. If the regulator (who is the principal) cannot observe costs, but the network (the agent) can, we first show that still, the regulator could design a set of fees that induces the agent to follow the same, first-best real-option investment rule. This is costly, though, as the agent receives information rents from its advantaged position. The principal can do a better balancing act between efficient investment and rent extraction by setting fees that delay investment, compared to the real-option benchmark. This delay is greater for an agent having higher ex-ante cost levels. In section 5, we turn to the application. For a specific, constant elasticity welfare function, we explore the trade-offs in terms of option values and information rents between traditional and innovative technologies. We conclude with a discussion of the results and the assumption of regulatory commitment.

[1] We assume commitment on fees for the regulator. If the regulator could not commit, additional distortions would be introduced. The agent would have incentives not to respond truthfully to protect future rents, resulting in a ratchet effect (Laffont and Tirole, 1988). We also assume that there is no danger of renegotiation. Renegotiation typically increases agency costs (Battaglini, 2007; Bester and Strausz, 2001; Hart and Tirole, 1988; Laffont and Tirole, 1990).

2. Model

Let us consider a continuous time investment model for a firm with initial capacity Q_0 and the opportunity to continuously increase this capacity by making irreversible investments. The marginal investment costs C_t are stochastic, evolving according to a geometric Brownian motion,

$$dC_t = \mu C_t dt + \sigma C_t dz.$$

We have in mind the case in which the drift $\mu < 0$, so that costs are expected to fall, but fluctuate around that expected path with volatility σ. The social benefits of having capacity Q are measured by a flow of surplus, $w(Q)dt$, with $w(Q)$ increasing but concave. Marginal benefits decrease to zero, reached at some level Q^* which may be infinite.

Irreversible investment will be carried out, on behalf of a principal (who is the regulator), by an agent (the regulated network) who has private information on the stochastic costs C_t. The principal will contract with the agent at $t = 0$ on capacity investments, capacity Q is contractable.[2] The principal's prior on costs C_0 at time 0 is that these are distributed on $[C_L, C_H]$ according to cumulative distribution $F(C_0)$, with density $f = F'$. As in Arve and Zwart (2016), we adopt the technical assumption that the distribution of the logarithm of C_0 has a monotone hazard rate.[3] The principal does not observe the evolution of C_t, but the parameters of the stochastic process, μ and σ, are assumed to be common knowledge, as is the discount rate r.

The principal can use a set of capacity-dependent fees to encourage optimal behavior. In generality, these fees might consist of $p(Q)$, a capacity-dependent flow fee, $\phi(Q)$ a contribution towards investment costs whenever Q is increased, and an upfront lump sum contract fee ϕ_0.[4] The principal is assumed to maximize the present value of surplus $w(Q)$, minus the payments made to the agent: for a given choice of fees (p, ϕ, ϕ_0), the principal's expected surplus is given by

$$W = E\left(\int_{t=0}^{\infty} e^{-rt}(w(Q_t) - p(Q_t))dt - e^{-rt}\phi(Q_t)dQ_t - \phi_0\right). \tag{1}$$

The first term encapsulates the expected benefits of network capacity, and its expansion over time as costs fall. The other parts are the present value of the expected fees: the continuous flow $p(Q)$, the additional fees paid out when Q is increased by the agent, and the upfront lump sum ϕ_0. The expectation here is not only on the evolution of costs C_t over time, but also over the initial value of costs C_0, the latter known to the agent but unknown to the principal. Here, dQ_t is the process of investments in capacity expansion.

This process of capacity expansion is chosen by the agent, who determines a privately optimal threshold cost level $\bar{C}(Q)$. The agent will expand capacity whenever costs drop below this capacity-dependent threshold level. The optimal threshold for the agent depends on the structure of the ex post fees, $p(Q)$ and $\phi(Q)$. The agent chooses investment so as to optimize his expected utility $U(Q_0, C_0)$, i.e. the sum of the ex ante fee ϕ_0, and the continuation utility $V(Q_0, C_0)$,

$$U(Q_0, C_0) = \phi_0 + V(Q_0, C_0) = \phi_0 + E_{C_0}\left(\int_{t=0}^{\infty} e^{-rt}p(Q_t)dt + e^{-rt}(\phi(Q_t) - C_t)dQ_t\right), \tag{2}$$

with dQ_t governed by the agent's optimal choice of investment threshold $\bar{C}(Q)$. The expectation is here conditional on the stochastic process starting at C_0. The agent's participation constraint is $U(Q_0, C_0) \geq 0$ for any $C_0 \in [C_L, C_H]$.

3. First best

As a benchmark, we first analyze the case without asymmetric information. The principal will in that case instruct the agent to adopt the first-best investment rule, and remunerate the investment costs, leaving the agent zero rents. The principal's objective then is to prescribe an investment rule maximizing expected total surplus,

$$W(Q_0, C_0) = E_{C_0}\left(\int_{t=0}^{\infty} e^{-rt}w(Q_t)dt - e^{-rt}C_t dQ_t\right), \tag{3}$$

with the first term representing the flow of gross surplus, and the second term the capital outlays as capacity is expanded by an increment dQ_t. The optimal rule is (Pindyck, 1988) to invest whenever costs C drop to a capacity-dependent threshold level $\bar{C}(Q)$. The optimization consists of finding that optimal threshold.

