UCD CENTRE FOR ECONOMIC RESEARCH

WORKING PAPER SERIES

2019

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WP19/20

September 2019

UCD SCHOOL OF ECONOMICS
UNIVERSITY COLLEGE DUBLIN
BELFIELD DUBLIN 4

Optimal Contracts for Renewable Electricity

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Abstract: Companies are increasingly choosing to procure their power from renewable energy sources, with their own set of potential challenges. In this paper we focus on contracts to procure electricity from renewable sources that are inherently unreliable (such as wind and solar). We determine the contracts that minimize the cost of procuring a given amount of renewable energy from two risk-averse generators. We contrast outcomes arising when investments are set in centralised and decentralised settings, with the absence of reliability addressed by either issuing orders in excess of what is needed or by investing in improved reliability. Our results suggest that future contracts may be geared towards a greater reliance on order inflation and lower investments in reliability as the cost of renewable energy keeps falling. The implications of these results for grid congestion and electricity spot market prices should be of interest to regulators and transmission system operators.

JEL Classification: D81, D86, L14, L24, L94, Q21

Keywords: Renewable electricity contracts, Power purchase agreements, Newsvendor model, Risk aversion, Order inflation, Moral hazard.

1. Introduction

In recent years, growing recognition of the threat of climate change and energy security has motivated many countries to try to diminish their reliance on fossil fuels. Increasing the share of renewable electricity can reduce carbon emissions from the power sector and enable the decarbonisation of heat and transport through their electrification. For these reasons, EU Member States, for example, have set targets to increase the share of renewable energy and electricity in 2020 and 2030. Investment in renewable energy has also increased substantially, reaching nearly €290 billion in 2019 globally and far outstripping investment in new fossil fuel power (REN21, 2019). This trend is set to continue as more countries set targets for shares of renewable energy to decarbonise the energy sector and secure domestic sources of energy supply.

Notwithstanding its decarbonisation advantage, renewable electricity presents a number of potential challenges. Globally, the main sources of renewable electricity, after hydropower, are onshore wind and solar photovoltaic energy (REN21, 2019). These sources of energy generate variable and intermittent power that leads to uncertainty in supply and on average significantly lower utilisation rates or capacity factors than fossil fuel power plants (Pollitt and Anaya, 2016).[1] These depend on the renewable technology; for example the capacity factor of onshore wind ranges from 24.7 (EU average[2]) to 34.7% (US), while the capacity factor for solar photovoltaic generation is between 10% and 25%.[3] Intermittent energy technologies such as wind and solar electricity cannot be controlled by system operators in the same way as dispatchable technologies; they are driven by natural factors such as wind speed and cloud cover that are not wholly predictable (Joskow, 2011). This can lead to social costs, as well as the benefits associated with carbon mitigation and the security of domestically-produced electricity (Gowrisankaran et al., 2016; Linn and Shih, 2019).

[1] The capacity factor is the unitless ratio of the actual electricity produced by a particular power plant over a year, divided by the maximum possible electricity output, ie if it were operating at full capacity constantly for the same period.

[2] https://windeurope.org/wp-content/uploads/files/about-wind/daily-wind/daily-wind-first-half-2017.pdf

[3] The capacity factor is the ratio of the energy generated to the capacity installed. As a comparison a coal fired power plant has a capacity factor of 50-60% and combined cycle gas turbine plant is 40-50%.

Electricity is a peculiar good; on the one hand it is a homogeneous product, while on the other it is heterogeneous in its value across time and space (Fell and Linn, 2013; Hirth et al., 2016). It can only be stored in small amounts and hourly demand is also uncertain, leading to volatile electricity wholesale market prices. Electricity is generally procured through pooled electricity markets and/or bilateral agreements between electricity generator and the customer. Long-term contractual agreements can protect companies and retailers from spot market volatility and high prices at peak times (Boroumond et al., 2015; De Braganca and Daglish, 2017). They can also allow the contractor to set conditions on the type of electricity procured. This situation is increasingly arising where the customer is an energy supplier or retailer (utility) or an energy-using company committed to sourcing renewable electricity exclusively.

Bloomberg Energy Finance estimated that in 2018 approximately 13.4GW of renewable energy contracts were signed by 121 corporations in 21 different countries, more than doubling the amount of 2017 (BNEF, 2019).[4] In addition, many electricity suppliers offer green electricity programmes to their residential and industrial customers, often for a small premium, and may be forced to procure additional renewable electricity from third party generators (Ma and Burton, 2016).[5] A long-term contractual arrangement such as a power purchase agreement is generally employed between companies and renewable energy generators in these situations.[6]

Facilitating increased shares of renewable electricity requires new strategies and investment from both companies and the electricity market to avoid power outages and guarantee constant supply. Across electricity markets, market operators' perception of increased uncertainty in the security of supply is discernible from the proliferation of

[4] See for example RE100, a group of 160 companies committed to 100% renewable electricity that includes among its members Microsoft, Ikea, Aviva etc (http://there100.org/re100). Other examples include the Green Power Partnership in the USA that assists in partnering energy-using companies with green energy suppliers, see https://www.epa.gov/sites/production/files/2016-01/documents/purchasing_guide_for_web.pdf. Platforms such as the Renewable Exchange in the U.K. facilitate renewable electricity PPAs https://www.renewableexchange.co.uk/platform?gclid=EAIaIQobChMI--zSvq2n4wIVxeFRCh0n_gjUEAAYASAAEgL3ffD_BwE

[5] In Ireland for instance, Energia commits to its customers to selling 100% renewable electricity which it buys from renewable energy generators.

[6] Under a power purchase agreement, a company agrees to purchase electricity directly from a renewable energy generator at a fixed price. The green rights attributable to such power typically transfers to the corporate (see p.6 Huneke et al. (2018), also https://www.philiplee.ie/the-rise-of-the-corporate-ppa/). For a description of one company's rationale for entering into a green PPA, see: https://sustainability.google/projects/ppa/

capacity and balancing markets running in parallel to wholesale markets to assure supply. All market players adopt various strategies to try and limit the consequences associated with supply uncertainty with the increased reliance on green energy. Large industrial consumers can fine-tune their electricity demand and deliver demand reduction when requested. Energy suppliers can use technical solutions to uncertainty, such as increasing electricity storage with resulting co-benefits such as the ability to arbitrage electricity across time but this is likely to be limited (O'Dwyer et al., 2018; Carson and Novan, 2013), and/or relying on a diversified portfolio of renewable electricity that includes more stable (dispatchable) but expensive sources such as geothermal and biogas power. Grid service operators have increased balancing and congestion management costs associated with higher shares of renewable electricity and balancing and capacity markets have emerged in many jurisdictions to manage uncertainty at the market level (Joos and Staffell, 2018).

In this paper we are interested in bilateral contracts issued to risk averse green energy generators who are not able to guarantee the amount of energy they can supply, and therefore are unreliable. Depending on the generating technology and their infrastructures, the generators have a given installed capacity. However, the ability of generators to supply energy at any point in time depends on conditions that are not enforceable. The contractor can be an energy supplier who seeks to increase its share of green energy sales, or a corporate energy user; we do not differentiate between them.

Clearly, the risk of outage is an important feature of this industry (Praktiknjo et al., 2011) and the consequences are more likely to impact energy suppliers who may have to deal with disgruntled customers. Yet, the suppliers' overall exposure to risk is lessened by the fact that they generally have the possibility to diversify their portfolio relying on different energy generators (Contreras et al., 2017). Conversely, risk aversion on behalf of the generators is assumed because their ability to address uncertainty is very limited. Wind farm owners, or any other renewable energy suppliers with intermittent, variable sources, are at the mercy of the weather and have limited options to reduce the risk they face and yet have fixed costs such as workforce commitments and potential loan repayments.

Common practice used in the operations research literature to handle the reliability issue consists of inflating orders, investing in increased process reliability and diversifying the supply base. Yet, the sourcing strategies available to a renewable electricity supplier may be limited. For example, in other sectors with a large number of subcontractors then the manufacturer could diversify the supply base and let the orders depend on each subcontractor's characteristics (Babich et al., 2007; Dada et al., 2007, Ferdergruen and Yang, 2008 and 2009; Tang and Kouvelis, 2011; Xu et al., 2011; and Yang et al., 2015). However, in the case of wind generators and electricity suppliers, it may not be possible to diversify the generator base, as all generators in a geographical area are dependent on a resource of the same quality, namely wind.[7] Under such circumstances, the electricity supplier can devote resources to improving the generators' performance, through reliability investments.[8] This strategy has been extensively documented for the car industry under single or dual sourcing (Handfield et al., 2000; Wouters et al., 2007; Liker and Choi, 2004). Snyder et al. (2016) provide a comprehensive survey on this strand of literature that accounts for the reliability issue and the many diverse approaches to handle supply disruptions.

