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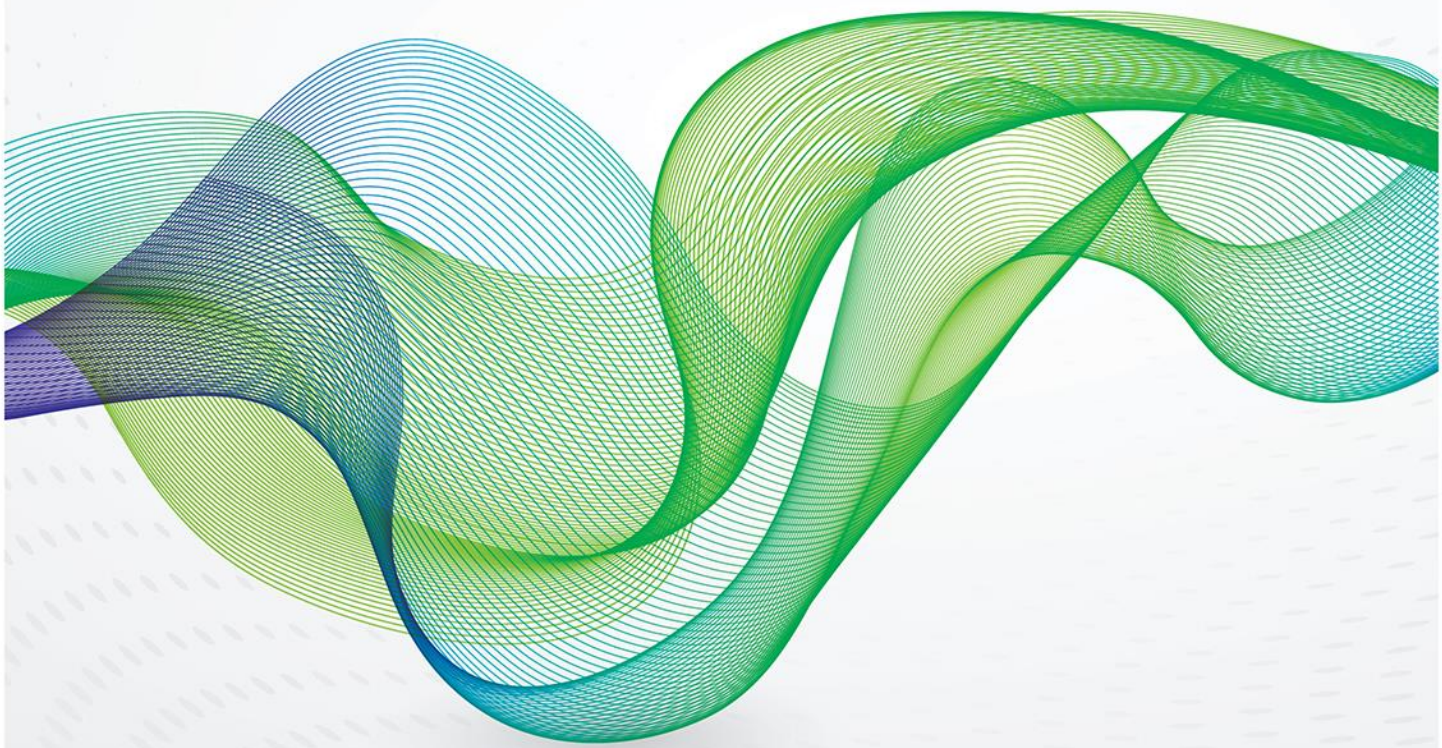

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Electricity Networks: Technology, Future Role and Economic Incentives for Innovation

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Abstract

While the economics of low carbon generation technologies is fast improving due to a mix of policy and market driven incentives, innovation in electricity networks has been relatively sluggish. This slow adaptation of electricity networks is challenging as they are key to the energy transition. Further electrification of the economy requires significant investment and innovation in the grid segment of the electricity supply chain. Traditional regulatory models of natural monopoly network utilities are designed to incentivise cost efficiency, with the assumption that network business is costly and the task of regulation is to encourage cost reduction subject to firm achieving a certain level of reliability. A feature of innovation activities is that they are riskier in comparison with the business-as-usual activities of network firms. This paper reviews the evolution of electricity grids from the technological and organisational perspectives and analyses the efficacy of existing incentive models in encouraging innovation. We show that incentive mechanisms that do not take uncertainty into account in the outcome of innovation efforts divert the attention of network utilities from innovation to normal efficiency gains. We also demonstrate that the issue of risk can distort the outcome of a competitive scheme for innovation funds when bidders are heterogeneous in their risk tolerance. Finally, based on the results of our analysis about the role of risk in innovation activities and a review of innovation incentive mechanisms in the UK and Italy, we provide recommendations for addressing the problem of innovation under regulation.

Keywords: Electricity networks, economic regulation, technology, organisation, business model, innovation incentive, UK, Italy

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1. Introduction

Innovation is crucial to enable transformation of the energy sector. In Europe, this is recognised by the European Commission and is reflected in one of the five dimensions of the Energy Union Communication adopted in 2015 (European Commission, 2015). In relation to electricity networks, which are at the centre of major trends in the industry (such as electrification, decentralisation, and digitalisation) the issue of innovation is more important than ever. The power grid needs to adapt to its changing operating environment. The electrification of the heat and transport sectors, which are currently being pursued as a default strategy by many European countries, has serious implications for grid infrastructure. Without intervention, the combined electrification of heat and transport can cause the peak electricity demand of a developed economy to grow as much as 1 GW per year post 2030 (ENA, 2017). This means the electricity networks require more agility, control, automation, new regulatory models, and innovative business models, both at transmission and distribution network levels. The problem is even more critical at low voltages, because this is a place where most disruptive technologies are located and this area has traditionally been managed in a passive manner.

Innovation can be defined as a process through which new methods are created or alternative methods are adopted, with the aim of providing improved outcomes (UKRN, 2015). In the context of infrastructure service businesses (such as: electricity, gas, and telecommunication networks) this can be expanded into technical innovations, process innovations, and commercial innovations.

- Technical innovation occurs when existing technologies are improved or new technologies are introduced, so that goods and services can be delivered more efficiently and/or reliably.
- Process innovation relates to improvements in management and the operations of organisations, in order to lower costs.
- Commercial innovation is the introduction of new business models to offer services that otherwise would not have been commercially feasible.

These all mean that the grid requires improving not only in technological aspects but also in organisational and business models dimensions. In recent years, efforts at the level of the low-voltage grid have largely been focused on dealing with issues such as renewable intermittency, congestion, load shifting, and bidirectional flow. In the future, technological innovation at the grid edge[1] will facilitate the development of markets for distributed resources, service-oriented business models, and end-to-end integrated grid management. This implies the role of the grid is evolving beyond just supplying electricity to consumers. There are multiple pathways here but one scenario envisions the electricity network as a platform that also maximises the value of grid edge technologies such as distributed generation, storage, energy efficiency, demand response, and electric vehicles. Therefore a new paradigm (including a technical, regulatory, and business model) is required at grid level to integrate disruptive technologies, find new ways of operating to meet customers' expectations, and facilitate grid edge transformation.

Innovation in the electricity industry has generally been sluggish, but it is even more so when it comes to the network segment. This is because the capital intensive network infrastructures exhibit natural monopoly characteristics that result from high economies of scale relative to market size. Due to the absence of direct competition in these regulated industries, infrastructure providers rarely undertake the appropriate level of innovation activities to optimise their operation and improve the continuity and quality of their services. Therefore, innovation needs to be incentivised through economic regulation.

[1] The terms grid edge refers to a variety of devices which are close to the end-user and connected to the grid such as distributed generation and storage, smart meters, smart appliances and electric vehicles.

Traditionally, the regulatory regimes of network companies have been designed to incentivise cost reduction in the business-as-usual activities of firms (including provision of quality of service) and innovation was largely dealt with implicitly as part of cost reduction. An important difference between innovation and the business-as-usual activities of a network company is that innovation is not only costly, but is also risky as it does not always produce successful outcomes. The justification for incorporating innovations, despite these being risky activities, is that learning can be obtained both from successful and unsuccessful outcomes; it is thus rewarding in the long term despite being costly in the short run. However, regulatory models of network companies in many places are still efficiency-oriented rather than innovation-oriented. A recent report which analyses the regulatory models of distribution network companies in 20 EU member states shows that in 2016 only seven countries had provided explicit incentives for innovation (Eurelectric, 2016).

This paper addresses the issue of innovation in regulated electricity networks by asking the following key questions:

(i) What technical, process, and commercial innovations are happening in electricity networks?
(ii) How can innovation be incentivised through economic regulation?

The outline of this paper is as follows. The next section provides a brief history of grid evolution and reviews the technological as well as the organisational and business model aspects of grid innovation. Section 3 addresses the issue of incentivising innovation through regulation. Section 4 presents two case studies of the ways in which innovation is treated in the regulatory models of network companies in the UK and Italy. Finally, Section 5 provides some concluding remarks.

2. Power grid: the past, the present and the future

In 2016, the continental European power transmission grid consisted of more than 490,000 km of circuits and cables, connecting 1137 GW of generation capacity and 612 GW of demand in 35 countries (ENTSO-E, 2017). If power distribution networks are also added to this number, it will be evident that the size of grid is huge. Therefore, it is hardly surprising that the modern power grid, together with the generation and load devices that it connects, has been called the largest man-made machine in the world (Martin & Wade, 2016). How did this amazing machine come into being? The most widespread design of existing power grids – where meshed high-voltage transmission lines transport electricity from production to consumer hubs, while radial low-voltage distribution lines carry electricity to most consumers – took shape in the early 20th century. However, this design was not the first form taken by the electricity grid.

When electricity was first put to productive use in the 1880s, it was in the form of direct current (DC) generated by dynamos powered by reciprocating steam engines. The father of incandescent lightbulbs, Thomas Edison, was instrumental in putting in place the world's first commercial system of electricity transmission and conversion, based on direct current. Edison worked on improving the design and construction of larger dynamos, which were then used in the Pearl Street Station (commissioned in 1882 in densely populated Manhattan) to power lightbulbs that replaced oil and gas-based lighting. He also improved the design of DC transmission lines and obtained a patent for a feeder-and-main distribution system design. By 1884, the Pearl Street station was serving more than 10,000 lamps; by 1891 more than 1300 plants of similar design were in operation in the USA (Smil, 2005).