[2] There is no loss in generality in assuming all contracting to take place at $t = 0$. Since the only verifiable information to the principal will be the capacity additions by the agent, there is no benefit in postponing part of contracting to later stages, as any future contracting contingent on such capacity additions can already be specified at $t = 0$. There could be a downside to later contracting, if this also means respecting the agent's participation constraints at those later dates. This would impose additional constraints on the principal's maximization problem.

[3] Commonly, the monotone hazard rate assumption is made on the type itself, to avoid solutions involving bunching. In our case, due to the multiplicative nature of the stochastic process, we need to make that assumption on the log of C_0.

[4] There is some redundancy in this formulation: both the investment contribution $\phi(Q)$ and the lump sum ϕ_0 may be subsumed, by suitable shifts, into the flow fee $p(Q)$, keeping the present value of the fees the same. Such a regulation with only a flow fee is more likely to be observed in practical cases, as we will explain in section 5. We keep the general fee structure here for clarity of the theoretical exposition.

To maximize $W(Q_0, C_0)$, we first evaluate the right-hand side using standard real option methods (see e.g. Dixit and Pindyck, 1994). In the region in which no investment occurs, $C > \bar{C}(Q)$, total welfare $W(Q, C)$ satisfies a Hamilton-Jacobi-Bellman equation,

$$rW(Q,C) = w(Q) + \mu C W_C + \frac{1}{2}\sigma^2 C^2 W_{CC},$$

where subscripts denote partial derivatives. This equation is solved by[5]

$$W(Q,C) = \frac{w(Q)}{r} + g(Q)C^{\lambda_-}.$$

for some function $g(Q)$, and λ_- the negative root of the characteristic equation $r = \mu\lambda + \frac{1}{2}\sigma^2\lambda(\lambda - 1)$. The first term here equals the present value of future surplus from current capacity, whereas the second term represents the real option value of expanding capacity further when C_t drops. To find $g(Q)$, we use the boundary condition at the investment threshold $\bar{C}$. At the threshold, we have a value-matching (continuity) condition,

$$W_Q(Q, \bar{C}) = \bar{C},$$

or

$$\frac{w_Q}{r} + g_Q(Q)\bar{C}^{\lambda_-} = \bar{C}.$$

stating that investment occurs when marginal costs of adding capacity, $\bar{C}$, equal the marginal benefits, consisting of the present value of the additional surplus flows, and the change in the value of the option to expand capacity even further in the future.

To determine $g(Q)$, we use the boundary condition at large capacity, where there is no value to further investment, $g(Q^*) = 0$, so that

$$g(Q) = \int_Q^{Q^*}\left(\frac{w_Q(q)}{r} - \bar{C}(q)\right)\bar{C}(q)^{-\lambda_-}dq.$$

Now, optimizing W over the threshold $\bar{C}(Q)$ is achieved by optimizing $g(Q)$. Using pointwise maximization of the integrand, we find the first-order condition

$$-\lambda_- \frac{w_Q(Q)}{r} - (1 - \lambda_-)\bar{C}(Q) = 0,$$

or[6]

$$\bar{C}(Q) = \frac{\lambda_-}{\lambda_- - 1}\frac{w_Q(Q)}{r}. \tag{4}$$

Since the factor $\lambda_-/(\lambda_- - 1) < 1$, investment is delayed beyond the moment at which marginal investment costs equal marginal increase in present value of the surplus flow. The difference is accounted for by the option value of delaying the investment (McDonald and Siegel, 1986).

4. Agency problem

Now consider the case where the principal needs to delegate the capacity expansion to an agent who has superior knowledge about the evolving costs C_t. The principal needs to remunerate the agent for the investment costs incurred, but also to incentivize the agent to invest at the correct cost thresholds $\bar{C}(Q)$.

As outlined above, we assume that the principal can use a set of capacity-dependent fees to encourage optimal behavior: $p(Q)$, a capacity-dependent flow fee, $\phi(Q)$ a contribution towards investment costs, and an upfront contract fee ϕ_0. The principal's expected surplus for a given structure of those fees, $W(Q)$, is given by (1). The principal's problem, therefore, is to choose a menu of fees (p, ϕ, ϕ_0), so as to optimize his expected surplus, subject to a participation constraint for the agent, and subject to the agent choosing his privately optimal investment threshold $\bar{C}(Q)$ given those fees.

4.1. Incentivizing first-best investment

As a preliminary step, let us consider a scheme that succeeds in incentivizing investment at the first-best investment threshold $\bar{C}(Q)$. Suppose first the principal offers only a single stream of fees $p(Q)$, to be paid to the agent. The agent, after having accepted this contract, will choose to invest in a way that maximizes its utility,

$$V(Q_0, C_0) = E_{C_0}\left(\int_{t=0}^{\infty} e^{-rt}p(Q_t)dt - e^{-rt}C_t dQ_t\right).$$

[5] Using the boundary condition that as $C \to \infty$, W should not diverge.