In this paper, we consider contracts that minimize the overall cost of procuring a fixed amount of green energy. These contracts allow the contractor to rely on two strategies to minimize the overall procurement cost and address the generators' lack of reliability. The contractor can issue orders in excess of what is needed. Large orders can minimize the risk of a shortfall and having to rely on an alternative, more expensive source of power. But order inflation may also trigger some costs when excessive energy is produced, such as system costs due to grid upgrades, increased operating costs, and unnecessary congestion on the grid (Joos and Staffell, 2018). Alternatively, the contractor can require that energy generators invest in increased reliability. Investments in increased capacity, infrastructure, research or even maintenance can improve the generators' reliability.[9] Thus, the paper focuses on the strategic use of

[7] Unless the generators were located in regions with different meteorological conditions, however this might require transmission of electricity over a long distance with other risks and costs associated.

[8] Krause (1997, 1999), Krause et al., (1998, 2007) provide empirical supports for the supplier development strategies available to manufacturers.

[9] Some argue that reliability issues are misguided (see https://www.ucsusa.org/clean-energy/renewable-energy/barriers-to-renewable-energy#.W_0JBej7SM8). But in general, there seems to be an agreement that while weather forecasting is becoming more accurate, the production of renewables remains subject to uncertainty because it is reliant on natural meteorological processes.

order inflation and investment in greater reliability to address supply uncertainty. Finally, we consider that these investments may be contractible or not. In doing so, we analyse whether energy generators are more reliable when part of a vertically integrated structure or when they decide on their investments independently and non-cooperatively.

We model the procurement problem as a newsvendor optimisation problem under supply uncertainty whereby each generator's production is the realization of a random variable which follows an exponential distribution. The rate of occurrence of the distribution reflects the supplier's reliability as it depends on how much they invest in measures to combat unreliability. Our modelling approach captures the fact that larger orders are subject to a great risk of non-completion.

The optimal contract specifies the monetary transfers to the energy producers, the level of investment (when contractible) and the order sizes. The monetary transfers can potentially depend on whether the generator successfully completes the order or not. With risk averse generators however, profit dispersion is costly to the contractor who must account for a risk premium.

The issue of bilateral electricity agreements under uncertainty has been modelled more generally by others (Mateus and Cuervo, 2009; Khatib et al., 2007; Khatib and Galiana, 2007; Kovacevik, 2019), without the constraint of renewable electricity generation. There is also a wider financial literature on risk aversion in the formation of long-term contracts in electricity markets, but again without the condition of renewable electricity-only contracts (Powell, 1993; Neuhoff and de Vries, 2004; Baldursson and von der Fehr, 2007; Downward et al., 2016). This gap may be due to the lack of prevalence of this type of contract until recently. On risk aversion, Neuhoff and de Vries (2004) find that if risk-averse consumers could sign "long-term contracts or invest directly in electricity generation, they would develop a higher volume of generation capacity than risk-neutral investors or consumers". However, this may not hold for risk averse generators, whose optimal strategy might be less commitment to (bilateral and futures) contracts and retention of the flexibility of participation in spot markets (Falbo and Ruiz, 2019).

This paper fills a gap in the literature in applying contract theory to bilateral electricity contracts that require 100% renewable electricity, which it might be argued is an important trend and challenge for the sector over the next decade. It addresses this by focusing on the role of order sizes and investments in reliability in a setting where risk of completion is negatively correlated with the order size due to generators facing some form of capacity constraints. An important element of the analysis performed here is the consideration of risk aversion on behalf of the generators. Under such an assumption, the generators respond to increased transfers but also to profit dispersion resulting from the use of penalties and bonuses. As a result, we find that under moral hazard reliability may actually increase. It also raises the question of whether optimal contracts from the perspective of the contractor lead to an alignment of societal and private welfare objectives in the electricity sector. The paper is organized as follows. The next section presents the model. Sections 3 and 4 characterise the optimal outsourcing strategy under the two situations:- centralised and decentralised investments. Section 5 concludes with some insights for policy makers.

2. The Model

A risk neutral contractor, either a public or private energy supplier, must procure a quantity Q^* of renewable energy (MWh) to address a given demand for electricity. Let us assume, without loss of generalities, that $Q^* = 1\ MWh$. Understanding that renewable energy production is subject to uncertainty, the contractor seeks to minimize the cost associated with procuring $Q^* = 1$ units of renewable energy.

Two risk averse, renewable energy generators (1 and 2) can be contracted. The contract specifies an order for q_i as well as the monetary transfer, $w(q_i^D)$, paid upon the generation of q_i^D $(i = 1,2)$.

We introduce the reliability issue assuming that the energy delivered by generator i $(i = 1,2)$, q_i^D, is subject to uncertainty. Specifically, let $q_i^D = \min\{q_i, s_i\}$ where s_i is the realization of a random variable $\tilde{s}_i \in [0, +\infty[$. The random variables $\tilde{s}_1$ and $\tilde{s}_2$ are independent. We consider that $\tilde{s}_i$ follows an exponential distribution with a rate of occurrence λ_i. The cumulative distribution function is given by $F(s) = 1 - e^{-\lambda_i s}$ while the density is given by $f(t) = \lambda_i e^{-\lambda_i s}$. The rate of occurrence reflects the installed capacity of the energy generator.[10] Indeed, given its distribution, the expectation of $\tilde{s}_i$ is equal to $\left(\frac{1}{\lambda_i}\right)$. Therefore, the ratio $\left(\frac{1}{\lambda_i}\right)$ can be understood as producer i's installed capacity and serves as a proxy for his reliability to deliver an amount $q \quad i$. Larger values of λ_i are associated with lower installed capacity and therefore a less reliable energy generator. We consider that generator i's installed capacity is the realization of a random variable that depends on the investment undertaken. When generator i invests an amount $I(\lambda_i)$ it achieves a rate of occurrence $\lambda_i + \tilde{\varepsilon}$ where $\tilde{\varepsilon}$ is a random variable with zero mean.

Thus, while the contractor can observe and verify the installed capacity of a generator, he does not observe the exact investment undertaken by the generator. This enables us to consider a situation where this investment is subject to moral hazard.

Let $I_i \equiv I(\lambda_i)$ denotes the *expected* investment needed to achieve a rate of occurrence λ_i. The function $I(\lambda_i)$ is decreasing and convex so that $I'(\lambda_i) < 0$ and $I''(\lambda_i) \geq 0$, where we use prime to denote the first derivative and double prime the second derivative.

We assume that both generators exhibit the same risk preferences and marginal cost c which is verifiable. Hence orders are not driven by a cost heterogeneity or a difference in risk aversion. Specifically, when a producer incurs an initial investment I and then generates q^D units of energy at cost $c > 0$ it gathers the following profits

$$\pi\left(w(q^D) - cq^D\right) - I$$

where $\pi(.)$ is an increasing and concave function. The separability of revenue and investment is a common assumption in the classical contractor-agent theory.[11]

The optimal contract depends on the size of the following exogenous variables. Firstly, the cost of production of the green energy, which depends on the type of

[10] The reliability of a wind farm is a function of other factors such as wind speeds, location, turbine size, but we consider the installed capacity to be the primary indicator of likelihood to deliver a fixed quantity of electricity, ceteris paribus.

[11] See for instance Laffont and Martimort (2002).

generating technology. Secondly, the cost at which the contractor can procure substitute electricity, should the renewable energy producers fail to complete their orders.[12] This cost depends on what alternative sources of electricity are available, the carbon intensity of the substitute (if a carbon price is applied), and the time of day (peak or off-peak). Finally, the cost associated with an excess supply of renewable energy. If it can be sold then this cost may be negative. However, in most instances, excess supply can be costly to the contractor who must store or spill unused energy.[13]

Let $Q^D = q_1^D + q_2^D$ denotes the overall quantity of energy that is delivered. The contractor's cost of procurement accounts for the following two possibilities:

- When $Q^D < 1$ not enough renewable energy is produced and the contractor incurs a cost c_S to address the *shortage* of green energy supply. This cost can for instance be the price charged by another, not necessarily green, energy supplier or may reflect a carbon tax incurred on electricity produced from fossil fuels.
- When $Q^D > 1$ there is an excess supply of renewable energy. Whether this is beneficial or costly to the contractor is not clear. In some instances, the contractor could sell the excess supply. However, in most instances, excess supply is costly to the contractor who must store unused energy. Let c_E denote the cost (or benefit) associated with *excess* supply.