The dominance of these early Edisonian DC power systems did not last long. Between the late 1880s and 1900, the system of generation, transmission, and use was completely transformed by the invention of steam turbines, transformers, and motors. Compared to steam engines, steam turbines have higher efficiency and lower mass for the same power rating. Paired with alternators, they rapidly replaced the engine–dynamo set to become the power generator of choice. Transmission of electricity has the smallest losses at high voltages, but it is easiest to generate, and more convenient to use, at low voltages. The invention of transformers provided the interface that is required to convert between

alternating current of high and low voltages, making long-distance transmission of electricity practical. Finally, the advent of AC current-powered induction electric motors greatly expanded the use of electricity beyond lighting.

In 1886, competition between DC and AC systems was perceived as evenly matched. But a few years later, the progress made in technologies complementary to the AC system guaranteed its future dominance (Smil, 2005). By the 1900s, the blueprint of the large-scale 20th century power grid was already in place: high-voltage transmission of electricity from large efficient power generation units to load centres, across vast distances (see Figure 1). Incremental innovations have taken place since then to improve the efficiency, and increase the scale, of these operations, but the fundamental logic of power grid operation has not changed significantly (until now).

The economies of scale made possible by the early forms of large centralised AC generation and transmission technologies (in which the average cost of providing services at higher throughput, to more users, is lower than at smaller scale) gave the power sector the characteristics of a natural monopoly. Furthermore, the provision of electricity is an activity with significant positive social externalities. Hence, the organisational arrangements that have evolved to cope with these issues were regulated or government-owned, horizontally and vertically integrated monopolies (Joskow, 1996). However, since the 1980s, many countries around the world have been implementing power sector reforms. Power generation and retail functions have been liberalised and re-evaluated to perform as competitive segments, given that small-scale power generation plants (such as combined cycle gas turbines (CCGTs) and small-scale combined heat and power plants) have become competitive with large-scale generation facilities (Künneke, 2008). Nevertheless, network segments of the value chain – transmission and distribution – are still considered to be natural monopolies and thus subject to regulation.

The operating environment of network segments was largely unchanged during the 20th century, until the beginning of the new century when the importance of environmental policies rose in the agenda of policy makers around the world. The Kyoto Protocol, which was adopted in 1997 and entered into force on 16 February 2005, committed its parties to an internationally binding target for emission reduction. In addition the Paris Accord, which came into effect in November 2016, strengthened the global response to climate change threats through an agreement which aims to keep temperature rise this century below 2 degrees Celsius above the preindustrial level, and encourages efforts to limit it to 1.5 degrees if possible. Meanwhile in Europe, the EU embarked on an ambitious environmental programme to reduce greenhouse gas emissions by 80 per cent below 1990 levels by 2050, with interim milestones of 40 per cent and 60 per cent cuts by 2030 and 2040 respectively. Although the plan envisions a contribution from all sectors of the economy according to their technological and economic potentials, the power sector is perceived to have the highest potential for decarbonisation. This is because alternative energy sources (such as wind, solar, hydro, biomass, and nuclear) can replace fossil fuel power generation (fossil fuel plants with carbon capture and storage (CCS) can also be part of the low-carbon generation mix), thus greening the electricity grid. Furthermore, decarbonisation of the power sector paves the way for further decarbonisation of the economy through electrification of heat and transport. However, this requires significant investment and innovation in the power sector, specifically at the level of delivery infrastructure – which is the grid.

Electrification of the heat sector requires the use of highly efficient heat pumps. While these will impact the entire electricity network, their effect on the high-voltage transmission network will be much lower than on the low-voltage distribution grid, because its ability to alleviate their impact is much more limited. In the UK, for example, heat demand in the winter is around five times higher than electricity demand; this means a significant surge in the electricity demand and the consequent straining of national and local electricity grids, should electrification of the heat sector go forward (Love et al., 2017). Overall, four potential issues, at national and local levels, can occur as a result of the mass deployment of heat pumps.

- The national level issues, which exacerbate the need for capacity and flexibility in the system are:
    - increase in the peak demand,
    - increase in the ramp rate.

- At the local level challenges are:
    - voltage drop beyond the statutory limits,
    - insufficient thermal capacity of the low-voltage feeders and transformers.

Therefore, unless electricity networks are reinforced (both at transmission and distribution levels) electrification of the heat sector can be hampered by the inadequacy of existing infrastructures.

Electrification of the transport sector presents a slightly different problem. Through smart charging, part of the electric vehicle (EV) fleet can be accommodated in the existing network without any considerable reinforcement. For example, a recent study of the Spanish electricity system shows that off-peak charging can facilitate the roll out of a large number of EVs – enough to represent a quarter of the current total car fleet in the country (Colmenar-Santos et al., 2017). Furthermore, EVs can be suppliers of various services to the grid through the vehicle-to-grid (V2G) concept. Nonetheless, a full penetration of EVs in the electricity system would not be possible without a significant reinforcement of existing infrastructures.

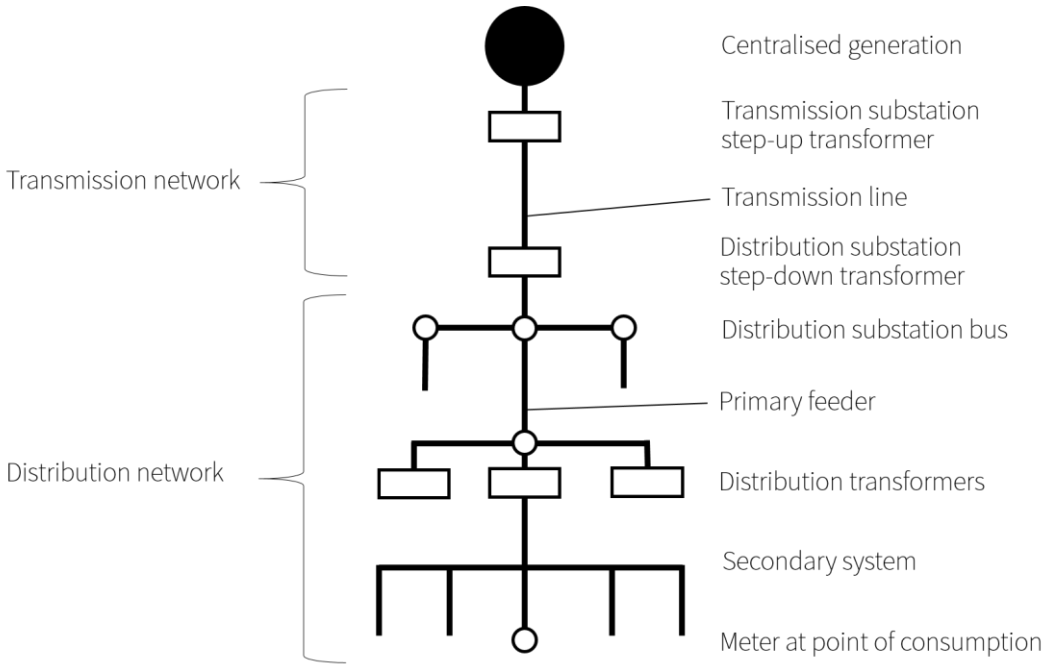
The main challenges of EV penetration are the provision of charging infrastructure and improvements in the charging time given the limited capacity of power that can be drawn at residential properties. At the moment, the top of the range EVs available in the market, with a large battery capacity of around 90 kWh, travel around 300 miles on a single charge. With a 7 kW charger, it takes roughly around 10 hours for a battery of the aforementioned size to charge up from around 25 per cent to 100 per cent (National Grid, 2017). Furthermore, due to limited residential power capacity, EV charging reduces the opportunity of households to use other appliances – such a kettle, oven, or electric heaters – simultaneously. These problems could be exacerbated in the future when the size of batteries increases further, to deal with the issue of range anxiety.

Charging time can be reduced significantly (to the level of minutes) by the introduction of high-capacity charging infrastructure (for example 100 kW, 350 kW, or even higher). However, both batteries and existing network infrastructures need to withstand such charging capacity. Given that such capacity does not exist at residential properties, there is a need to establish dedicated fast-charging stations (similar to petrol stations) to provide users with an experience identical to conventional car re-fuelling. This, however, requires significant investment at distribution network level. Such investment might be necessary to encourage battery makers to invest in larger batteries.

2.1 A brief review of technological aspect of grid innovation

In the last two decades, technological progress in the generation and demand-end sectors has been widely observed and tracked, from the growth of intermittent and/or distributed energy resources to electrification of further energy services. Unlike previous incremental innovations, these changes fundamentally challenge the way the centralised power grid is operated and regulated (Tuttle et al., 2016). Increasingly, innovation in network segments is also being pursued to facilitate technological breakthroughs at the supply and demand ends. The overall theme is one of more intelligent network components throughout the power network, permitting more accurate, possibly automated, control operations under various conditions. Figure 1 illustrates the main elements contained in the electric grid at the transmission and distribution level, which are referred to throughout this section.

Figure 1: Elements of a power distribution system



Source: authors

2.1.1 Transmission network

The transmission network, which is roughly differentiated from the distribution network by its higher voltage level and meshed topography, consists mostly of overhead AC transmission lines and substations. Substations, where transmission lines are connected and generation plants/distribution networks are connected to the transmission network, host various electrical devices such as sensors and control equipment. The key tasks assigned to the transmission grid are: transferring bulk power to the distribution system and increasing interconnections with neighbouring power systems and remote renewable resources. Innovations showing promise in the transmission network can be roughly divided into two categories, those related to improving:

- the power transmission infrastructure, or
- the telecommunication infrastructure that the transmission network relies on for monitoring and control.