[6] The same result can also be found using a smooth pasting condition on W_Q at the threshold, i.e. $W_{CQ}(Q, \bar{C}(Q)) = 1$, (Dumas, 1991)

This problem is the same as the one encountered in the solution of the first-best problem (4), except for the substitution of $p(Q)$ instead of $w(Q)$. We therefore have that the agent's privately optimal threshold in this case will be given by

$$\bar{C}(Q) = \frac{\lambda_-}{\lambda_- - 1}\frac{p_Q(Q)}{r}. \tag{5}$$

Comparison with the first-best investment threshold (4) shows that we need that the marginal benefit for the agent of increasing capacity Q coincides with the marginal welfare, or in other words $p_Q = w_Q$.

Clearly, one example of such a scheme incentivizing first-best investment would be allocating the entire benefits of the network to the agent, $p(Q) = w(Q)$. In that case the agent is residual claimant to all social benefits and costs, and hence chooses the total welfare maximizing investment strategy. Such a scheme on its own does not, of course, maximize the principal's utility, as it leaves all surplus to the agent. To transfer part of that utility to the principal, the scheme would need to be complemented with a fixed fee, either in the form of an ex ante fee ϕ_0, or a fixed cash flow to be subtracted from the fee $p(Q)$. This construction amounts to a *sell-out contract*, where the principal transfers the entire project to the agent in return for a fixed payment.

This sell-out contract can, however, not transfer all of the surplus to the principal. The obstacle to that is the agent's participation constraint. Total surplus in the first best depends on the initial cost level C_0: the lower this initial cost level, the faster the agent will invest and benefit from larger flows. Hence, low-cost agents earn higher surplus than high-cost agents. Since initial costs are not observable to the principal, however, the only way to make the sell-out contract acceptable to any agent type, is to charge an upfront fee ϕ_0 (or the equivalent constant shift in fees $p(Q)$) that leaves the highest-cost agent, who starts at C_H, with zero rents:

$$\phi_0 = -W(Q_0, C_H),$$

since with the sell-out contract, $p(Q) = w(Q)$, total rents from the flow fee alone are equal to total welfare for this highest-cost type. With this upfront payment, lower-cost agents earn a rent $W(Q_0, C_0) - W(Q_0, C_H) \geq 0$.

Adding a payment $\phi(Q)$, a fee paid per unit of new investment, does not alter this analysis materially. It is straightforward to check that the same conclusions follow, but now with $p_Q(Q) + r\phi(Q)$ substituted for p_Q.

The principal can do better by dropping the requirement that investment is at the first-best timing. The optimal scheme consists of a menu that differentiates among initial agent types C_0. It delays investment thresholds for high-cost agents, to reduce the informational rents enjoyed by lower-cost agents. We next turn to the analysis of that optimal scheme.

4.2. The optimal scheme

The optimal scheme can be expressed in terms of a menu of fees, $\{p(Q;\, C_0),\, \phi_0(C_0) | C_0 \in [C_L,\, C_H]\}$, that is incentive compatible: an agent of initial costs C_0 will maximize its private utility $U(Q_0, C_0)$ by choosing, at $t = 0$, the combination of fees $p(Q;\, C_0)$ and $\phi_0(C_0)$ intended for that initial cost level C_0. For simplicity, and without loss of generality, let us again assume the remuneration for capacity investment $\phi(Q)$ is zero for all contracts in the menu. It is straightforward to check that as in the previous subsection, any non-zero $\phi(Q)$ is equivalent to a change in p_Q.

The principal's problem is then to maximize its own utility, the expected value of flow of welfare $w(Q)$ minus the payments made to the agent, taking into account that the agent chooses the investment threshold $\bar{C}(Q)$ in response to the fees it is offered, maximizing its utility $U(Q_0, C_0)$. The principal's optimization over menus is subject to the incentive compatibility (i.e. out of the menu of sets of fees on offer, agents prefer to opt for the set of fees intended for their individual initial cost level C_0) and to the agent's participation constraint, $U(Q_0, C_0) \geq 0$ for any initial cost level C_0. By substituting the expression for the agent's continuation utility, (2), in the principal's surplus, equation (1), we have

$$W = \max_{\{p(Q;C_0),\phi_0(C_0)\}} \int_{C_L}^{C_H} \left[E_{C_0}\left(\int_{t=0}^{\infty} e^{-rt} w(Q)dt - e^{-rt} C_t dQ_t \right) - U(Q_0, C_0) \right] dF(C_0), \tag{6}$$

$$\text{s.t. incentive compatibility and participation constraints.}$$

Note that, again, expectation is not only taken over the future path of costs C_t (captured by the expectation operator E), but also explicitly over its initial value C_0, distributed according to $F(C_0)$.