We consider that $c \leq c_S$ and that $(c + c_E) \geq 0$. Should the green energy suppliers fail to satisfy their order, the contractor would have to purchase some energy from other suppliers at cost c_S. We argue that assuming that $c \leq c_S$ is not far-fetched as the cost of renewables is falling to the point where it will become cheaper than fossil fuels and nuclear power by 2020.[14] A carbon price is also levied on non-renewable electricity through the EU emissions trading scheme and/or green certificates or carbon taxes in some countries. Note that if instead we had $c > c_S$ then clearly, and as the analysis

[12] This may be on the wholesale electricity market.

[13] For more on what to do with excess supply see https://www.researchgate.net/post/What_does_happen_to_the_extra_generation_of_a_wind_farm_solar_power_plant_if_it_is_not_possible_to_be_consumed_by_customers

[14] https://www.theguardian.com/commentisfree/2017/sep/26/offshore-wind-power-energy-price-climate-change

performed below will show, there is a motivation from the contractor to avoid green energy all together.

We assume that $(c + c_E) \geq 0$. If excess supply of green energy is costly, then this inequality will obviously hold. If, however, the excess supply of green energy can be sold we would have $c_E < 0$ and the assumption made suggests that the contractor cannot make a profit out of buying and selling green energy as the most he could charge for green energy is c. If the contractor could make a profit selling green energy then we would face a situation where he would systematically issue large orders, not to cover the demand but to profit from it. We want to stay away from such considerations.

In the first part of the paper we consider that investments are verifiable. Hence the contractor requires that energy generator i invest an amount I_i $(i = 1,2)$. The orders and monetary transfers must then compensate each producer for the investments undertaken.

We then contrast this situation with one where investments are set independently and non-cooperatively by the generators and are subject to moral hazard. In this case the contractor suggests the level of investment each producer should undertake but cannot verify the amount invested despite observing the installed capacity.

In either situation, each generator has the option to reject the contract, in which case we assume that the reservation profits equal zero.

Finally, we refer to *order inflation* (Tang et al. (2014)) as a situation where the contractor orders more than 1 MWh of green energy.

3. Optimal contracts under centralized investments.

In this section we fully characterize the level of investments, the orders and monetary transfers that minimize the cost of procurement. Specifically, the contractor's profits, upon the generation of Q^D renewable energy units, are given by

$$\Pi\left(Q^D\right) = R - W\left(Q^D\right) - c_S\left\{1 - Q^D, 0\right\} - c_E\left\{Q^D - 1, 0\right\}, \qquad (1)$$

where $R > 0$ is the revenue from selling energy on to consumers, and $W(Q^D) = w(q_1^D) + w(q_2^D)$ is the sum of monetary transfers to the energy generators.

We solve for the optimal contract characterizing first the optimal transfers and orders for all possible reliability parameters and then the optimal investments. In the next subsection the parameters λ_1 and λ_2 will be considered as exogenous.[15]

3.1 Optimal monetary transfers and order sizes.

The only constraints are the participation constraints (one for each producer) highlighting the condition under which the contracts are accepted.

Generator i accepts his contract provided

$$\int_0^{+\infty} \pi(w(q_i^D) - cq_i^D) f_i(s_i) ds_i - I_i \geq 0, (i = 1,2), \tag{2}$$

where $q_i^D = \min\{q_i, s_i\}$.

This inequality can also be written as

$$\int_0^{q_i} \pi(w(s_i) - cs_i) f_i(s_i) ds_i + \int_{q_i}^{+\infty} \pi(w(q_i) - cq_i) f_i(s_i) ds_i \geq I_i \; (i = 1,2).$$

The first term measures the profits when the generator cannot not complete the order, while the second term denotes the profits when he does.

Lemma 1: *When investments are contractible, the optimal contracts are efficient and such that energy generators get no rents. Specifically, we have* $w(q_i^D) = cq_i^D + \pi^{-1}(I_i)$ $(i = 1,2)$ *so that energy generators are neither rewarded for supplying enough power not penalized for failing to do so.*

Proof: See Appendix 1.

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[15] This approach is standard in the literature, see, for instance, Macho-Stadler and Pérez-Castrillo (2001).

Given the optimal transfers, we can write the contractor's profits as a function of the orders and the investments. The specific form depends on whether the contractor uses order inflation, defined as setting total orders greater than one, or not.

- When the orders are such that $(q_1+q_2)\le 1$, we have

$$\Pi(q_1,q_2,\lambda_1,\lambda_2)|_{(q_1+q_2)\le 1} = R - c(q_1+q_2) - c_S(1-q_1-q_2) - (c_S - c)\left[\int_0^{q_1} F_1(s)ds + \int_0^{q_2} F_2(s)ds\right] - \pi^{-1}(I_1) - \pi^{-1}(I_2). \tag{3}$$

The monetary transfer covers the cost of production and the investment. The last term in (3) measures the compensations for the investments. The first two terms are the profits when both orders are completed. The third term accounts for the cost of ordering less than $Q^* = 1$. Finally, the fourth term reflects the losses associated with shortages.

- When the contractor inflates orders so that $(q_1+q_2)\ge 1$, there is a risk of excess supply of renewable energy and we have

$$\Pi(q_1,q_2,\lambda_1,\lambda_2)|_{(q_1+q_2)\ge 1} = R - c(q_1+q_2) - c_E(q_1+q_2-1) - (c_S + c_E)\left[\int_0^{1-q_2} F_1(s)ds + \int_0^{1-q_1} F_2(s)ds + \int_{1-q_2}^{q_1} F_2(1-s)F_1(s)ds\right] + (c+c_E)\left[\int_0^{q_1} F_1(s)ds + \int_0^{q_2} F_2(s)ds\right] - \pi^{-1}(I_1) - \pi^{-1}(I_2). \tag{4}$$

The last term is once again the compensation for the investments. Recall that the contractor commits to pay the cost of the quantity delivered. When more than one unit of energy is ordered and delivered, the contractor must therefore pay for the cost of producing energy he will not use. Therefore, the first three terms measure the profits upon order completion, taking into account the fact that the contractor needs at most one unit. The fourth term measures the net cost of not being able to satisfy the demand when less than one unit is generated. Finally, the fifth term measures the savings associated with individual order incompletions which means that less unnecessary energy has been produced.

It is straightforward to verify that the profits function is continuous at $(q_1+q_2)=1$ and we have

$$\Pi(q_1, q_2, \lambda_1, \lambda_2)|_{(q_1+q_2)=1} = R - c - (c_S - c)\left[\int_0^{q_1} F_1(s)ds + \int_0^{q_2} F_2(s)ds\right] - \pi^{-1}(I_1) - \pi^{-1}(I_2). \quad (5)$$

Lemma 2: *The contractor always orders at least one unit of energy. If at least one of the two energy generators is reliable then he orders exactly one unit of power. More specifically, when producer i $(i = 1 \text{ or } 2)$ is reliable, meaning that $\lambda_i = 0$ while producer j $(j = 1 \text{ or } 2, j \neq i)$ is not, meaning that $\lambda_j > 0$, we have $q_i = 1$ and $q_j = 0$. When both energy generators are reliable $(\lambda_i = 0 \text{ for } i = 1,2)$ then any combination of orders such that $(q_1 + q_2) = 1$ is optimal.*

Proof: For any given rates of occurrences, we have

$$\frac{\partial}{\partial q_i}\Pi(q_1, q_2, \lambda_1, \lambda_2)|_{q_1+q_2\leq 1} = (c_S - c)\left(1 - F_i(q_i)\right) \geq 0. \quad (6)$$

Therefore, the optimal orders are such that $(q_1 + q_2) \geq 1$.[16]

For all $q_i \geq 1 - q_j$ with $i, j = 1,2$ and $i \neq j$, we have

$$\frac{\partial}{\partial q_i}\Pi(q_1, q_2, \lambda_1, \lambda_2) = \left(1 - F_i(q_i)\right)[F_j(1 - q_i)(c_S + c_E) - (c_E + c)]. \quad (7)$$

If supplier j $(j = 1,2)$ is fully reliable so that $F_j(1 - q_i) = 0$, the expected profits are decreasing with q_i so that it is optimal to set $q_i = 0$ and $q_j = 1$. When both suppliers are reliable, the function $\Pi(q_1, q_2, \lambda_1, \lambda_2)$ decreases in q_1 and q_2 for all $q_1 + q_2 \geq 1$ and, according to (6), increases in q_1 and q_2 for all $q_1 + q_2 \leq 1$. It reaches a maximum along the line $q_1 + q_2 = 1$.█

We now characterize the optimal orders when both generators are unreliable $(\lambda_i > 0 \text{ for } i = 1,2)$. To do so, we analyze the equivalent of the "best-reply functions" that is the optimal order to producer i as a function to the producer j's order.