2.1.1.1 Power transmission infrastructure

The power that can be transmitted on a transmission line is constrained by thermal, voltage stability, or transient stability[2] constraints. Depending on the length of the transmission line, one particular type of constraint may be more limiting than others: the thermal constraint[3] is more significant for short lines of up to 80 km, whereas the transient stability constraint is more restricting for long lines of more than 240 km (MIT, 2011). Historically, the thermal ratings of transmission lines were determined statically, taking conservative, seasonal, worst-case assumptions. The addition of two sensors to power lines – one to measure its tension, and the other the air temperature – can allow operators to determine average

[2] Transient stability: the ability of the power system to return to a stable condition after a major fault develops in the system.
[3] At high temperatures (either due to ambient conditions or resistive heating of the line), the sag of the powerline can reduce the line's clearance from ground to a level that is no longer acceptable.

conductor temperature, the main factor determining the power line's thermal rating. This results in transmission capacity ratings that better reflect the reality on the ground – providing a boost in line capacity when conditions are favourable, and restricting operations in extreme weather situations.

The issues of energy loss and line capacity are ongoing areas of technology advancement in grid infrastructure. Specifically, in recent years there has been interest in the idea of super conductors. Superconductors are materials that have very low electrical resistance when cooled below a material-specific critical temperature. High-temperature superconductors (HTSC) have critical temperatures which are relatively easy to achieve. If the critical temperature is maintained through adequate cooling, a transmission line that makes use of superconducting material can achieve much higher power capacity than a conventional conductor of the same size. In areas where new rights-of-way are difficult to obtain (for example, in areas of natural beauty), replacing an existing line with an HTSC cable is particularly attractive. This is an example of adopting new technologies at transmission grid level.

Another area of development at transmission grid level is AC to DC conversion, and vice versa, together with the ability to control a large amount of power and voltage. Development in this field has allowed high voltage direct current (HVDC) transmission lines in niche applications where conventional AC lines are not suitable (subsea transmission and the interconnection of asynchronous AC grids when two interconnected countries use different grid frequencies). Moreover, because of its cost structure, beyond a certain break-even distance, an HVDC transmission system, including the line and converters, is always less expensive than its AC equivalent, and power flow over an HVDC line can be accurately controlled. This makes HVDC very attractive for the connection of remote renewable resources. However, reliable control devices for HVDC systems are not yet available, preventing the development of meshed HVDC grids (Franck, 2011).

Similarly, another major technological development at transmission level is that of Flexible AC Transmission Systems (FACTS). These are power electronics which are used to dynamically control voltage and other key parameters in HVAC lines, thereby influencing power flow across the lines. Without such devices, the power flow across an AC network follows the path of least resistance. FACT devices are specifically helpful for cross-border trade as they can make power flow in an AC line compatible with the result of market operation. Furthermore, the adjustments that FACT devices allow are more rapid and precise than those enabled by conventional controllers located at substations, providing grid services such as voltage control, reactive power control, steady-state support, and dynamic stability more effectively.

2.1.1.2 Telecommunication infrastructure

The elements that constitute the transmission network are usually centrally monitored and controlled from a control centre.[4] Real-time information about the status of the system (power flows, substation voltages, output of all generators, status of all transmission lines and substation circuit breakers, transformer tap settings) are collected by special equipment and sent to the control centre, typically being displayed via a user interface. This equipment also relays back control commands issued by operators at the control centre. Since the 1980s, remote control devices have been equipped with microprocessors capable of receiving control signals from, or sending data to, an external source; they are also able to exercise distributed control, managing substations independent of the control centre (Thomas and McDonald, 2015). This allows for a more decentralised management of electricity networks in the power system. All these devices – including sensors/controllers, communication channels, and user interfaces at the control centre – make up the Supervisory Control and Data Acquisition (SCADA) system.

Given that not all power flows and voltages of interest in the system are measured, data collected is fed into a mode-based state estimator at the control centre, which then estimates the approximate state of

[4] There may be one control centre for the entire country or several.

the power grid based on its input. Other functions also performed by SCADA are the analysis of operating conditions and the determination of line flows or bus voltages under various hypothetical system contingencies.

Significant advances have been taking place in measurement devices; these were traditionally only able to measure scalar quantities, no other specifications of electrical wave were possible (Monti et al., 2016). The new devices can extract several useful parameters of power, following which their measurements can be synchronised using GPS time signals. These advanced measurement devices provide centralised and distributed controllers with superior measurements in terms of resolution and accuracy. There are also wide area measurement systems which are capable of very rapid analysis of anomalies over very large geographical areas (Gadde, Biswal, Brahma, & Cao, 2016).

2.1.2 Distribution network

In comparison to the transmission network, the distribution network contains many more elements and plays a larger role in the quality of service received by electricity consumers. It consists of:

- distribution substations (stepping down the voltage between the transmission network and primary feeders – the main supply lines that connect to secondary networks),
- distribution transformers (which further step down the voltage between the feeders and consumer premises), and
- all the interconnecting lines in between.

Radial systems, where consumers only have connection to one primary feeder, are common in low load density areas. This mode of operation was prevalent due to its simplicity, the ease of coordinating protecting devices, and overall economics. **Loop systems**, where consumers are connected to two primary feeders in a closed loop, are introduced where there are higher requirements for reliability.[5] While one section is out of service or being repaired, customers can be serviced by the other feeder.

Distribution network upstream of the primary feeders is monitored and controlled via SCADA systems. In general, automated remote sensing and control here is less developed than that in the transmission grid. Individual equipment monitoring has been seen as economically inefficient, given the large number of distribution transformers and customers connected. Traditionally, meters located on customer premises are used for billing, and suppliers visit the premises to read meters manually. Overall, the main direction of innovation in the distribution network is in improving distribution monitoring, control, and data processing/automation. This can be done at the medium-voltage level, low-voltage level, or for islanded microgrids.

2.1.2.1 Medium-voltage level

Given that monitoring and control of networks at low-voltage levels is uncommon, the restoration of customers after an outage can be a lengthy process: the distribution network operator is notified of the blackout through customers' calls, only then are crews sent out to track down and manually restore the system. Consequently, automatic Fault Detection, Isolation, and Restoration (FDIR) is being developed to reduce the time of outage.[6] This involves more extensive deployment of smart circuit breakers, sensors, and advanced control algorithms at the medium-voltage level.

FDIR has two main stages: fault location detection and isolation, followed by service restoration. Once the fault is located, the smallest possible part of the network is isolated by (remotely) opening the first upstream and downstream switches from the fault. To restore service to customers, suitable backup feeders need to be identified and the loads in out-of-service criteria are temporarily transferred to these

[5] A primary distribution network – a grid of interconnected primary feeders – offers the highest reliability in the case of a fault in one part of the circuit, since consumers can then be served by other interconnected feeders. This network is mainly found in downtown areas of large cities (Casazza & Delea, 2010).

[6] An automated approach to network restoration is why smart grids are sometimes referred to as being 'self-healing'.

feeders through switch operations, until the faulty section is completely repaired. Expert algorithms (in which expert knowledge and experience are translated into rule-based programming logic), mathematical programming approaches (where restoration plans are formulated as an optimisation problem), and multi-agent based approaches (where grid components such as intelligent agents with sensors, actuators, and processing capability have been introduced) have been used in this area (Zidan et al., 2016).

Another area for improvement in the medium-voltage level distribution network is in voltage control. Adjustable transformers (voltage regulators) and capacitors that can be switched in and out (capacitor banks), as well as other devices, are used to regulate voltages within a specified range along an entire path. These devices are controlled from the distribution substation. Voltage, the variable of interest, declines along the distribution line. Traditionally, given limited sensing capability within the distribution network, voltage is measured at the substation but not at the end of the line. Therefore, operators commonly set substation voltage to the upper end of the allowable voltage range, to ensure that the voltage at the end of the line is within limits. A new voltage/reactive regulation approach is also being developed that relies on a voltage sensor at the end of the distribution line. It allows a tighter control of voltage: the substation voltage can now be adjusted to maintain the line-end voltage at the lower end of its limit. This reduces the variation of voltage and lowers the average voltage across the line. The voltage and reactive power control applied at peak time is also known as conservation voltage reduction. Since the same load will draw less power at a lower voltage, then if the feeder voltage is reduced to the lowest acceptable value, the total power drawn throughout the network will decrease (Peskin, Powell, & Hall, 2012).

2.1.2.2 Low-voltage level

Another source of innovation in the distribution network is the extension of sensing and control to the end customers at the low-voltage level. Two types of smart meters are being rolled out across the world to enable this process.

- Automated meter reading (AMR), which broadcasts signals via short-range radio frequency. Meter readings can be captured from the street using special vehicles.
- Advanced Metering Infrastructure (AMI) represents a step above AMR. It is equipped with two-way communication capabilities and is capable of recording near real-time data on power consumption and reporting data to utility companies every hour, or more frequently. Utilities can communicate with AMI meters remotely and can also make connections/disconnections.

Availability of real-time measurement from the low-voltage grid (only enabled by AMI) allows the distribution network operator to understand customer behaviour and power quality phenomena at a resolution unseen before. Instead of balancing the grid based on customers' contracted power, the distribution network can now be balanced on the basis of the actual load/generation profiles in the network (Barbato et al., 2017). A major source of potential benefits associated with smart meters is residential load control and demand management. Consumers now have access to real-time information on their electricity consumption and grid status (time-of-use price or real-time prices), which allows them to more actively manage their consumption and self-generation when savings/incentives exist. But, smart meters by themselves cannot realise these system benefits. They must be incorporated into an integrated system that includes:

- customer-side controllers (allowing easy control of energy consumption devices),
- intelligent energy management system software (partially or fully automating the control process, taking into consideration consumer preferences), and

- communication channel between all these elements.[7]

2.1.2.3 Microgrids

The rise of distributed generation, located in proximity to electricity load, makes the design and operation of microgrids a new area of advancement in network technology. A microgrid is defined as a group of interconnected loads and distributed energy resources which acts as a single controllable entity with respect to the grid; it can operate in main grid-connected and in island modes (Parhizi, Lotfi, Khodaei, & Bahramirad, 2015). Thus, in contrast to being just the last link of an extended supply chain radiating outward from a few centres, distribution network sections which qualify as microgrids are self-governable small power systems; they have distributed energy resources (including storage) which are adequate to meet their own demand, and an independent control system capable of optimising between connected and islanded modes.