To analyze this problem, we first rephrase the question in terms of finding the optimal threshold $\bar{C}(Q; C_0)$ for each initial cost level. We already know, from equation (5), that the choice of a threshold is equivalent to the choice of a fee $p(Q)$ up to an integration constant. In addition, we need to express the agent's continuation utility, $V(Q, C_0)$, in terms of that threshold. To do so, we note that, for any C, the agent's continuation utility $V(Q, C)$ satisfies an HJB equation, with value matching and smooth-pasting determining the boundary conditions at $\bar{C}(Q)$, analogous to the equations solved by total welfare W in the first-best analysis in section 3 (smooth-pasting holds because the agent chooses the threshold $\bar{C}(Q)$ to optimize its value):

$$rV(Q, C) = p(Q) + \mu C V_C + \frac{1}{2}\sigma^2 C^2 V_{CC} \tag{7}$$

$$V_Q(Q, \bar{C}(Q)) = \bar{C}(Q) \tag{8}$$

$$V_{QC}(Q, \bar{C}(Q)) = 1 \tag{9}$$

From this HJB equation, we can derive the following relation linking value $V(Q, C)$ and the threshold:[7]

Lemma 1. *Privately optimal investment for the agent makes sure that its continuation utility $V(Q, C)$ satisfies the condition*

$$V_{QC}(Q,C) = \left(\frac{C}{\bar{C}(Q)}\right)^{\lambda_- - 1} \tag{10}$$

for all $C < \bar{C}(Q)$.

We can now turn to the principal's ex ante problem of specifying a threshold designed for each agent type, $\bar{C}(Q; C_0)$. Once we know that threshold, we can choose a flow of fees $p(Q; C_0)$ implementing that threshold according to equation (5). $\phi_0(C_0)$ is going to do the job of extracting the rents generated from the ex post fees, up to an information rent necessary to induce the agent to reveal his initial cost level C_0 (i.e., incentive compatibility).

Restricting to direct incentive compatible mechanisms, we can rewrite the principal's optimization (6) as choosing a menu of ex ante fees and investment thresholds $\left(\phi_0(C_0), \bar{C}(Q; C_0)\right)$, rather than the fees $p(Q; C_0)$.

To solve the constrained optimization, we use the standard (Mirrlees) observation that optimality of truthfully revealing C_0 implies that

$$\frac{dU}{dC_0}(Q, C_0) = \frac{\partial V}{\partial C_0}(Q, C_0). \tag{11}$$

Moreover, the resulting optimal investment threshold should be decreasing in the ex ante type C_0. We will ignore this monotonicity condition for now, and check that it holds ex post, due to our monotonicity assumption on the hazard rate. We proceed by using (11), in conjunction with a binding participation constraint for the highest cost type, to write $U = -\int_{C_0}^{C_H} V_C dC$. Plugging this into the principal's objective function (6) and doing a partial integration then yields

$$W = \int_{C_L}^{C_H} \left(E_{C_0}\left[\int_{t=0}^{\infty} e^{-rt} w(Q)dt - e^{-rt}\bar{C}(Q; C_0)dQ_t\right] + \frac{F}{f}(C_0)V_C(Q, C_0)\right)dF(C_0). \tag{12}$$

We need to optimize this expression by choosing an appropriate investment threshold $\bar{C}(Q; C_0)$ for each value of initial cost level C_0. To do so, first we evaluate the expected continuation utility, the first expected value term under the integral, for a given initial cost level C_0 and a given choice of threshold $\bar{C}(Q)$. (This is the same computation as in solving the first best in section 3.)

$$E_{C_0}\left[\int_{t=0}^{\infty} e^{-rt} w(Q)dt - e^{-rt}(\bar{C}(Q))dQ_t\right] = \frac{w(Q)}{r} + \int_Q^{Q^*} \left(\frac{C_0}{\bar{C}(q)}\right)^{\lambda_-} \left(\frac{w_Q}{r} - \bar{C}(q)\right)dq.$$

For the second term in the integrand in (12) we can use lemma 1 to write

$$V_{C_0}(Q, C_0) = -\int_Q^{Q^*} V_{QC_0} dq = -\int_Q^{Q^*} \left(\frac{C_0}{\bar{C}(q)}\right)^{\lambda_- - 1} dq.$$

Combining these two expressions, it is straightforward to compute the optimal threshold $\bar{C}(Q; C_0)$ for each value of $C_0 \in [C_L, C_H]$, [8]

Proposition 1. *The optimal menu results in a different investment threshold depending on the agent's initial cost level C_0, given by*

$$\bar{C}(Q; C_0)\left(1 + \frac{1}{C_0}\frac{F}{f}(C_0)\right) = \frac{\lambda_-}{\lambda_- - 1}\frac{w_Q}{r}. \tag{13}$$

Comparing with the first-best threshold (4), we see a similar expression except for the appearance of the factor involving the distribution of the initial costs $F(C_0)$. For the lowest type, $C_0 = C_L$, $F(C_L) = 0$ so we get no distortion there,

$$\bar{C}(Q; C_L) = \frac{\lambda_-}{\lambda_- - 1}\frac{w_Q}{r}.$$

Higher cost types, in contrast, get a distortion, leading to lower thresholds than the first-best ones. This means that the optimal regulatory scheme induces the agent to delay investment compared to the first-best real-option benchmark. The reason is that lower cost types have to be awarded an information rent to reveal their true ex ante type; the delay in investment reduces the rents obtained by claiming higher than actual costs initially. This in turn reduces the required rent to induce agents to report their initial costs truthfully.