Let

$$\hat{c} = \frac{(c_S + c_E)}{(c_S - c)}.$$

[16] Notice that if $c_S < c$ then it is optimal to avoid renewable energy.

We have $\hat{c} > 1$ by assumption. The variable $\hat{c}$ measures the relative cost of the renewable energy lack of reliability. The larger $\hat{c}$ is the greater the cost of using an unreliable source of energy. Unreliable sources may trigger energy shortages or excess supply of energy. The cost of each of these is captured in the numerator. The denominator captures the cost discrepancy between renewables energy and other, reliable sources of energy.

Using (7) one can easily show that is optimal for the contractor to rely on order inflation and set $q_i > 1 - q_j$ provided

$$\frac{\partial}{\partial q_i} \Pi(q_1, q_2, \lambda_1, \lambda_2)|_{q_i=1-q_j} > 0 \Leftrightarrow \lambda_j q_j \geq \ln \hat{c}. \tag{8}$$

When (8) holds, the optimal order for generator i is such that $F_j(1-q_i)(c_S + c_E) - (c_E + c) = 0$. It follows that the best reply function $q_i(q_j)$ $(i, j = 1{,}2\ i \neq j)$ is given by

$$q_i(q_j) = \begin{cases} 1 - q_j \text{ for } q_j \leq \min\left\{1, \dfrac{\ln \hat{c}}{\lambda_j}\right\}, \\ 1 - \dfrac{\ln \hat{c}}{\lambda_j} \text{ for } q_j \geq \min\left\{1, \dfrac{\ln \hat{c}}{\lambda_j}\right\}. \end{cases} \tag{9}$$

Figures 1 and 2 below represent the two possible outcomes. The first is such that we have a unique equilibrium in which the contractor relies on order inflation (Figure 1). This equilibrium is more likely to arise when energy generators are unreliable. Alternatively, there is a second outcome with a multiplicity of equilibria such that the contractor orders no more than one unit of inputs (Figure 2). Our findings are summarized in proposition 1 below in the Figures 1 and 2.

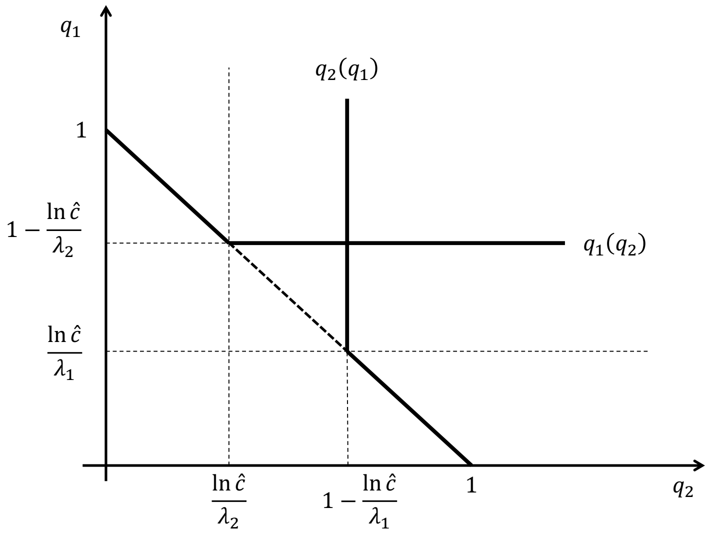


Figure 1 Best response functions when $\frac{\ln \hat{c}}{\lambda_i} < 1 - \frac{\ln \hat{c}}{\lambda_j}$, $i, j = 1,2\ i \neq j$.

In the situation above, the optimal orders are such that

$$q_i = 1 - \frac{\ln \hat{c}}{\lambda_j}\ i, j = 1,2\ and\ i \neq j.$$

If we now allow λ_j to fall to such an extent that we have $\frac{\ln \hat{c}}{\lambda_i} > 1 - \frac{\ln \hat{c}}{\lambda_j}$ then the best reply functions are represented below.

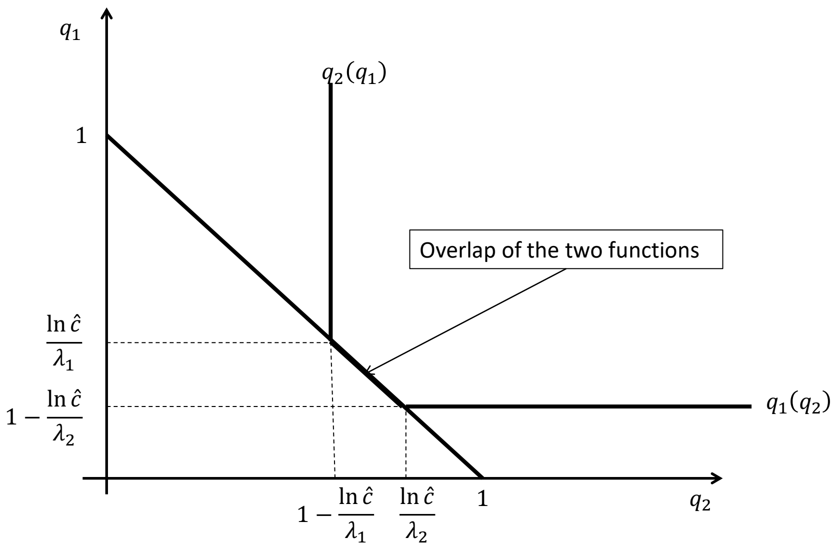


Figure 2: Best response functions when $\frac{\ln \hat{c}}{\lambda_i} > 1 - \frac{\ln \hat{c}}{\lambda_j}$, $i, j = 1,2$ $i \neq j$.

In this case we have a multiplicity of equilibria characterized as follows:

$$q_1 + q_2 = 1 \text{ and } \left\{1 - \frac{\ln \hat{c}}{\lambda_j}, 0\right\} \leq q_i \leq \left\{\frac{\ln \hat{c}}{\lambda_i}, 1\right\} \text{ with } i, j = 1,2 \; i \neq j.$$

Proposition 1: *Consider the level curve characterized by*

$$\frac{\lambda_1 \lambda_2}{(\lambda_1 + \lambda_2)} = \ln \hat{c} \text{ , where } \hat{c} = \frac{c_S + c_E}{c_S - c}.$$

- *When* $\frac{\lambda_1 \lambda_2}{(\lambda_1 + \lambda_2)} \leq \ln \hat{c}$, *we have a multiplicity of equilibria. All are such that the sum of orders equals 1 and*

$$\left\{1 - \frac{\ln \hat{c}}{\lambda_j}, 0\right\} \leq q_i \leq \left\{\frac{\ln \hat{c}}{\lambda_i}, 1\right\} \text{ with } i, j = 1,2 \; i \neq j.$$

- *When* $\frac{\lambda_1 \lambda_2}{(\lambda_1 + \lambda_2)} \geq \ln \hat{c}$, *the equilibrium is unique and such that the sum of orders is at least equal to 1 (implying that there is potential order inflation) and we have*

$$q_i = 1 - \frac{\ln \hat{c}}{\lambda_j} \; i, j = 1,2 \text{ and } i \neq j.$$

Proof: The proof follows from the analysis of the best reply functions. Notice that when there is order inflation we have $q_1 + q_2 = 2 - \left(\frac{\lambda_1 + \lambda_2}{\lambda_1 \lambda_2}\right) \ln \hat{c}$. In the Appendix, we show that the second order condition holds whether or not there is order inflation.∎

Figures 3 and 4 below give a visual representation of the optimal order. Figure 3 represents all (λ_1, λ_2) for which there is order inflation. Figure 4 depicts, with more precision, the multiple equilibria that occur when there is no order inflation.