The most salient feature of a microgrid is its ability to operate in island mode. In case of disturbances upstream, the microgrid can be disconnected from the main grid, and resynchronised once the disturbance is removed. Hence the reliability of the grid is increased, especially in situations of significant transmission failure. Other possible benefits are the reduction of transmission and distribution costs, by using local and potentially less costly/renewable energy resources. Improved reliability via distribution automation, and improved efficiency through real-time sensing and control of customer-end load (described above as innovation paths for distribution networks), can also be applied in a microgrid setting.

2.1.2.4 Computing infrastructure and IT

For both transmission and distribution networks in the future, real-time wide-area situational awareness of grid status through advanced metering and monitoring systems is the trend. The increased amount of data created by smart grid devices (phasor measurement units and smart meters, for example) and the increasingly complex models in which they are used, can overwhelm the utilities if the underpinning data management ability and computing power have not been scaled up accordingly (Daki, El Hannani, Aqqal, Haidine, & Dahbi, 2017; Green, Wang, & Alam, 2013). Increasing incorporation of Big Data technologies and high-performance computing into the electricity network of the future is therefore expected.

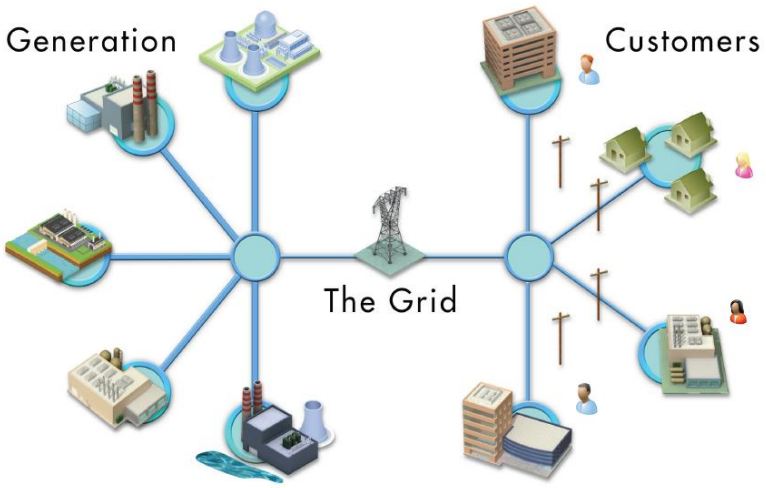
Another important area of technological innovation is blockchain technology and its application in electricity network operation. Blockchain is a fundamental technology that can provide an open and shared public network in order to execute transactions at very low costs. It is a cryptographically secure, shared record of transactions, updated by a network of computers rather than a central authority. The combination of blockchain technology and the Internet of Things (IoT) is likely to lead to innovation in the operation of electricity networks. It is likely that new opportunities will arise from blockchain-based systems which transform the way in which data are collected and shared.

Blockchain technology can impact all elements of the value chain across the electricity industry, from generation and wholesale to grid and retailing. In the context of the grid, blockchain can act as the backbone of the industry's smart grid management system, in which network issues are diagnosed automatically and reconfigured accordingly. In relation to grid infrastructure, we have the concept of an integrated network (see Figure 3), in which smart devices, computers, and other devices are directly connected to each other. This is an alternative to the traditional top-down model of organising and controlling a grid (see Figure 2) and can provide greater security and privacy, as traffic does not go through a central system. The advance here is that the concept of an integrated network can be

[7] Several types of communication schemes between smart grid devices have been proposed, such as power line communication, wireless networks using radio waves, and virtual private networks (based on the internet infrastructure) (Gungor & Lambert, 2006). In the home-area network, where smart meters and appliances are located, the wireless protocol ZigBee appears to have the most momentum, but others cannot yet be ruled out.

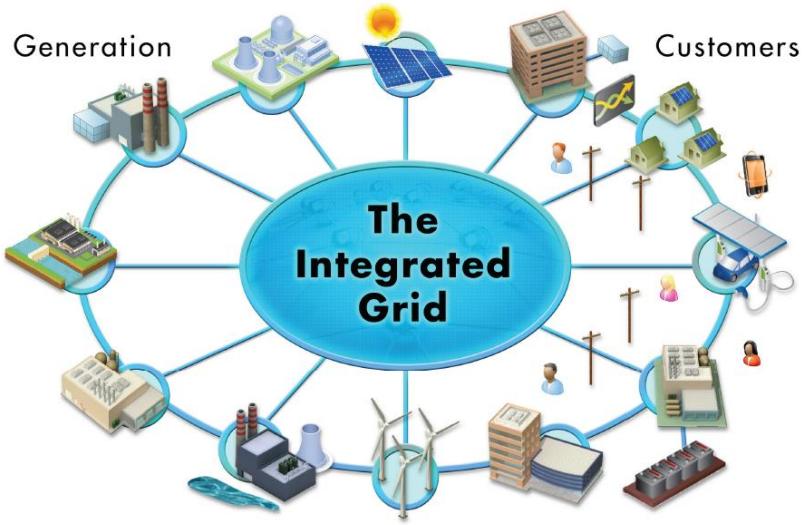
combined with blockchain technology to address complex grid infrastructure problems, monitor the condition of the grid, and avoid large blackouts.

Figure 2: The convectional grid



Source: EPRI (2014).

Figure 3: Integrated grid concept



Source: EPRI (2014).

2.2 Organisational and business model aspect of grid innovation

It is not only the technological side of the grid which is subject to innovation; the relevant organisational and business models are also improving. New operational areas become available as the operating environment of electricity networks changes, and a re-definition in the role and business models of these companies is required. At the level of distribution networks, where most of these changes are happening, the core areas of operation have traditionally been investment in, and operation of, the network – maintaining the security of the system and technical data and finally loss management. This traditional model assumes distribution grids as distribution network operators (DNOs), the very same model that has prevailed in the electricity industry since liberalisation. With integration of distributed energy resources and the need for more active management of grid operations, the role of distribution companies started to evolve from that of a DNO to one of distribution system operator (DSO). The difference between the two is that, under the DSO model, the distribution company assumes a role similar to that of the transmission system operator (TSO), but at a local level. Therefore, a DSO not only manages voltage and reactive power but also balances the distribution network to manage congestion in real time, using distributed resources, in coordination with the TSO.

A shift from DNO to DSO requires electricity distribution companies to enter into areas of operation which, based on the current regulations, can be considered as being beyond their core business or 'grey'. In other words, it is not clear whether or not these activities of distribution network companies violate the unbundling paradigm. Such activities include flexibility services such as demand response and storage, as well as smart metering, electric vehicles, customer data management, and telecommunication. At the same time, there are operational areas that, under the unbundling paradigm of network companies, are clearly and completely banned (such as generation and retailing).

2.2.1 Distribution system platform

There are many pathways that electricity networks could take as their role in the power system evolve. This is particularly relevant for distribution network companies who need to make significant investment decisions and could evolve in different directions (ENA, 2017). For example, they can move towards further implementation of smart solutions to improve their efficiency or undergo more fundamental changes and become a neutral market facilitator with some system operator capability.

In recent years, there has been a growing interest in the notion of the distribution system platform (DSP) as a future model for electricity distribution networks (Energy Institute, 2017). The aim of a DSP is to integrate new and innovative energy resources and allow them to compete with traditional centralised sources of energy on a level playing field. According to this model, it is not enough for distribution network utilities to be just providers of wire connection to the customers. They need to act as intermediary platforms which connect participants, reduce the costs of transaction, and convert data to information that helps consumers and suppliers to offer/achieve goods in a more efficient way. The shift in business model from network operator to platform provider creates tremendous possible alternatives to the need for building more physical network infrastructure. The network as a platform provider also enables business opportunities for other players to offer their services without owning expensive assets.

Under the platform model, the revenue of network utilities comes from acting as an intermediary connecting retailers, consumers, and prosumers; this is similar to the role of the software company Uber when providing a means of connection between rider and driver. The charge for the costs of networks can be subscription-based, transaction-based, marginal cost pricing, or premium pricing and it can be charged to one side or to both sides of the market (generators and consumers).

The concept of Transactive Energy (TE)[8] also envisions the grid as a place that captures the benefits of network effects. Similar to the sharing economy business models, in the TE model, distribution and transmission companies can access reliability products (such as voltage support, supplemental reactive power, and ancillary services) through a market place based on the grid (Energy Institute, 2017). The term 'transactive' in this context indicates that decisions are made on the basis of a value. This model relies on the high penetration of communication technologies. The demand for current and future transactions determines the location and investment planning of distributed energy resources.

The implementation of the platform model in the context of other businesses has been easier than in electricity networks. This is because many internet-based businesses (such as Uber and Airbnb) are not capital intensive and are not held back by a legacy system either in physical or institutional terms. Re-design of electricity networks as platforms can be more challenging.

Looking forward, there are still many open questions regarding the role, institutional structure, and business model of electricity network companies. For instance, it is not clear whether the operations of distribution companies need to be performed by an independent entity (similar to the independent system operator in the case of transmission) or if the owners should continue the role of operatorship. Furthermore, there are suggestions that DSOs become 'not for profit' organisations, as opposed to the 'for profit' status of current entities.

In terms of the revenue model, although platform markets are compatible with many forms of charging strategies, it is still not clear what model works best for DSOs. Many successful platform markets charge both sides of the market; however, given the small amount of energy involved in residential transactions, the network utilities may struggle to recover their costs. Furthermore, a platform model grows and becomes economic when the number of customers connected also grows. However, network utilities are bound by their service areas. This means that for platform services, they cannot attract customers from outside their designated area.

In terms of products and services that a platform can offer there is more flexibility. These products can range from traditional energy and capacity to distribution-specific products such as low-voltage congestion reduction and reactive power. There is also the possibility of specific services such as risk management for customer bill volatility, and software programmes that free up consumers from direct energy making decisions. However, how these services should be designed, and whether the revenue from them will be sufficient to recover the costs of operating and maintaining the platform, is yet to be seen. Finally, there are still important questions about how the distribution-level market model should coordinate with the existing bulk power system so as to avoid physical and financial operational conflict.