[7] proof in the appendix

[8] and verify that it satisfies the required monotonicity in C_0

It remains to compute the actual menu of contracts, including the upfront fee ϕ_0 and the ex-post fee $p(Q)$. This fee can simply be chosen according to equation (5), leading to

$$\left(1 + \frac{1}{C_0}\frac{F}{f}(C_0)\right)p_Q = w_Q, \tag{14}$$

making the agent residual claimant to the total utility generated modulo a correction factor. The corresponding upfront fee ϕ_0 is then set so as to make sure that total utility equals the required information rent $U = -\int_{C_0}^{C_H} V_C dC$.

5. Application: traditional or innovative infrastructure?

Let us now apply these results to answer the following question. Consider a greenfield situation in which the network firm has to build a new network infrastructure, say, connecting a newly built neighborhood to the grid. Suppose there are two alternative technologies to do so.

The first involves choosing a traditional, well-understood, technology, for which there is no asymmetry of information between the network firm and the regulator. The second alternative is a new technology, for which the network firm has superior information, and which therefore suffers from agency frictions.

Both technologies have stochastically falling costs, C_t^{old} and C_t^{new}, respectively. These evolve according to geometric Brownian motions, with $\mu^{\text{old}}, \mu^{\text{new}} \le 0$, and likewise volatilities that may be technology-specific.[9] At time zero, the technology is chosen. For either technology, depending on the initial value $C_0^{\text{old, new}}$, the firm will first build an initial capacity $Q_0^{\text{old, new}}$, and will subsequently keep on expanding capacity, using that same technology, as costs fall.

The question facing the regulator is, when it should ask the firm to build infrastructure using the traditional, well known technology; and when it should instead encourage the firm to start building the new grid technology, which might have lower cost, or higher likelihood of future cost declines, but which may necessitate rents left to the firm in view of the information asymmetry that needs to be overcome.

We analyze the regulator's choice in the specific case when the social surplus flow $w(Q)$ is of constant-elasticity type,

$$w(Q) = \frac{w \cdot Q^{1-\gamma}}{1-\gamma}$$

with $0 < \gamma < 1$ the inverse elasticity (as in Dobbs, 2004; Willems and Zwart, 2018). The factor w measures quality, and could be different for the two technologies, w^{old} versus w^{new}. For instance, the new technology might be more conducive to accommodating environmentally friendly generation inside the network, making $w^{\text{new}} > w^{\text{old}}$.

For analyzing the optimal investment strategy let us first, as a benchmark, establish the optimal investment rules, and total welfare, in the first-best cases without information asymmetry, for either technology.

Lemma 2. *In the greenfield investment project with constant elasticity social surplus, optimal investment in the real option case with current cost level C_0 involves building initial capacity Q_0,*

$$w \cdot Q_0^{-\gamma} = rC_0 \frac{\lambda_- - 1}{\lambda_-},$$

and expanding capacity when the threshold $\bar{C}(Q) = \frac{\lambda_-}{\lambda_- - 1}\frac{w \cdot Q^{-\gamma}}{r}$ is crossed. Total (expected) surplus (including the costs C_0Q_0 of the initial investment) is

$$W(C_0) = \frac{\gamma}{1-\gamma} \cdot \frac{\gamma(\lambda_- - 1)}{\gamma(\lambda_- - 1) + 1} \cdot C_0 Q_0.$$

In the symmetric information setting, the regulator's optimal choice between traditional or new technology is then clear: pick the alternative yielding the largest expected surplus. In the special case when both technologies' costs follow the same stochastic processes, so that $\lambda_-^{\text{old}} = \lambda_-^{\text{new}}$, we have that

$$W^{\text{new}} \ge W^{\text{old}} \text{ is equivalent to } \frac{w^{\text{new}}}{w^{\text{old}}}\left(\frac{C_0^{\text{old}}}{C_0^{\text{new}}}\right)^{1-\gamma} \ge 1.$$

Clearly, in the absence of differences in quality, $w^{\text{new}} = w^{\text{old}}$, it is optimal to choose the lowest cost technology, for which initial investment is higher. Modifications for differences in the stochastic parameters are straightforward, and reflect potential differences in the expansion option value of either technology.

Let us now add asymmetry of information on the costs C_t^{new} for the new technology, where the regulator only knows the distribution of initial costs, $F(C_0^{\text{new}})$, bounded between lowest and highest levels C_L and C_H, respectively. The traditional technology is well known, and does not suffer from informational asymmetry. We can use our results from proposition 1 for

[9] For instance, the established technology may have lower scope for reducing costs, or lower volatility of the cost process, than the new technology.

computing the optimal regulation if we only focus on the new technology: a firm of initial costs C_0^{new} is incentivized to invest as if its costs were larger by a factor

$$\alpha(C_0^{\text{new}}) \equiv 1 + \frac{1}{C_0^{\text{new}}} \frac{F}{f}(C_0^{\text{new}}).$$

In our setting with constant elasticity surplus, this means that initial capacity is distorted downwards compared to its symmetric information counterpart in lemma 2, to

$$w^{\text{new}} \tilde{Q}_0^{-\gamma} = r\alpha(C_0^{\text{new}}) C_0^{\text{new}} \frac{\lambda_- - 1}{\lambda_-},$$

and the regulator's expected surplus, which is now reduced because of the information rents left to the firm, becomes, using the analogous calculation as in lemma 2

$$\bar{W}^{\text{new}} = \frac{\gamma}{1-\gamma} \cdot \frac{\gamma(\lambda_- - 1)}{\gamma\lambda_- + 1 - \gamma} \int_{C_L}^{C_H} \alpha(C_0^{\text{new}}) C_0^{\text{new}} \tilde{Q}_0 dF(C_0^{\text{new}}).$$

Compared to a symmetric information average over the different initial costs levels C_0^{new}, the integrand here is reduced by a factor $\alpha(C_0^{\text{new}})^{1-\frac{1}{\gamma}} < 1$ (note the extra factor of α coming from the distorted capacity choice, $\tilde{Q}_0$).