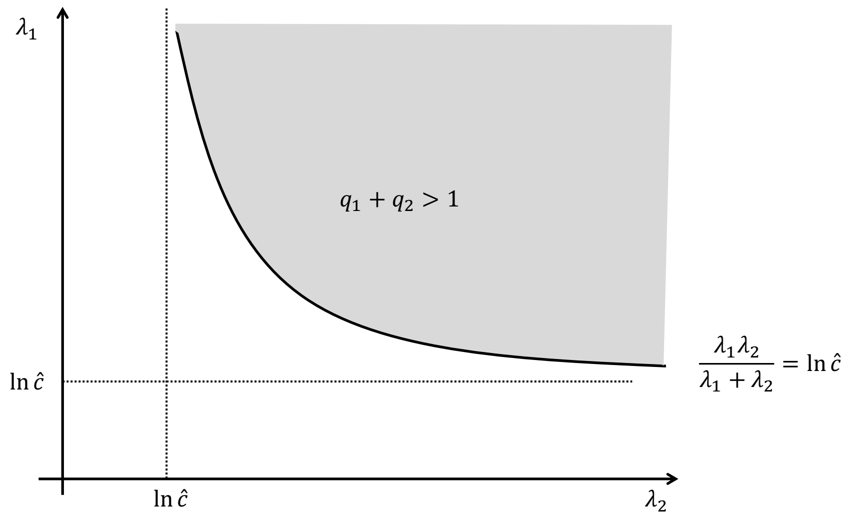
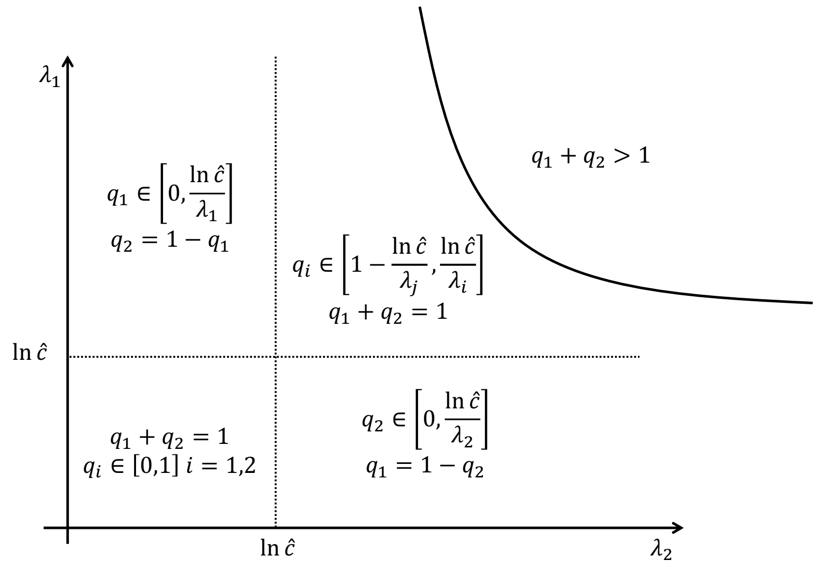


Figure 3. The area of (λ_1, λ_2) in which order inflation holds.

The equilibrium is unique above the level curve and we have order inflation. On the level curve the equilibrium is unique and we have $q_1 + q_2 = 1$ and $q_i = 1 - \frac{\ln\hat{c}}{\lambda_j}$ $i, j = 1{,}2$ and $i \neq j$. Below the level curve we have a multiplicity of equilibria but the orders sum to 1. Figure 4, below, emphasizes those equilibria.

Clearly, whenever we have $\lambda_1 = \lambda_2$ only two of the four regions depicted above are relevant (the south west and north east ones) and one particular equilibrium is such that $q_1 = q_2 = \frac{1}{2}$.



$$\hat{c} = \frac{c_S + c_D}{c_S - c} > 1.$$

Figure 4. Optimal orders when $q_1 + q_2 = 1$.

Before we characterize optimal investments, we present some comparative statics.

Lemma 3: *For given reliance parameters, the contractor is more likely to rely on order inflation when renewable energy is produced and disposed of at a low cost and when the cost associated with alternative sources of energy is high.*

The results stated above are very intuitive and driven from the fact that

$\frac{\partial \hat{c}}{\partial c_S} < 0$ and that $\frac{\partial \hat{c}}{\partial c} > 0$ and $\frac{\partial \hat{c}}{\partial c_E} > 0$.

3.2 Optimal investments.

Taking into account the optimal orders, we can now solve for the optimal investments of generators. We handle this problem as one that characterizes the optimal rates of occurrence. We then compare the marginal revenue to the marginal cost associated with an increase in reliability. Clearly, we expect that a marginal increase in the rate of occurrence will have a negative impact on the revenue.

Lemma 4: *Whether the contractor relies on order inflation or not, the marginal impact on the revenue associated with an increase in λ_i is negative and increasing in λ_i. In other words, the contractor's revenue is decreasing and convex in λ_i $(i = 1, 2)$. It is also continuously differentiable in λ_i $(i = 1, 2)$.*

Proof*:* See Appendix.

Lemma 4 suggests that an increase in the rate of occurrence of a generator impacts negatively on the revenue, and that the marginal impact decreases as the generator becomes more and more unreliable.

The cost associated with the investments is given by $\sum_{i=1,2} \pi^{-1}(I_i)$. Thus the marginal cost is negative and increasing since we consider that the function $I(\lambda_i)$ is decreasing and convex while $\pi(.)$ is increasing and concave.

Depending on the shape of the investment function, several possibilities arise. To guarantee the existence of an interior solution it is sufficient to impose that the function $\pi^{-1}(I_i)$ be everywhere more convex than $\Pi(q_1, q_2, \lambda_1, \lambda_2)$ as shown in Figure 5 below. It represents the marginal cost and marginal loss associated with an increase in λ_i.

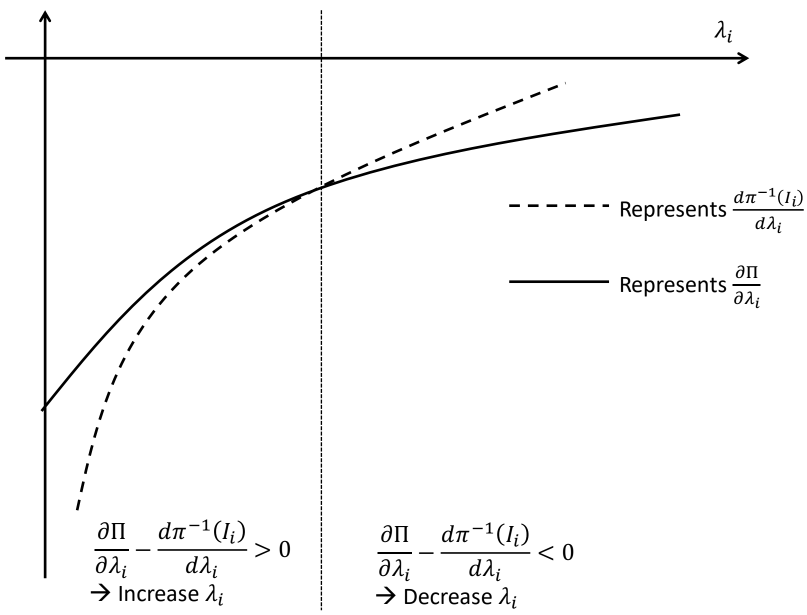


Figure 5 The existence of an interior solution.

Given that an interior solution does exist, we can now characterize it.

Proposition 2: *Provided the investment function is sufficiently convex, there exists a unique interior solution for the occurrence rates. A symmetric solution* (λ^*, q^*) *is characterized as follows.*

- *Assume that there exists* $\lambda^* \leq 2\ln\hat{c}$ *which solves*

$$\frac{d\pi^{-1}\left(I(\lambda^*)\right)}{d\lambda^*} = -(c_S - c)\int_0^{\frac{1}{2}} s[1 - F_i(s)]\,ds,$$

  then the optimal rate of occurrence is λ^* *and* $q^* = \frac{1}{2}$*.*

- *Assume that there exists* $\lambda^* \geq 2\ln\hat{c}$ *which solves*

$$\frac{d\pi^{-1}\left(I(\lambda^*)\right)}{d\lambda^*} =$$

$$(c_S + c_E)\left[\int_{1-q^*}^{q^*} s[1-F(s)][1-F(1-s)]ds - (1-F(1-q^*))\int_0^{q^*} s[1-F(s)]ds\right],$$

  then the optimal rate of occurrence is λ^* *and* $q^* = 1 - \frac{1}{\lambda^*}\ln\hat{c}$*.*

Proof: See the proof of Lemma 4 for the equation characterizing the optimal rate of occurrence. The rest of the proposition is then straightforward as it relies on information given in previous propositions and Lemmas. Notice that the symmetric equilibrium rate $\lambda^*$is on the level curve $\frac{\lambda_1\lambda_2}{(\lambda_1+\lambda_2)} = \ln\hat{c}$ provided $\lambda^* = 2\ln\hat{c}$.▌

The two equilibria that can arise differ in how unreliability is optimally managed. The first, whereby $\lambda^* \leq 2\ln\hat{c}$ and $q^* = \frac{1}{2}$, captures a situation where investment is used to improve reliability. This equilibrium is more likely to arise when $\hat{c}$ is large. As explained previously, $\hat{c}$ measures the relative cost of relying on an unreliable source of energy. As such, larger values of $\hat{c}$ provide incentives to invest in greater reliability. The second type of equilibrium, whereby $\lambda^* > 2\ln\hat{c}$ and $q^* > \frac{1}{2}$, captures a situation where order inflation is used to deal with the potential risks associated with unreliability. This type of equilibrium is more likely to arise when renewables cost little to produce and the cost of dealing with excess supply is low.