At the moment, there are some demonstration projects around the world which try to test distribution platform markets in order to better understand the platform concept and explore answers to questions raised above. One such initiative is taking place in the US state of New York, which is pushing for experimentation with DSP under Reforming the Energy Vision (REV). For instance, ConEdison is testing the aggregation of distributed energy resources, such as solar and batteries, by creating a virtual power plant (VPP) and connecting 300 homes. Another example along the same lines is the Decentralised Energy Exchange project in Australia, whereby a software package reviews availability and prices bid for demand response and other related services, and selects bids on a least cost basis in order to deliver energy and demand reduction to the distribution network operator. Finally, the Transactive Energy concept is being implemented in multiple pilot projects around the world. For instance, the PowerMatching City demonstration project in the Netherlands has created an integrated smart grid system of 25 houses in Groningen city that interconnects renewable energy generators,

[8] TE is usually defined as 'a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter' (NIST, 2017). In other words, TE refers to the use of a mix of economic and control techniques to improve the reliability and efficiency of the grid. These techniques can also be used to optimise operations within customers' premises.

electric vehicles, smart appliances, and smart meters. The initiative uses market platform software in order to make real-time operational decisions based on five minute intervals, in order to match supply and demand. The second stage of this project is expected to include 40 households and to develop new models.

In summary, these small initiatives, which often rely on blockchain or similar technologies, herald a change in the operation of electricity networks and highlight the importance of innovation, not only in technological dimensions but also in the business model and organisational aspects of power grid companies.

3. Economic incentive for grid innovation

Incentive regulation (such as price cap and revenue cap), was originally designed with the aim of improving the efficiency of natural monopoly infrastructures. The issue of innovation was not dealt with explicitly in regulation, as it was assumed that the incentive for cost reduction also promotes innovation. Therefore, the standard regulatory model of network companies incentivises only cost reduction or static efficiency gain, subject to meeting certain levels of reliability. This is usually done through sharing with the firm a percentage of its cost reductions during the regulatory period. However, the risk profile of innovation efforts is different from that of the normal activities of firms. This means that the conventional efficiency-oriented model of grid regulation is inadequate to stimulate innovation. In this section we first show the reason why a focus on costs reduction does not necessarily deliver innovation. We also examine the effects of risk, in the context of competitive schemes for innovation funds. Finally, we review the regulatory options for explicitly dealing with innovation in the regulatory model of network companies.

3.1 Incentive for innovation versus incentive for cost efficiency: one regulation two tasks

Implementation of incentive regulation per se does not necessarily incentivise network companies to undertake innovation, especially when the objective of innovation is beyond cost efficiency. This is even true when the objective of innovation is cost efficiency but the way of achieving it is through implementation of less certain technologies and processes. We distinguish between innovation and normal efficiency gain based on the level of risks involved in these two activities: normal efficiency gain is assumed to be less risky compared with innovation efforts.

In order to investigate this, let's consider the incentive regulation model in (1):

$$z = \beta + \alpha_1 x_1 + \alpha_2 x_2 \qquad (1)$$

Where:

z: allowed compensation of the firm for its innovation and efficiency gain efforts.

β: fixed part of compensation plan that is directly transferred to the consumer through an uplift in network tariffs.

x_1: the normal efficiency gain of the firm from its effort.

x_2: the gain of the firm from its innovation effort.

α_1: is a number between zero and one that determines the share of the firm from its efficiency gain.

α_2: is a number between zero and one that determines the share of the firm from its innovation gain.

A firm can exert effort to reduce its costs as part of its normal operation, but cost reduction is not guaranteed. Therefore, we assume the amount of cost reduction (x_1) is a function of effort of the firm (e_1) and a risk parameter (ε_1) which has a normal distribution with mean zero and constant variance σ_1^2 as in (2).

$$x_1 = e_1 + \varepsilon_1 \qquad \varepsilon_1 \sim N(0, \sigma_1^2) \tag{2}$$

The size of variance (ε_1) shows the amount of risk that the firm faces with respect to the outcome of its cost reduction efforts.

At the same time the regulator aims to incentivise innovation as part of the regulatory model, by allowing the firm to claim a share ($0 \leq \alpha_2 \leq 1$) of the value of its innovation outcome (x_2). The implicit assumption here is that the innovation outcome is verifiable and measurable by the regulator. For example, suppose that the firm creates a considerable level of efficiency gain, but this increased productivity is the result of activities with a different (higher) level of risk profile. Alternatively, it creates a process or product that has a present value of x_2. (For example, the regulator has defined *ex ante* what counts as innovation and how its value will be estimated. An increase in the number of distributed resources and the utilisation of intelligent network management could be used as an innovation indicator and their value calculated by the amount of investment deferred, and by all other savings such undertakings can provide.)

Similar to the previous case, there is uncertainty in the outcome of innovation activities, so we assume that innovation gain (x_2) is a function of the firm's effort (e_2) and a risk parameter (ε_2), which indicates the uncertainty in the outcome of the firm's effort, with mean zero and constant variance (σ_2^2) as in (3).

$$x_2 = e_2 + \varepsilon_2 \qquad \varepsilon_2 \sim N(0, \sigma_2^2) \tag{3}$$

When innovation is motivated within the existing regulatory model of network companies, incentive regulation is supposed to fulfil an additional purpose – in other words, in addition to the normal cost reduction, the regulatory regime needs to incentivise the firm to carry out costlier and perhaps riskier innovation activities. This means that the optimum regulatory scheme in this case should not only allocate the risk and compensate the firm for its effort, but also allocate attention between two tasks.

In order to analyse the behaviour of the firm under the regulatory regime presented in (1) we employ the multi-task moral hazard model proposed in Holmstrom and Milgrom (1991). Under this setting, the regulated firm chooses the vector of effort $e = \binom{e_1}{e_2}$ in order to produce the vector of outcome $x = \binom{x_1}{x_2}$ which is affected by risk (ε) as in (4).

$$x = e + \varepsilon \qquad \varepsilon \sim N(0, \Sigma) \quad \text{where} \quad \Sigma = \begin{bmatrix} \sigma_1^2 & \sigma_{12} \\ \sigma_{12} & \sigma_2^2 \end{bmatrix} \tag{4}$$

The firm experiences the cost of $c(e)$ for its efforts. We assume that the regulated firm is risk averse and that its risk preference can be represented by a Constant Absolute Risk Averse (CARA) utility function as $u(z) = -\exp\big(-rz - c(e)\big)$, where r measures the degree of risk aversion.

We assume the shape of the firm's cost function ($c(e)$) for carrying out cost-reducing efforts (e_1) and innovation efforts (e_2) as in (5) where $|\theta| < \rho$.

$$c(e_1, e_2) = \frac{1}{2}\rho(e_1^2 + e_2^2) + \theta e_1 e_2 \tag{5}$$

The variance matrix in (4) allows for the possibility that the risk of two activities (innovation and efficiency) can be correlated. Likewise, the cost function in (5) allows for the possibility of shared technological features between efficiency and innovation activities. Apart from the fact that these assumptions can be reasonable, given that the two activities are conducted within the same firm with the same resources, and have similar purposes, being able to make general assumptions allows for general solutions which cover a wide range of possibilities.

In terms of the solution the main aim is to understand:

(i) What is the optimal level of α_1 and α_2?
(ii) How do the optimal values for α_1 and α_2 change when the risk of innovation increases compared to the efficiency gain?
(iii) How does the effort of a firm undertaking two tasks change with increased risk of innovation activity?

The regulator (namely the principal) is assumed to be risk neutral and obtain the gain (on behalf of consumers) equal to $x - z(x)$ after compensating the firm according to the plan $z(x) = \beta + \alpha^T x$ where α^T is the transposed vector of the firm's share from efficiency and innovation gain which is represented by vector x.

Solving equation (1) on the basis of the aforementioned assumptions leads to an expression for the optimal share of firms from efficiency gain and innovation, as presented in A(13), and to another for the optimal level of effort as in A(14) (see appendix for the details).

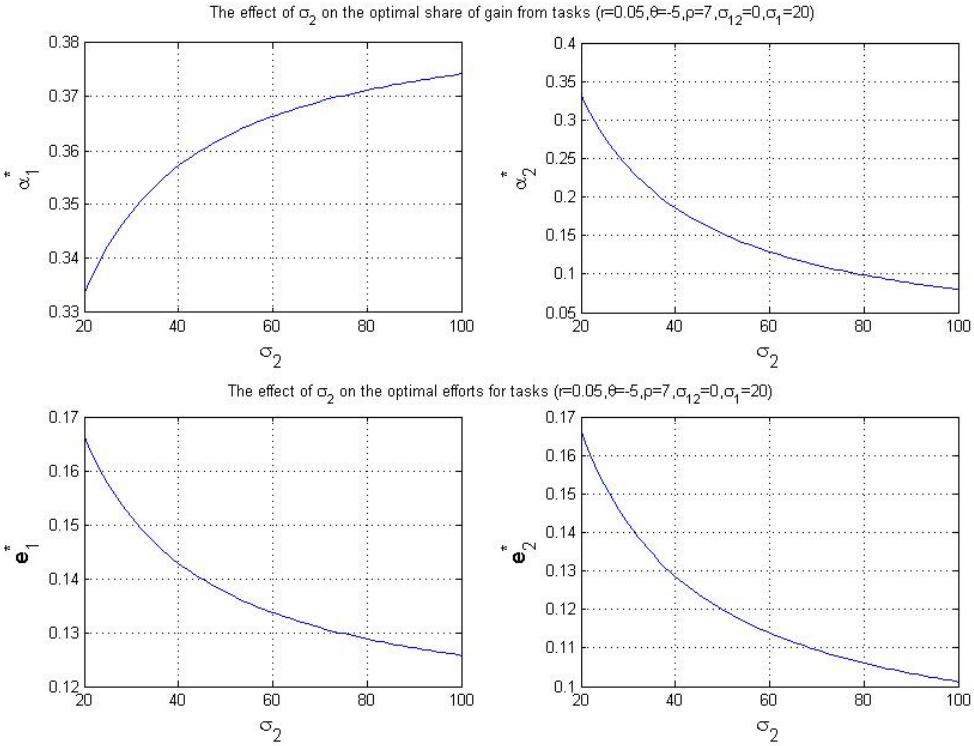
Equations A(13) and A(14) in the appendix reveal some interesting features on the structure of an optimal compensation plan for innovation and efficiency gain when they are treated similarly despite having different risk profiles. In order to understand what the implications of incentivising innovation under the regulatory model in (1) are, we carry out some simple simulation analysis.