A simple first attempt to making the trade off between using the traditional established technology versus the new technology with its information rents, is to compare the two expected surpluses, W^{old} and $\bar{W}^{\text{new}}$, and direct the firm to choose whichever technology gives highest surplus.

The regulator can do better, however, by allowing the firm to make that technology choice itself, using its superior information on the actual value of C_0^{new}. Provided that the lowest cost level for the new technology, C_L, gives a better outcome than using the traditional technology, or $W^{\text{new}}(C_L) > W^{\text{old}}$, the optimal regulation will involve at least some probability of deployment of the new technology.

Proposition 2. *In the greenfield investment project with constant elasticity social surplus, optimal regulation involves investment in the new technology for low-cost types, and traditional investment for higher costs levels of the new technology. The transition occurs at an initial cost level $\tilde{C}$ for the new technology for which*

$$W^{\text{new}}(\alpha(\tilde{C})\tilde{C}) = W^{\text{old}}(C_0^{\text{old}}).$$

Compared to the first-best trade-off, in the presence of information asymmetry, we need to switch between traditional and new technologies guided by the virtual costs of the new technology, which are inflated by the factor $\alpha(C_0^{\text{new}})$. This means that the traditional technology will be selected more frequently than with symmetric information. The intuition is that opting for the traditional technology is optimal not only if it allows building more capacity at lower costs (efficiency); having the traditional technology as an outside option also allows the regulator to cut down on the information rents that need to be paid to the firm in cases where new technology costs are low, and the new technology is selected.

Since the mark-up factor α is equal to one for the lowest cost type, $C_0^{\text{new}} = C_L$, and increases for higher cost realizations, we have the following corollary.

Corollary 1. *If for $C_0^{\text{new}} = C_L$, the new technology dominates the traditional technology, then also with information asymmetry, optimal regulation will implement that technology for low cost realizations. In contrast, even if for high initial costs C_H the new technology is more efficient than the old one, optimal regulation may call for traditional technology in that situation.*

Low costs do not lead to distortions in the optimal scheme, and we have the efficient outcome. Decisions for high costs are distorted, on the other hand, and are taken as if costs are even higher by a factor $\alpha(C_H) > 1$. What matters for choice of old versus new technology is not C_H, but $\alpha(C_H)C_H$ as compared to the old technology's cost level C_0^{old}.[10]

How could the optimal regulation scheme be implemented in practice? In many countries, regulation involves setting an allowed level of revenues for the firm to collect from its consumers through its cumulative tariffs for all services it offers. This level may be computed by multiplying a regulatory rate of return with the firm's regulatory asset base.[11] In the context of the current application, we may envisage an existing network firm that is allowed regulated revenues from charging tariffs for all its services to all its customers. We can then incorporate the optimal scheme for the current greenfield project into such a country's regulatory scheme by determining the contribution to the firm's allowed revenues from this particular greenfield project.

If the firm chooses investing in traditional technology, according to the optimal investment trajectory Q_t^{old}, it should receive additional allowed revenues equal to r times its investment outlays, making good its capital costs, but earning no rents on top. If, on the other hand, it opts for the new technology, the project's contribution to allowed revenues will depend

[10] Of course, taking into account potential differences in stochastic process for either technology (embodied in λ_-), as well as quality differences, the w-factor.

[11] See, for instance, CEER (2017) for an overview of computation of these inputs to the regulated allowed revenues in regulation in Europe.

on the capacity investment Q_0^{new}. Depending on the choice of Q_0^{new}, contributions to the firm's allowed future revenues will be set to the sum of a Q-dependent contribution

$$p(Q) = \frac{w^{\text{new}} \cdot Q^{1-\gamma}}{\alpha(Q_0^{\text{new}})(1-\gamma)},$$

and a fixed contribution, $\frac{\phi_0(Q_0^{\text{new}})}{r}$. Here, $\alpha(Q_0^{\text{new}})$ is determined to be the mark-up factor for initial costs C_0^{new} consistent with the optimal choice of initial capacity Q_0^{new}, i.e. solving

$$C_0^{\text{new}} = \frac{\lambda_-}{\lambda_- - 1} \frac{w^{\text{new}} \cdot (Q_0^{\text{new}})^{-\gamma}}{\alpha(C_0^{\text{new}})r}.$$