To further illustrate what equilibrium emerges we provide two numerical examples.

Let us consider that $\pi(w) = \sqrt{w}$ and that $I(\lambda) = e^{-\lambda/2}$. Furthermore, assume that $c_S - c = 1$. In this case, we have $\hat{c} = c_S + c_E$.

Situation 1: Relying on investments to address reliability issues.

When $\hat{c} = 8$, we have $\lambda^* = 0.43$ and $q^* = 0.5$. Notice that orders are set below each supplier's expected supply $(q^* < 1/\lambda^*)$. The risk of energy shortage is low due to the large investment in reliability.

Situation 2: Relying on order inflation to address reliability issues.

When $\hat{c} = 2$, we have $\lambda^* = 3.06$ and $q^* = 0.77$. Notice that orders are set above each supplier's expected supply $(q^* > 1/\lambda^*)$. Investments are low and the contractor relies on order inflation to address potential shortages.

With the cost associated with renewables falling and better possibilities to store or even sell excess supply of energy, we should observe a greater reliance on order inflation and lower investments in reliability.

This completes the analysis of the optimal sourcing strategy when investments are contractible.

4. Optimal contracts under decentralized investments

The question we address now is: would we observe higher investments in reliability if this decision was taken privately, and non-cooperatively, by the energy generators?

In this situation, the contract specifies the order size and the monetary transfers to the supplier which depend on how much is delivered. We introduce, without loss of generalities, the reward functions $t^S(.)$ and $t^F(.)$ such that: $w(q_i) = cq_i + t^S(q_i, \hat{\lambda}_i)$ is the payment upon *successful* delivery and $w(s_i) = cs_i + t^F(q_i, \hat{\lambda}_i)$ is the transfer when the producer *fails* to complete the order and delivers a quantity $s_i < q_i$. The variable $\hat{\lambda}_i$ is the *recommended* level of reliability.

The optimal contract must satisfy the participation constraints given by (2). Taking into account the expressions for the remuneration functions, (2) can be re-written as

$$\pi\left(t^S(q_i,\hat{\lambda}_i)\right)-\left[\pi\left(t^S(q_i,\hat{\lambda}_i)\right)-\pi\left(t^F(q_i,\hat{\lambda}_i)\right)\right]F(q_i)-I_i\geq 0 \quad (i=1,2). \tag{10}$$

The optimal contract must also satisfy an incentive constraint stating that producer i will select reliability $\lambda_i=\hat{\lambda}_i$ that maximizes its profits, meaning that

$$-q_i[1-F_i(q_i)]|_{\hat{\lambda}_i}\left[\pi\left(t^S(q_i,\hat{\lambda}_i)\right)-\pi\left(t^F(q_i,\hat{\lambda}_i)\right)\right]-I_i'(\hat{\lambda}_i)=0\,. \tag{11}$$

The second order condition guaranteeing that $\hat{\lambda}_i$ is a maximum holds, provided that $I''(\hat{\lambda}_i)+q_iI'(\hat{\lambda}_i)>0$, which holds provided the investment function is sufficiently convex.

Lemma 5: *The optimal contract is such that the functions* $t^S(q_i,\hat{\lambda}_i)$ *and* $t^F(q_i,\hat{\lambda}_i)$ *depend on both the order size and the recommended rate of occurrence. Specifically, we have*

$$t^S(q_i,\hat{\lambda}_i)=\pi^{-1}\left(I_i(\hat{\lambda}_i)-I_i'(\hat{\lambda}_i)\frac{F_i(q_i)}{q_i(1-F_i(q_i))}\right) \text{ and } t^F(q_i,\hat{\lambda}_i)=\pi^{-1}\left(I_i(\hat{\lambda}_i)+I_i'(\hat{\lambda}_i)\frac{1}{q_i}\right).$$

Proof: In equilibrium the optimal contract is such that both; the participation and the incentive constraints bind. The above functions satisfy this requirement. ▌

As one would expect, the contract is no longer efficient. Each generator is penalized in the event of an energy shortage and gets a bonus when the order is successfully completed since

$$\left(I_i+I_i'\frac{1}{q_i}\right)<I_i<\left(I_i-I_i'\frac{F_i(q_i)}{q_i(1-F_i(q_i))}\right). \tag{12}$$

The implementation of penalties and bonuses introduces some dispersion which is inefficient but necessary to guarantee incentive compatibility. However, and more interestingly, (11) implies that the payoff distortion imposed on the producers, and hence the extent to which the contract is inefficient, depends on the order size. This means that the order size plays an additional strategic role. Lemma 6, below, brings to light the relationship between investment, contract efficiency and order sizes.

Lemma 6: *Given any order set below the energy generator's expected supply (i.e.* $q_i<\frac{1}{\lambda_i}$*) any given investments can be implemented via lesser profit dispersion by marginally increasing the order size. Given any order set above the energy generator's* *expected supply (i.e. $q_i > \frac{1}{\lambda_i}$) any given investments can be implemented via lesser profit dispersion by marginally decreasing the order size.*

Proof: Notice that the incentive constraint requires that

$$\left[\pi\left(t^S(q_i,\hat{\lambda}_i)\right)-\pi\left(t^F(q_i,\hat{\lambda}_i)\right)\right]=\frac{-I_i'(\hat{\lambda}_i)}{q_i[1-F_i(q_i)]|_{\hat{\lambda}_i}}. \tag{13}$$

Simple calculations lead us to

$$\frac{dq_i[1-F_i(q_i)]}{dq_i}=\lambda_i[1-F_i(q_i)]\left[\frac{1}{\lambda_i}-q_i\right]. \tag{14}$$

Therefore, for any given investment, the necessary inefficiency decreases with order size provided $\left[\frac{1}{\lambda_i}-q_i\right]>0$. ∎

The optimal contract in a decentralized setting relies on fine-tuning the order size and the payoff distortion. This fine-tuning exercise is complicated because increasing the order size triggers two countervailing forces. Larger orders are associated with lower expected profits for the generators (due to a higher risk of being penalized) as well as higher risk. The former implication impacts investments negatively while the latter would stimulate them.

Lemma 6 indicates that the contractor can reduce his reliance on profit dispersion and lower the contracting cost by managing the order size carefully. He can either slightly increase small orders and rely on the increased risk as a stimulus for investment, or, and by opposition, slightly decrease larger orders to increase the generators' expected profits and stimulate investment.

Finally, while we cannot solve for the optimal contract in this complex setting, we bring to light an interesting insight. When investment decisions are decentralized, there are some circumstances where the suppliers are more reliable and other circumstances where the contractor may be able to reduce his reliance on order inflation. Loosely speaking, while we cannot reach a win-win situation, i.e. achieving both reliability and no order-inflation, it is possible for the contractor to reach an improvement on one of the attributes.

Using Lemma 5, one can easily verify that the contractor's profits in a decentralized setting can be written

$$\widehat{\Pi}(q_1,q_2,\lambda_1,\lambda_2) = \Pi(q_1,q_2,\lambda_1,\lambda_2) + \sum_{i=1,2} \pi^{-1}(I_i)$$
$$-\sum_{i=1,2}\left[F(q_i)\pi^{-1}\left(I_i - I_i'\frac{1}{q_i}\right) + (1-F(q_i))\pi^{-1}\left(I_i - I_i'\frac{F(q_i)}{q_i(1-F(q_i))}\right)\right. \tag{15}$$

where $\Pi(q_1,q_2,\lambda_1,\lambda_2)$ is given by (3), (4) or (5) depending on whether the sum of orders is below, above or equal to one. In a decentralized setting, the cost associated with the investments increases and the contractor's profits decrease.

In order to analyse optimal outsourcing in the presence of decentralized investment decisions we consider once again the specific form $\pi(w) = \sqrt{w}$. In this case we have

$$\widehat{\Pi}(q_1,q_2,\lambda_1,\lambda_2) = \Pi(q_1,q_2,\lambda_1,\lambda_2)$$
$$+\sum_{i=1,2} I_i^2 - \sum_{i=1,2}\left[\frac{F(q_i)}{(1-F(q_i))}\frac{(I_i')^2}{(q_i)^2}\right]. \tag{16}$$

Assuming that $I(\lambda) = e^{-\lambda/2}$. Using Proposition 2 we are able to fully characterize the symmetric information solution. We then evaluate the derivative of $\widehat{\Pi}(q_1,q_2,\lambda_1,\lambda_2)$ at the solution that would prevail if investments were implementable by the contractor.

Assume once again that $c_S - c = 1$ so that $\hat{c} = c_S + c_E$.