3.1.1 Simulation of results

Below we provide some simple simulated results under various scenarios with respect to cost structure and the uncertainty of outcome of two tasks. In each case, we show what happens to optimum incentive structure and effort, when innovation is more uncertain compared with the normal efficiency gain of the regulated firm.

(i) In the first case we assume that the risk profiles of the two tasks are independent ($\sigma_{12} = 0$). We also assume that there is synergy between the two activities (doing them together is less costly than doing them separately – in other words, $\theta < 0$), so the shape of an optimal compensation scheme for some chosen values that satisfy our assumptions would be as in Figure 4.

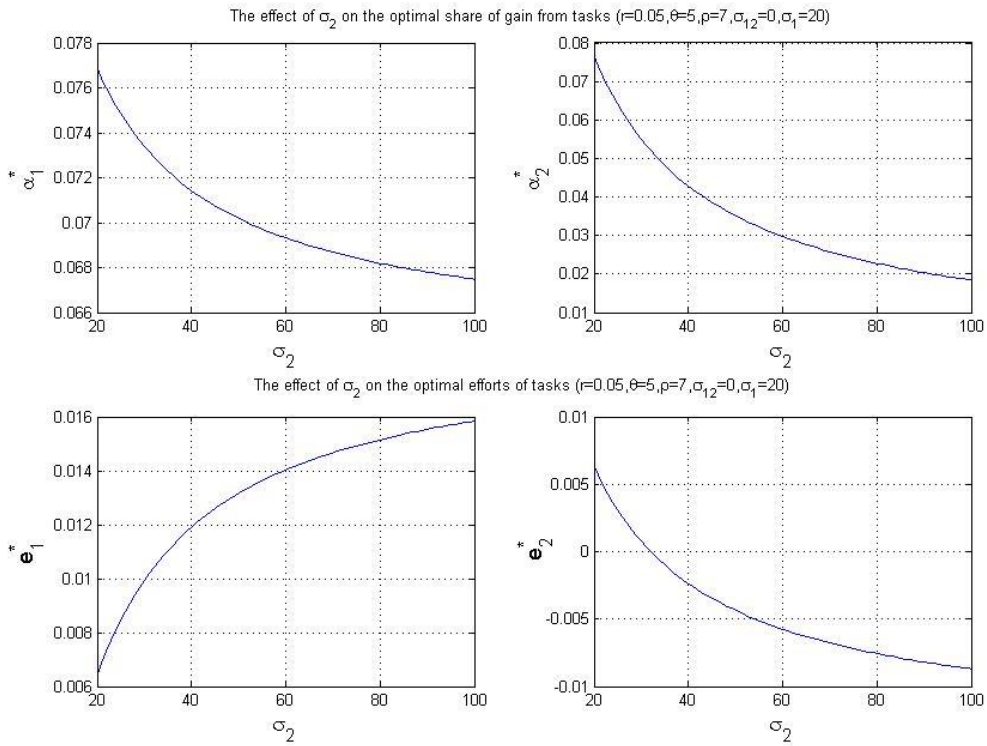
Figure 4: the effect of increase in uncertainties of innovation on optimal share of firm and its effort (when there is synergy between tasks)



As can be seen from Figure 4, when there is synergy between tasks, the increase in uncertainty of innovation has an increasing effect on the optimal share of the firm from its conventional efficiency gain (meaning that the compensation for efficiency needs to be based more on outcome) but a decreasing effect on that of innovation gain (meaning that compensation for innovation needs to reduce its reliance on outcome). This means that although the optimal shares of the two tasks start as being of similar magnitudes (when the risks are similar), they move in completely opposite directions as the risks of innovation increase. However, the level of effort for both activities reduces with the increase in uncertainties in the outcome of innovation effort. This suggests that when there is synergy between two tasks, the risks associated with innovation negatively affect the effort not only of innovation but also of conventional efficiency gain. This is an indication of the distortionary effect of performance-based schemes for innovation under assumptions made about costs synergy and risk in this scenario.

(ii) In the second case (similar to the first case) we assume that the risks of two tasks are independent ($\sigma_{12} = 0$). However, we assume that there is no synergy between the two activities (doing them together is more costly than doing them separately – in other words, $\theta > 0$). The shapes of optimal compensation and efforts when there is no synergy between two tasks are presented in Figure 5.

Figure 5: the effect of increase in uncertainties of innovation on the optimal share of firm and its effort (when there is no synergy between tasks)

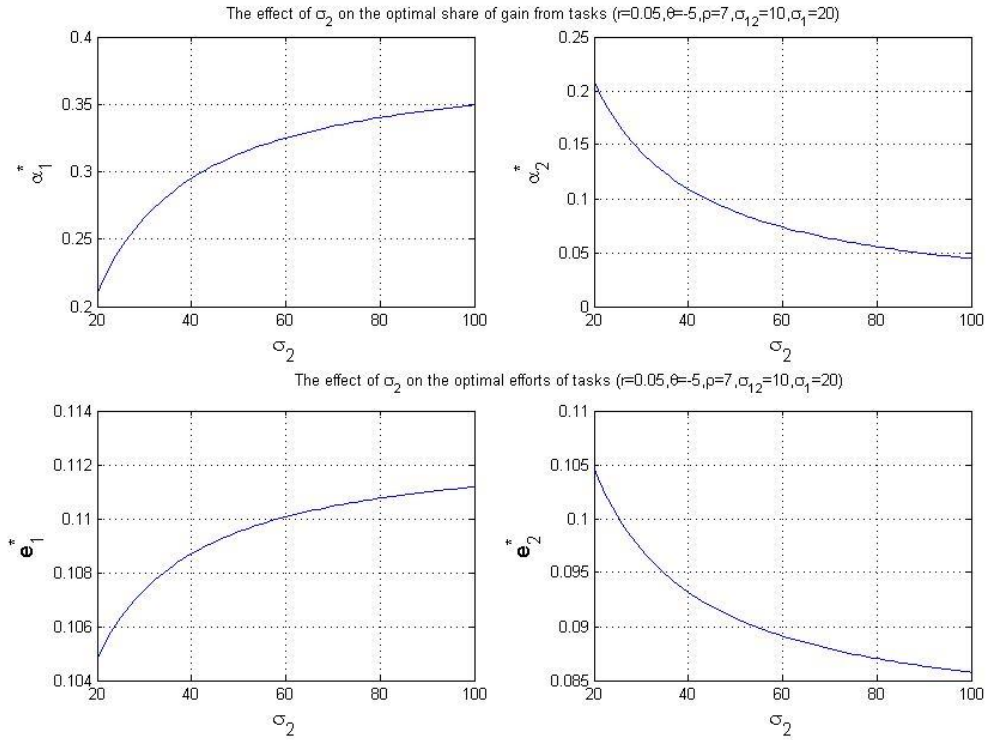


As can be seen from Figure 5, an increase in uncertainty of innovation outcome leads to a reduction in optimal share of the firm from the outcomes for both efficiency gain and innovation achievement (this means that the regulator needs to reduce the reliance of compensation on outcome). However, the optimal effort for the two tasks goes in opposite directions and the two tasks will become substitutes. In other words, as the innovation becomes riskier, the firm diverts its attention from innovation to conventional efficiency gain activities. Thus innovation effort will approach zero when it becomes sufficiently risky (the firm will only engage in normal cost efficiency).

(iii) In the third case we assume that uncertainties relating to the outcome of the two tasks are correlated ($\sigma_{12} > 0$). It is also assumed that there is synergy between the two activities ($\theta < 0$). The shapes of optimal compensation and efforts are presented in Figure 6.

As depicted in Figure 6, when there is synergy between the two activities and the risks associated with them are correlated, an increase in the risk of innovation activities leads to a reduction in the attention of the firm to innovation (and simultaneously to increased attention on efficiency gain). In this case, the regulatory model needs to increase the reliance of the compensation scheme on performance for efficiency gain and reduce it for innovation activity (innovation to be compensated mainly through a fixed sum).

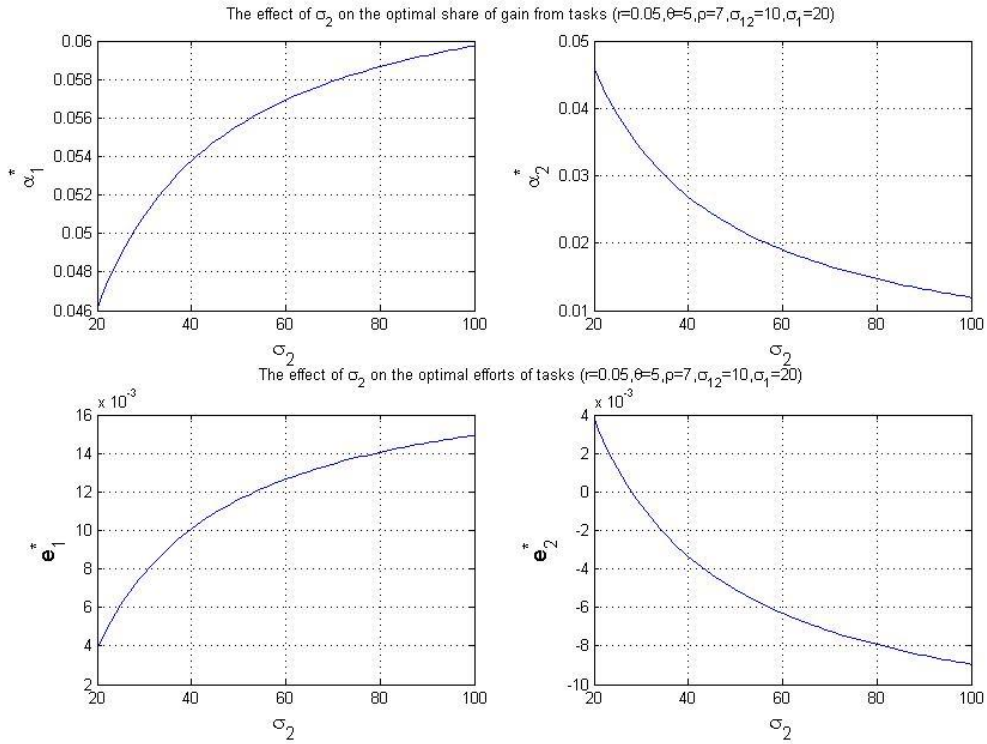
Figure 6: the effect of increase in uncertainties of innovation on the optimal share of firm and its effort (when there is synergy between tasks)



(iv) The fourth scenario assumes that the risks related to the two tasks are correlated ($\sigma_{12} > 0$) but there is no synergy between the two activities ($\theta > 0$). We investigate the effect of synergy and correlation of risks on the firm's effort and the optimal shares from the two activities. The results are presented in Figure 7.