The allowed revenues component equal to $p(Q)$ determines how allowed revenues increase as the asset base Q increases, giving the right incentives for optimal investment in capacity expansion as future costs decrease. The firm receives positive expected rents from this Q-dependent component. These rents can be computed analogously to the computation of the first-best social surplus, and are equal to

$$V = \frac{\gamma}{\gamma - 1} \frac{\gamma\lambda_-}{(\gamma\lambda_- - \gamma + 1)} \frac{w^{\text{new}} \cdot (Q_0^{\text{new}})^{1-\gamma}}{\alpha(Q_0^{\text{new}})r}.$$

The ϕ_0/r component to the allowed revenues does not change as capacity is later increased: it is a component to total allowed revenues that stays fixed over time. It is used to shift total rents for the firm such that they become equal to the required information rents. In particular, for $C_0^{\text{new}} = \tilde{C}$ – the maximal level of costs above which the firm should refrain from investing in the new technology, but should adopt the traditional technology instead – total information rents need to be zero. For that cost-level, therefore, this component is negative, $\phi_0 = -V$. For lower C_0^{new}, there need to be positive information rents, to ensure incentive compatibility, and ϕ_0 will be larger than $-V$.

6. Discussion: commitment versus learning

The solution to the optimal regulation problem makes clear that only the initial cost level, C_0, plays a role in the setting of the investment thresholds $\bar{C}(Q)$; subsequent updates of these costs, as a result of the stochastic process that C follows, do not alter the optimal policy. Indeed, were C_0 common knowledge ex ante, as we saw in section 4.1, the regulator could achieve the first-best result by using the sell-out contract with $p_Q = w_Q$, and extracting all rents through an appropriate ex-ante fixed fee (or, alternatively, a fixed shift in the stream of fees p).

In contrast, the information advantage that the agent obtains at later dates, as a result of stochastic movements of C_t after $t = 0$, does not result in any additional rents to the agent, and as a consequence does not necessitate further distortions in the threshold. The intuition for this (see Baron and Besanko, 1984; Eső and Szentes, 2017) is that those later updates are ex-ante symmetric information: the expectation value of any information rents that the agent might obtain in the future can already be extracted initially when signing the contract.

A crucial assumption in the current model is that the regulator is able to commit, ex-ante, to the regulatory schedule. As is well known from the literature on dynamic mechanism design and the ratchet effect in regulation theory (Baron and Besanko, 1984; Laffont and Tirole, 1988), it is crucial that the regulator can also commit *not* to use the information learnt from the agent's choice of contract (the choice of threshold) to later adjust thresholds to some value closer to the first-best.[12] Of course, ex-post such an adjustment would be optimal: once informational asymmetry has been resolved, there is no longer any need for distorted investment. From an ex-ante point of view, however, such learning, and updating the incentive scheme on the basis of that learning, would be detrimental to the regulator's objective. The reason is that the agent will anticipate such regulatory behavior, and, knowing that future rents will be extracted by the regulator based on the agent's earlier revelation of private information, the agent will in response require higher ex ante transfers in order to truthfully reveal its initial cost level. By spreading distortions across periods and ignoring potential updates based on information revealed through the agent's choices, total welfare costs are minimized.

Regulatory commitment has been well appreciated as being of high importance in the energy sector. In the absence of such commitment, firms would refrain from sinking investments, for fear of ex post regulatory expropriation. In the US, firms are protected from such 'regulatory takings' through legal measures following the Supreme Court's *Hope Gas* ruling. In Europe, CERRE (2013) argues that the setting of the regulatory asset base can provide such regulatory commitment.[13] Since, as we saw, our scheme of regulatory fees can be implemented in terms of contributions to this regulatory asset base, this provides some comfort that commitment can be feasible in practice.

[12] Even aside from private information, the exogenous changes of the stochastic process could also give rise to commitment problems for the regulator. See for instance Di Corato (2013) who in a real option setting studies the risk of expropriation of a company's assets by a foreign host country, and the resulting distortions in profit sharing contracts this engenders.

[13] In particular, "There is general agreement that RABs are an effective commitment device for natural monopoly elements of infrastructure companies – provided that regulators keep to the spirit as well as the wording of the rules" (section 4.3.3 of CERRE, 2013)

Proof of Lemma 1.. We have that $V(Q, C)$ satisfies the HJB equation

$$rV(Q,C) = p(Q) + \mu C V_C + \frac{1}{2}\sigma^2 C^2 V_{CC}.$$

We can take Q- and C-derivatives from this equation and rewrite to obtain

$$rCV_{QC}(Q,C) = \mu C \frac{\partial}{\partial C}(CV_{QC}) + \frac{1}{2}\sigma^2 C^2 \frac{\partial^2}{\partial C^2}(CV_{QC}),$$

so the function CV_{QC} itself also satisfies an HJB equation without a source term.