Considering the two specific situations highlighted in the previous section, we explain how the equilibrium level of investment and orders change as we move from centralized to decentralized investments. We shall see that decentralization can exacerbate a tendency to invest large amounts or low amounts.

Situation 1: Relying on investments to address reliability issues.

Let $\hat{c} = 8$, under centralized investments we had $\lambda^* = 0.43$ and $q^* = 0.5$ $(q^* < 1/\lambda^*)$.

When investment decisions are decentralized the contractor implements larger investments via a greater reliance on order inflation. As a result, reliability is improved. In this case, decentralization will exacerbate a trend and lead to increased investments and increased reliability.

Situation 2: Relying on order inflation to address reliability issues.

Let $\hat{c} = 2$, under centralized investments we had $\lambda^* = 3.06$ and $q^* = 0.77$ $(q^* > 1/\lambda^*)$.

When investments are no longer contractible the contractor reduces the investments and the order sizes (that is, he reduces his reliance on order inflation). There is a loss in terms of the expected reliability which is partly balanced by a gain in the lower risk of facing excessive energy supply as orders are curtailed. However, once again, the investment strategy is exacerbated.

Therefore, we conclude that the contractor will increase his reliance on order inflation unless the orders under a centralised structure are high (second situation). This enables him to alleviate the cost triggered by the incentive constraint.

5. Conclusions

Increased shares of electricity from renewable energy sources are driving changes in electricity markets. This is leading *inter alia* to new types of bilateral contracts in power purchase agreements where the contractor is increasingly interested in procuring 100% renewable electricity. We have examined in this paper the optimal contract with unreliable renewable electricity generators.

When reliability investments are contractible and centralized such as in markets with vertically integrated electricity companies, we show that profit dispersion is sub-optimal: energy generators are neither rewarded for supplying enough power nor penalized for failing to do so. We then demonstrate that the incentive to invest in greater reliability is higher when the cost of energy production and the cost of dealing with excess supply are large. This is not necessarily good news. Indeed, since the cost associated with renewables is constantly falling and better possibilities exist to either store energy or sell it, future contracts may be geared towards a greater reliance on order inflation and lower investments in reliability, which is less efficient in terms of the overall energy system.

When investments are non-contractible and decided upon by the energy generators who act independently and non-cooperatively, the overall procurement costs are higher. In this case, the contractor can only expect generator investments that maximise the generators' profits rather than reliability. The contractor must rely on bonuses and penalties to incentivise the generators to undertake appropriate investments in reliability. Profit dispersion is inefficient but necessary. We show that, in such a context, the order size can be used strategically to reduce the procurement cost. However, the relationship between order sizes and investments is not straightforward because increasing orders triggers two countervailing incentives.

Firstly, generators are keener to invest when the returns from investment, that is their expected profits, are high enough. This can be achieved by reducing the order size since smaller orders are more likely to be completed and are therefore associated with a greater possibility of getting bonuses. On the other hand, generators are also keener to invest in reliability to reduce the risk of being penalized. In contrast to the driver already mentioned, this stimulus can be achieved by issuing larger orders which are subject to greater risk.

Using order sizes astutely can reduce the procurement cost by reducing the contractor's reliance on profit dispersion. While it is quite complex to solve for the optimal contract under decentralized investment decisions, we show that in some instances, the optimal contract induces energy producers to invest less in reliability but produces a reduced dependence on order inflation. In other instances, higher investments in reliability are implemented meaning that generators are effectively more reliable. Using two numerical examples we show that investment strategies can be exacerbated in a decentralised setting. When investments in reliability would have been high in the centralised setting, the decentralised situation would produce even more reliability. However, when centralised investments would have been low in a centralized setting, the decentralised situation would have led to even lower investments and a worse reliability.

The results of this paper show that in a world with increased deregulation of electricity markets and a push by high profile companies to procure 100% renewable electricity, optimal contracts between energy suppliers and risk-averse generators may deliver adverse outcomes to the overall energy system. Instead of encouraging investment in measures to increase the reliability of renewable electricity supply, such as flexibility or storage measures or increased operations and maintenance budget, suppliers might be motivated to inflate their order. This has repercussions for the electricity grid, with congestion on transmission lines in periods favourable to renewable electricity generation already an issue of concern. The implications for renewable electricity generators are more ambiguous: on the one hand larger orders might be lucrative and provide higher revenue than the spot market in a world with higher shares of renewable electricity, but it may make long-term contracts less attractive in line with the assertion of Falbo and Ruiz (2019) that they reduce the flexibility of renewable generators. Bilateral contracts are commercially sensitive and therefore their details are not accessible to the public. Nonetheless, as the prevalence of contracting 100% renewable electricity grows, regulators will need to keep a close watch on whether there is a detrimental impact on the electricity system. Creating markets for ancillary and capacity services is one way in which regulators may support generators to invest in reliability in parallel with their bilateral contracts.

Acknowledgements

This research was supported in part by a research grant from Science Foundation Ireland (SFI) under the SFI Strategic Partnership Programme Grant number SFI/15/SPP/E3125.

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APPENDIX.

Appendix 1: Proof or Lemma 1

Let $R^S(x_1,x_2)$ denote the contractor's revenue in the event of a shortage of renewable energy supply and $R^D(x_1,x_2)$ denote the contractor's revenue when there is excess supply. Both are net of monetary transfers to producers:

$$R^S(x_1,x_2) = R - c_S(1 - x_1 - x_2) \text{ and } R^D(x_1,x_2) = R - c_E(x_1 + x_2 - 1), \tag{17}$$

where $R > 0$ is the revenue from addressing the demand.

Finally let $W(x_1,x_2)$ denote the sum of transfers to the suppliers: $W(x_1,x_2) = w(x_1) + w(x_2)$.

Assume the orders submitted are such that $q_1 + q_2 \leq 1$. This means that the contractor avoids facing excess supply. In this case, the contractor's expected revenue is given by the following expression:

$$\Pi(q_1, q_2, \lambda_1, \lambda_2) = \Pi_{s_1 \leq q_1, q_2} + \Pi_{s_1 \geq q_1, q_2} \tag{18}$$

where

$$\Pi_{s_1 \leq q_1, q_2} = \int_0^{q_1} \left[\int_0^{q_2} (R^S(s_1,s_2) - W(s_1,s_2)) f_2(s_2) ds_2 + \int_{q_2}^{\infty} (R^S(s_1,q_2) - W(s_1,q_2)) f_2(s_2) ds_2 \right] f_1(s_1) ds_1 \tag{19}$$

and

$$\Pi_{s_1 \geq q_1, q_2} = \int_{q_1}^{\infty} \left[\int_0^{q_2} (R^S(q_1,s_2) - W(q_1,s_2)) f_2(s_2) ds_2 + \int_{q_2}^{\infty} (R^S(q_1,q_2) - W(q_1,q_2)) f_2(s_2) ds_2 \right] f_1(s_1) ds_1 \tag{20}$$

Assume the orders submitted are such that $q_1 + q_2 \geq 1$. In this case, the contractor's expected revenue is given by the following expression

$$\Pi(q_1, q_2, \lambda_1, \lambda_2) = \Pi_{s_1 \le 1-q_2} + \Pi_{s_1 \in [1-q_2, q_1]} + \Pi_{s_1 \ge q_1} \quad (21)$$

where

$$\Pi_{s_1 \le 1-q_2} = \int_0^{1-q_2} \left[\int_0^{q_2} \left(R^S(s_1, s_2) - W(s_1, s_2)\right) f_2(s_2) ds_2 + \int_{q_2}^{\infty} \left(R^S(s_1, q_2) - W(s_1, q_2)\right) f_2(s_2) ds_2 \right] f_1(s_1) ds_1 \quad (22)$$

and

$$\Pi_{s_1 \in [1-q_2, q_1]} = \int_{1-q_2}^{q_1} \left[\int_0^{1-t_1} \left(R^S(s_1, s_2) - W(s_1, s_2)\right) f_2(s_2) ds_2 + \int_{1-t_1}^{q_2} \left(R^D(s_1, s_2) - W(s_1, s_2)\right) f_2(s_2) ds_2 + \int_{q_2}^{\infty} \left(R^D(s_1, q_2) - W(s_1, q_2)\right) f_2(s_2) dt_2 \right] f_1(s_1) ds_1 \quad (23)$$

and finally:

$$\Pi_{s_1 \ge q_1} = \int_{q_1}^{\infty} \left[\int_0^{1-q_1} \left(R^S(q_1, s_2) - W(q_1, s_2)\right) f_2(s_2) ds_2 + \int_{1-q_1}^{q_2} \left(R^D(q_1 s_2) - W(q_1, s_2)\right) f_2(s_2) ds_2 + \int_{q_2}^{\infty} \left(R^D(q_1, q_2) - W(q_1, q_2)\right) f_2(s_2) ds_2 \right] f_1(s_1) ds_1. \quad (24)$$

The Lagrangian, which takes into account constraint (2) in the text, can be written as

$$\mathcal{L} = \Pi(q_1, q_2, \lambda_1, \lambda_2) - \sum_{i=1,2} \beta_i \left[\int_0^{q_i} \pi(w(s_i) - cs_i)\, f_i(s_i) ds_i + \int_{q_i}^{+\infty} \pi(w(q_i) - cq_i) f_i(s_i) ds_i - I_i \right],$$

where β_i $(i = 1,2)$ are the Lagrangian multipliers and $I_i \equiv I(\lambda_i)$ for $i = 1,2$.