In case four, as shown in Figure 7, when the risks of the two activities are correlated but there is no synergy in their cost structure, an increase in the risk of innovation diverts the attention of the firm from innovation to normal efficiency gain. The figure also shows that the optimum regulatory model in this case entails reducing the sensitivity of compensation for innovation to performance. Conversely, efficiency needs to be more performance based.

Figure 7: the effect of increase in uncertainties of innovation on the optimal share of firm and its effort (no synergy between tasks and lower level of random noise covariance)



The four cases examined here cover almost all possible risk and technology relationships associated with cost efficiency and innovation. In all scenarios, the risker innovation is the less effective becomes performance-based regulation of innovation. Put another way, the results show that performance-based incentive regulation is an effective approach when the regulator deals with the less risky business-as-usual activities of the firm.

This means that the regulator cannot rely on pure incentive regulation to encourage innovation in network companies, without the introduction of additional modules that take into account the issue of the risk to which companies are exposed. Previous studies have argued that incentive regulation has resulted in the decline of R&D and innovation expenditure in the electricity sector (Jamasb and Pollitt, 2008). The nature of uncertainty of innovation requires the application of regulatory incentive mechanisms that take into account the risk of these activities. The message from this section of the paper is that incentivising innovation through the same mechanism as efficiency gain does not lead to innovation, even if the objective of innovation is productivity, but with a higher degree of risk.

3.2 Competitive innovation funds and the problem of risk

The issue of risk is relevant irrespective of the way in which innovation is incentivised. In recent years, there has been an interest in the introduction of competitive approaches to allocate innovation funds more efficiently and to encourage innovation in network companies. Although these schemes can be designed in various forms, a common feature is that firms submit proposals for the innovation fund to the regulator. The regulator then evaluates these submitted proposals and allocates the funds to the best projects according to some criteria (such as: the highest potential value for consumers/society and their impact on the government's objective of decarbonisation). The source of these funds can be rate payers or tax payers (or a combination of the two). In the rate payer approach, an uplift is added to network fees to be collected from end-user and innovation fund is established, the resource from which

will be allocated through a competitive process to the best projects (the regulator may or may not leverage these resources). In this way, electricity customers (rate payers) pay for the cost of innovation.

The competitive scheme for innovation funds is usually implemented for large and complex projects. The significance of the risk here is that preparing proposals for such projects is costly and usually requires the network firm to rely on outside resources. The cost of these resources is non-recoverable if the firm is not successful. Therefore, it is important to understand the implications of such a scheme and the way in which the risk attitude of the firms impacts the outcome of the competition in this context.

Suppose there are two firms operating in a regulatory environment where the first contributes v_1 and the second contributes v_2 to the innovation fund and so the total resource available for allocation is $v_1 + v_2 = w$. Both firms prepare innovation proposals and compete for innovation funds by submitting their proposals to the regulator. The regulator compares proposed innovation projects and the available fund will then be allocated to the project with a higher value (only one project is selected). We assume that the value of the project depends on the intrinsic quality of ideas and the effort of the firm in preparing a decent proposal, responding to the questions by reviewers, and in making case for the importance of the project. Thus the value of project ($f_i(e_i)$) can be presented by a linear function of the firm's effort and the quality of idea as follows:

$$f_i(e_i) = \lambda_i e_i \qquad \text{and } i \in \{1,2\} \tag{6}$$

where λ_i is the coefficient representing the quality of the idea, e_i is effort and i is a subscript that refers to the number of contestants. Therefore, equation (6) relates the value of innovation to the effort of the firm and the characteristics of the project. We assume that the probability of wining the competition for funds follows the following contest success function first introduced by Tullock (1980):

$$p_i = \frac{f_i(e_i)}{f_1(e_1)+f_2(e_2)} \qquad \text{and } i \in \{1,2\} \tag{7}$$

and where $e_1 = e_2 = 0$ then $p_i = \frac{\lambda_i}{\lambda_1+\lambda_2}$.

Also, we also assume that the firms' risk preferences can be presented by a CARA utility function as follows:

$$u_i(z_i) = -\exp(-r_i z_i) \tag{8}$$

where $z_i = I_i + w_i - e_i$ when the firm is successful and $z_i = I_i - e_i$ when the firm fails to win the innovation contest. I_i is the initial resource of the firm, w_i is the innovation fund, and e_i is the (cost of) effort exerted by the firm to win the competition for funds.

In terms of a solution, this is a simultaneous game of complete information, in the sense that each firm knows its own, as well as its rival's, characteristics. The firms exert effort in order to maximise their expected gain from competition, given the uncertainty of outcome and the cost of the effort in preparing and submitting the proposal. We solve the maximisation problem of the firm and obtain the ratio of success probability for the two firms ($q = \frac{p_2}{p_1}$), where q is an indicator of the competitive balance of the contest. The results are presented in the appendix in equation A(20) (the ratio of success probability) and A(21) (the ratio of optimum effort for two firms).

3.2.1 Simulation of results

In this section, we simulate some results from the competitive innovation fund model that we presented in the previous section. First we investigate the effect of quality of idea (λ_i) on the competitive balance of the competition (q). This result is illustrated in Figure 8. For a given level of risk aversion, the probability of wining the innovation competition increases with the firm's own quality of proposal and reduces with an increase in the competitor's quality of proposal. This result confirms the fact that by proposing a better innovation idea, the firm increases its chance of winning the contest.

However, the outcome of the innovation contest also depends on the effort of the firm in preparing the proposal, attending the panel of technical experts and responding to questions, and providing the regulator with evidence about the impact and significance of its innovation project. The regulator may not be aware of all the benefits of the proposal and thus it is incumbent upon the network company to spend time and money in order to make a strong case for its innovation initiative. However, not only are these efforts costly, but the outcome of the competition is uncertain. Faced with an uncertain outcome and unrecoverable initial costs in the case of competition loss, firms may show dissimilar levels of risk attitude (depending on their characteristics). The risk attitude, along with the quality of innovation, has an impact on the competitive balance of the outcome.

This result is depicted in Figure 9. It shows that when two rival firms have an innovation proposal of the same quality, the probability of winning the competition declines with an increase in the firm's own level of risk aversion (upper graph) but it increases with a rise in the opponent's level of risk aversion (lower graph). This happens because the less risk-averse firm is willing to sacrifice more resources in order to justify its proposal and convince the regulator of the value of its project, whereas the more risk-averse firm is acting in a conservative manner.

However, the effect of risk aversion on the competitive balance of the competition is not linear, as it depends on the initial quality of idea (λ). As illustrated in Figure 10, if one of the two firms has a higher quality innovation idea (which is reflected in a higher λ), an increase in its risk aversion initially increases its probability of success because risk aversion causes the firm to spend more resources and protect its initial investment in preparing the proposal. This is similar to the reasoning of a person who buys a lottery ticket, but in order to increase his probability of winning decides to buy more than one. This effect is called 'self-protection'. However, there is a point beyond which an increase in the risk aversion of a firm with a higher quality proposal lowers its probability of success in the contest. This is because beyond a certain point, the firm perceives competition as being too risky, and invests less in demonstrating the usefulness of its project. This effect is called the 'gambling effect'. As can be seen from Figure 10, at some level of risk aversion, the gambling effect can dominate the self-protection effect, such that a firm with a more innovative project can lose a competition for the innovation fund. This result has important implications for the design of competitive innovations schemes, because it shows that the existence of a competitive innovation fund does not necessarily lead to the selection of more valuable projects, as the risk attitude of the firm plays a decisive role. Put another way, just by holding a competition (irrespective of how fierce the competition is), the regulator cannot ensure that an innovation fund will be allocated to the innovation idea that has the highest value in terms of either consumer benefit or alignment with government objectives.

This means that the competitive approach needs to consider the difference between risk attitudes of firms in the face of possible non-recoverable investments. The other point is that the size of fund in competitive schemes needs to be sufficiently large to justify a company's initial investment, otherwise uncertainty of outcome may discourage the firm from participation in the scheme altogether. This is why competitive schemes have been used to allocate large amount of money to large projects.