Furthermore, we have the smooth-pasting condition on $\bar{C}(Q)$,

$$V_{QC}(Q, \bar{C}(Q)) = 1$$

which equivalently can be written as

$$\bar{C}(Q) V_{QC}(Q, \bar{C}(Q)) = \bar{C}(Q).$$

From these two equations, we learn that, given Q, above the boundary, $C > \bar{C}(Q)$, the function CV_{QC} satisfies an HJB equation and on that boundary, we know its value. From that information, we can find an explicit expression for CV_{QC}: it should be equal to

$$CV_{QC}(Q,C) = E\left(\bar{C}(Q)e^{-rT}\right) = \bar{C}(Q)\left(\frac{C}{\bar{C}(Q)}\right)^{\lambda_-}$$

from which follows the expression in the lemma,

$$V_{QC}(Q,C) = \left(\frac{C}{\bar{C}(Q)}\right)^{\lambda_- - 1}.$$

□

Proof of Proposition 1.. The principal optimizes its objective function which is written as equation (12),

$$W = \int_{C_L}^{C_H} \left(E_{C_0}\left[\int_{t=0}^{\infty} e^{-rt} w(Q)dt - e^{-rt}\bar{C}(Q; C_0)dQ_t\right] + \frac{F}{f}(C_0)V_{C_0}(Q, C_0)\right) dF(C_0).$$

In the main text, we have expressions for the two parts in this integral,

$$E_{C_0}\left[\int_{t=0}^{\infty} e^{-rt} w(Q)dt - e^{-rt}(\bar{C}(Q))dQ_t\right] = \frac{w(Q)}{r} + \int_Q^{Q^*} \left(\frac{C_0}{\bar{C}(q)}\right)^{\lambda_-} \left(\frac{w_Q}{r} - \bar{C}(q)\right) dq.$$

and

$$V_{C_0}(Q, C_0) = -\int_Q^{Q^*} V_{QC_0} dq = -\int_Q^{Q^*} \left(\frac{C_0}{\bar{C}(q)}\right)^{\lambda_- - 1} dq.$$

The combination of these two parts leads to

$$W = \int_{C_L}^{C_H} \left(\frac{w(Q)}{r} + \int_Q^{Q^*} \left(\frac{C_0}{\bar{C}(q)}\right)^{\lambda_-} \left(\frac{w_Q}{r} - \bar{C}(q) - \frac{\bar{C}(q)}{C_0}\frac{F}{f}(C_0)\right) dq \right) dF(C_0).$$

This we can optimize pointwise for each possible C_0, leading to

$$\bar{C}(Q; C_0)\left(1 + \frac{1}{C_0}\frac{F}{f}(C_0)\right) = \frac{\lambda_-}{\lambda_- - 1}\frac{w_Q}{r}.$$

Moreover, from the assumed monotonicity of the log of the hazard rate, this threshold is decreasing in C_0. □

Proof of Lemma 2.. With $w(Q) = \frac{w \cdot Q^{1-\gamma}}{1-\gamma}$, we have $w_Q = w \cdot Q^{-\gamma}$. Plugging this into the first-best cost-threshold from section 3, we have investment threshold (equation 4)

$$\bar{C}(Q) = \frac{\lambda_-}{\lambda_- - 1}\frac{w \cdot Q^{-\gamma}}{r}.$$

Total welfare at the investment threshold is

$$W(Q, \bar{C}(Q)) = \frac{w \cdot Q^{1-\gamma}}{(1-\gamma)r} + g(Q)\bar{C}^{\lambda_-},$$

with

$$g(Q) = \int_Q^{\infty} \bar{C}(q)^{-\lambda_-}\left(\frac{wq^{-\gamma}}{r} - \bar{C}(q)\right) dq$$

$$= \left(\frac{w\lambda_-}{r(\lambda_- - 1)}\right)^{-\lambda_-} \frac{w}{r(\lambda_- - 1)} \frac{Q^{\gamma(\lambda_- - 1)+1}}{\gamma(\lambda_- - 1)+1}.$$

We get total welfare for the greenfield project by subtracting construction costs to bring initial capacity to threshold, $\bar{C}(Q)Q = \frac{\lambda_-}{\lambda_- - 1}\frac{w \cdot Q^{1-\gamma}}{r}$. $\square$

Proof of Proposition 2.. The principal now has the outside option of obtaining W^{old}, the social welfare for the traditional technology, and has to determine the optimal cost level $\tilde{C}$ above which shutdown of the new technology will be preferred; this means optimizing

$$\int_{C_L}^{\tilde{C}} E_{C_0^{\text{new}}}\left[\int_{t=0}^{\infty} e^{-rt} w^{\text{new}}(Q)dt - e^{-rt}\alpha(C_0^{\text{new}})\bar{C}(Q; C_0^{\text{new}})dQ_t\right]dF(C_0^{\text{new}}) + (1 - F(\tilde{C}))W^{\text{old}}$$

over $\bar{C}$ as well as $\tilde{C}$. Here, $\alpha(C_0^{\text{new}})$ is the mark-up, $1 + \frac{1}{C_0^{\text{new}}}\frac{F}{f}(C_0^{\text{new}})$. Clearly, the maximum obtains for $\tilde{C}$ such that the virtual welfare (i.e., welfare as if cost level is inflated by $\alpha(C_0^{\text{new}})$) is equal to W^{old}, or, from lemma 2

$$\frac{\gamma}{1-\gamma} \cdot \frac{\gamma(\lambda_- - 1)}{\gamma(\lambda_- - 1)+1}\alpha(\tilde{C})\tilde{C}\tilde{Q} = W^{\text{old}},$$

with $\tilde{C} = \frac{\lambda_-}{\lambda_- - 1}\frac{w^{\text{new}} \cdot \tilde{Q}^{-\gamma}}{r}$. $\square$

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