The following first order conditions must hold for $i = 1,2$ and any $x_i \in \{s_i, q_i\}$

$$\beta_i \pi'(w(x_i) - cx_i) - 1 = 0 \ (i = 1,2). \quad (25)$$

It follows that $w(x_i) - cx_i$ is independent of how much is produced. To complete the proof of the Lemma 1 must use the fact that the participation constraint must hold.

Appendix 2: Proof of Second Order Condition for Proposition 1

Recall that for all $q_i \geq 1 - q_j$ with $i, j = 1,2$ and $i \neq j$, the first order condition is given by

$$\frac{\partial \Pi}{\partial q_i} = (1 - F_i(q_i))[F_j(1 - q_i)(c_S + c_E) - (c + c_E)] = 0. \tag{26}$$

Assume that the solution is unique and interior so that the second term is equal to zero.

In such a case the Hessian matrix is given by (at the solution)

$$H = (c_S + c_E)[1 - F_i(q_i)]\begin{bmatrix} -f_2(1 - q_1) & 0 \\ 0 & -f_1(1 - q_2) \end{bmatrix}. \tag{27}$$

The above is clearly negative definite.

Assume that we have a multiplicity of solutions and for each of these, the optimal orders are such that the second term of (26) is negative at $q_i = 1 - q_j$. Since the second term is decreasing in q_i, it is negative for all $q_i > 1 - q_j$ and therefore $\Pi(q_1, q_2, \lambda_1, \lambda_2)$ is decreasing and maximized at $q_i = 1 - q_j$.

Appendix 3: Proof of Lemma 4.

Consider Figures 3 and 4 in the text. First, consider all (λ_1, λ_2) located strictly below the level curve for which there is no order inflation and for which there is a multiplicity of equilibria such that $q_1 + q_2 = 1$. Given the multiplicity of equilibria, there is no loss in generalities from assuming that the contractor selects orders located in the middle of the non-empty and non-singleton interval over which the best reply functions overlap (see Figure 2 in the text). In such a situation, the contractor's revenue is given by (5) in the text and a marginal increase in the rates of occurrence has no impact on the individual orders. It follows that the first and second derivatives of the profits are given by

$$\frac{\partial}{\partial \lambda_i}\Pi(q_1,q_2,\lambda_1,\lambda_2)|_{\frac{\lambda_1\lambda_2}{(\lambda_1+\lambda_2)}<\ln \hat{c}} = -(c_S - c)\int_0^{q_i} \frac{\partial F_i(s)}{\partial \lambda_i} ds < 0. \tag{28}$$

since $\frac{\partial F_i(s)}{\partial \lambda_i} = s[1 - F_i(s)] \geq 0$,

$$\frac{\partial^2}{\partial \lambda_i^2}\Pi(q_1,q_2,\lambda_1,\lambda_2)|_{\frac{\lambda_1\lambda_2}{(\lambda_1+\lambda_2)}<\ln \hat{c}} = -(c_S - c)\int_0^{q_i} \frac{\partial^2 F_i(s)}{\partial \lambda_i^2} ds > 0. \tag{29}$$

since $\frac{\partial^2 F_i(s)}{\partial \lambda_i^2} = -s^2[1 - F_i(s)] \leq 0$.

Now let us consider all (λ_1,λ_2) located on or above the level curve for which we have an interior solution. In such a situation, the contractor's revenue is given by (4) in the text and the optimal orders (even on the level curve) solve $\frac{\partial \Pi(q_1,q_2,\lambda_1,\lambda_2)}{\partial q_i} = 0$ for $i = 1,2$. Using the fact that the first order condition holds in relation to the orders we have

$$\begin{aligned}\frac{\partial}{\partial \lambda_i}\Pi(q_1,q_2,\lambda_1,\lambda_2)|_{\frac{\lambda_1\lambda_2}{(\lambda_1+\lambda_2)}\geq\ln \hat{c}} &= (c + c_E)\int_0^{q_i} \frac{\partial F_i(s)}{\partial \lambda_i} ds \\ -(c_S + c_E)&\left[\int_0^{1-q_j} \frac{\partial F_i(s)}{\partial \lambda_i} ds + \int_{1-q_j}^{q_i} \frac{\partial F_i(s)}{\partial \lambda_i} F_j(1-s) ds\right]\end{aligned} \tag{30}$$

Using (26) we can replace $(c + c_E)$ by $F_j(1-q_i)(p + c_S + c_E)$ and since

$$\frac{\partial F_i(s)}{\partial \lambda_i} = s[1 - F_i(s)]$$

we can re-write the right hand side of (30) as:

$$(c_S + c_E)\left[\int_{1-q_j}^{q_i} s[1 - F_i(s)][1 - F_j(1-s)]ds - \left(1 - F_j(1-q_i)\right)\int_0^{q_i} s[1 - F_i(s)]ds\right].$$

Notice first of all that for all (λ_1,λ_2) located on the level curve the first term in the brack cancels out since $q_i = 1 - q_j$. Thus, for any such (λ_1,λ_2), $\frac{\partial}{\partial \lambda_i}\Pi(q_1,q_2,\lambda_1,\lambda_2)|_{\frac{\lambda_1\lambda_2}{(\lambda_1+\lambda_2)}\geq\ln \hat{c}}$ is negative.

For all (λ_1,λ_2) located above the level curve notice that for any $t \le q_i$ we have $[1-F_j(1-s)] \le [1-F_j(1-q_i)]$, therefore

$$\int_{1-q_j}^{q_i} s[1-F_i(s)][1-F_j(1-s)]ds \le [1-F_j(1-q_i)]\int_{1-q_j}^{q_i} s[1-F_i(s)]ds \quad (31)$$

It follows that $\frac{\partial}{\partial \lambda_i}\Pi(q_1,q_2,\lambda_1,\lambda_2)|_{\frac{\lambda_1\lambda_2}{(\lambda_1+\lambda_2)}\ge ln\,\hat{c}}$ is necessarily non-positive.

Finally, the second derivative of the profits is given by

$$\frac{\partial^2}{\partial \lambda_i^2}\Pi(q_1,q_2,\lambda_1,\lambda_2)|_{\frac{\lambda_1\lambda_2}{(\lambda_1+\lambda_2)}\ge ln\,\hat{c}} = (p+c_S+c_E)\left[\left(1-F_j(1-q_i)\right)\int_0^{q_i} s^2[1-F_i(s)]ds - \int_{1-q_j}^{q_i} s^2[1-F_i(s)][1-F_j(1-s)]ds\right] \quad (32)$$

Using once more the fact that for any $s \le q_i$ we have $[1-F_j(1-s)] \le [1-F_j(1-q_i)]$ proves that the above expression is positive.

We now prove that the function $\Pi(q_1,q_2,\lambda_1,\lambda_2)$ is continuously differentiable.

Just above the level curve $\frac{\lambda_1\lambda_2}{(\lambda_1+\lambda_2)} = \ln \hat{c}$ we have

$$\lim_{\frac{\lambda_1\lambda_2}{(\lambda_1+\lambda_2)}\to ln\,\hat{c}} \frac{\partial}{\partial \lambda_i}\Pi(q_1,q_2,\lambda_1,\lambda_2)|_{\frac{\lambda_1\lambda_2}{(\lambda_1+\lambda_2)}\ge ln\,\hat{c}} = -(c_S+c_E)\left(1-F_j(1-q_i)\right)\int_0^{q_i} s[1-F_i(s)]ds,$$

because $q_i = 1-q_j$. The expression above is equal to $\frac{\partial}{\partial \lambda_i}\Pi(q_1,q_2,\lambda_1,\lambda_2)|_{\frac{\lambda_1\lambda_2}{(\lambda_1+\lambda_2)}< ln\,\hat{c}}$ provided

$$(c_S+c_E)\left(1-F_j(1-q_i)\right) = (c_S-c).$$

Since at the solution we have $F_j(1-q_i)(c_S+c_E) = (c+c_E)$, the above is true.

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