Figure 8: The effect of λ_i – the coefficient representing the inherent quality of the idea – on the competitive balance of the contest

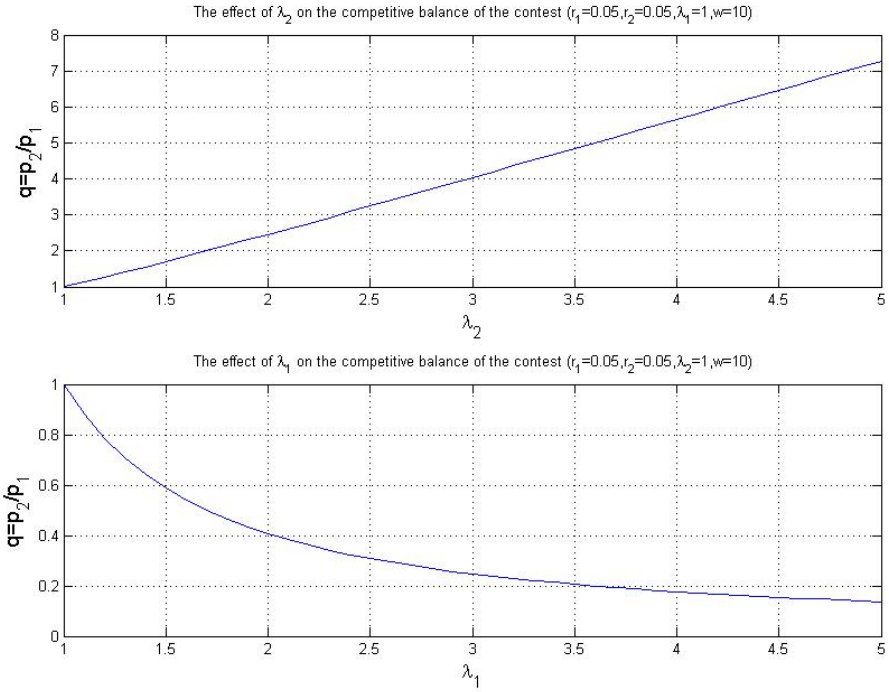


Figure 9: The effect of risk aversion of parties on the competitive balance of the contest (two projects have the same inherent quality of idea)

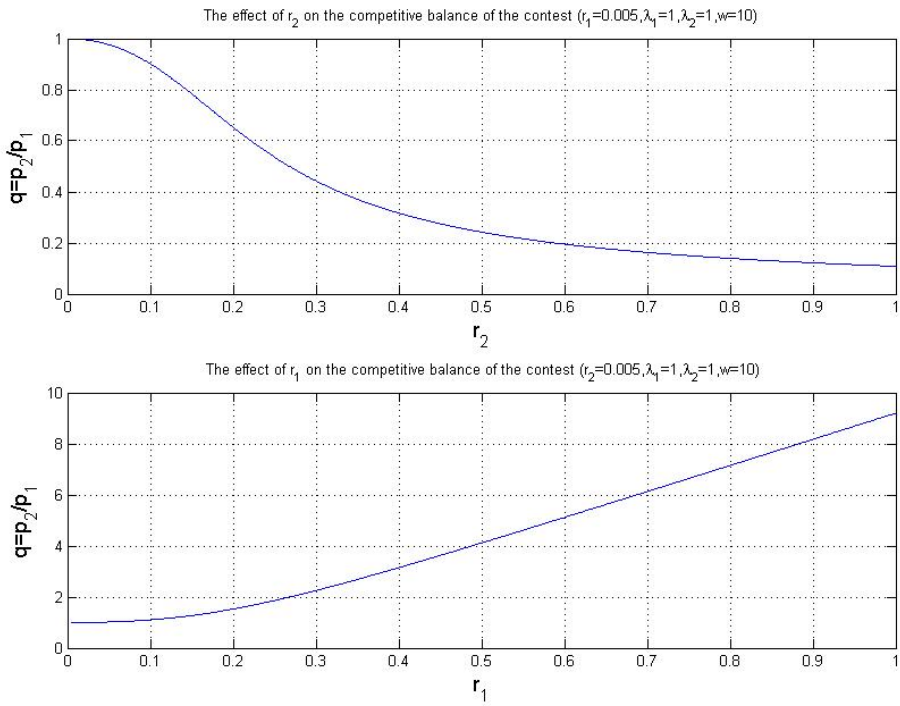
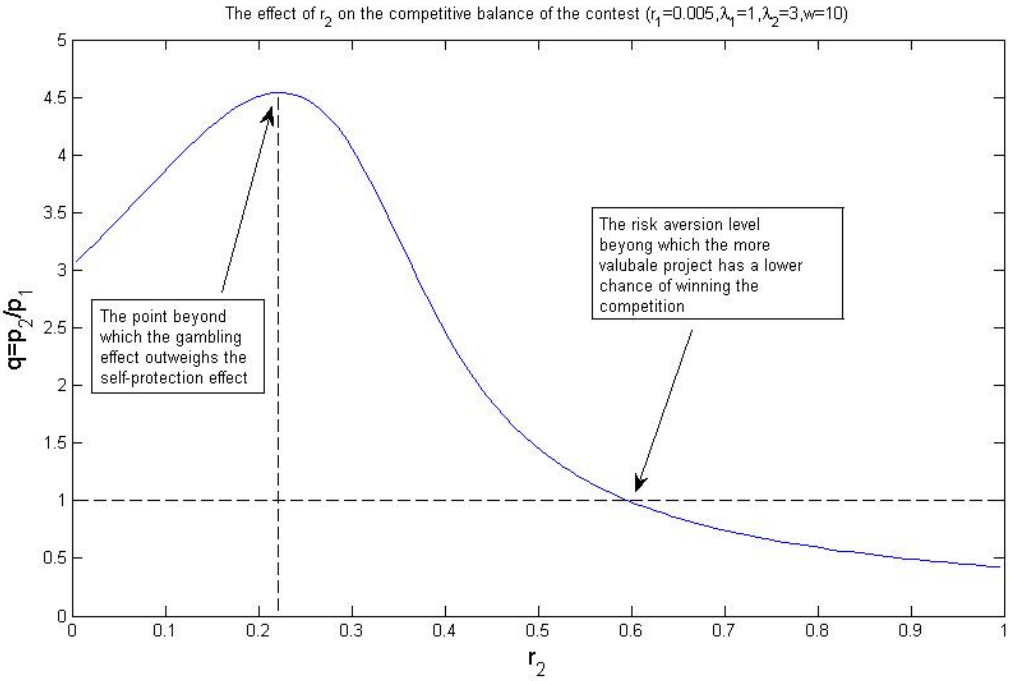


Figure 10: The effect of risk aversion on competitive balance when the firm which has the innovation project with higher potential value is also more risk averse



3.3 Discussion

Incentivising innovation efforts requires:

(a) designing a compensation plan that remunerates the network firm for its cost of efficient innovation and

(b) sharing the risk of innovation efforts between a firm and its customers in an efficient manner.

However, designing a scheme to encourage innovation, allowing the firm to have flexibility, while factoring in risk and information asymmetry, is not a trivial task. Information asymmetry exists because a regulator is usually unaware of innovation opportunities (in terms of costs reduction and other objectives) available to the firm and also of how good the firm is at exerting effort to realise these potentials (in other words, the quality of the firm and the efforts of its managers are unobservable to the regulator.) At the same time, the outcome of innovation efforts is uncertain, meaning that it is a risky undertaking.

Economic theory tells us that when the effort of the firm is unobservable, remuneration needs to be linked to the performance of the firm (at least partially) as this causes the firm to exert the optimal level of effort. This explains why performance-based regulation has been so popular in network industries. However, the same theory tells us that if the firm is risk averse and the outcome of the task is uncertain, the compensation scheme needs to provide the firm with insurance for its cost recovery, otherwise the firm does not have the incentive to engage in the task. This suggests that regulation of innovation is a delicate task of balancing between incentive and insurance provisions for the firm.

In practical terms, the regulator has many options to address innovation, but not all of them necessarily result in an efficient risk-sharing between network firms and consumers. The regulator can focus on inputs (innovation costs) or output (innovation outcome) or both (Bauknecht, 2011). In the input-oriented model, the regulator designs the incentive scheme based on the costs of innovation. In this way,

innovation costs can be included in the regulatory expenses and be subject to the same regulatory restriction as other costs. For example, the regulator can include them in their benchmarking practice, to be compared with the costs of peers in the industry. Alternatively, the regulator can treat innovation costs differently by passing them directly to consumers or including them in the regulatory asset base of companies, which entitles the firm to a minimum rate of return. Rather than inputs, the regulator can focus on innovation output and devise the incentive mechanism such that the firm benefits from successful innovation. This can be done in various ways, such as: allowing for additional revenue under a regulatory model based on the value of innovation, extending the regulatory period, and removing regulatory restrictions for a limited period (Bauknecht, 2011).

An input-based regulation of innovation costs (where innovation costs are treated separately) insures the firm against the downside risk of innovation, whereas an output-based regulation of innovation allows the firm to benefit fully from the value of a successful innovation. However, an input-based regulation, if not designed properly, can lead to overcapitalisation, whereas an output-based regulation of innovation can expose the firm to undesired risks. Furthermore, output-based regulation can run into the problem of verifiability and measurability. This is because innovation can be concerned with activities other than efficiency gain – such as facilitating integration of distributed resources, improving quality of service, reducing environmental impacts, providing resilience for service provision, enabling new market models at the grid level, and improving the business model of network companies. If the regulator cannot verify and measure innovation output, it cannot remunerate the company for its activities. The approaches suggested to address this issue are: using patents registered by the network firm as an indicator of output, or defining innovation output *ex ante* (for example, investment in smart grid or distributed resources as an alternative to grid capacity enhancement).

Whether a regulator should focus on input or output to incentivise innovation depends on several factors such as: innovation direction (namely whether the regulator wants the firm to undertake specific tasks), the cost of monitoring input versus output, and the risk attitude of the firm. If the regulator is interested in incentivising innovation in a particular area (such as smart grid), and inputs are observable, an input-based regulation can be used. This also holds when the cost of monitoring inputs is lower than that of measuring outputs, and when the firm is risk averse so that it requires a higher level of insurance against innovation costs given the uncertain outcome of such activities.

An important point here is that the regulator needs to distinguish between types of innovation by network firms and apply incentive instruments appropriate for the phase of innovation. There are four stages of innovation that are relevant to regulated networks:

- R&D,
- piloting,
- the introduction of new technologies/processes,
- the commercial stage.

Risk mitigation is crucial for innovation activities that are at the early stages of the spectrum. In the case of R&D and piloting (risky undertakings), the regulator can reduce the risk of these activities by adopting an input-based scheme in which innovation costs are treated differently than other costs of the firm (in other words, these costs are directly transferred to consumers). However, a separate treatment of innovation costs, at an early stage of innovation, needs to be done on the basis of an *ex ante* rule which clearly determines which expenses can be included in this category. This is to avoid strategic behaviour in the form of cost transfer between cost categories.

For innovation activities that are related to the two later stages (introduction of new technologies/processes and commercialisation), the regulator can adopt an output-based regulation. If the outcome of innovation at these stages is to be an efficiency gain, a revenue-sharing mechanism has proved to be an effective tool. This is because cost reduction can be verified and measured; sharing a percentage of cost reduction (resulting from innovation), with a company thus creates sufficient

incentive and results in efficient risk sharing. However, if the outcome of innovation at these later stages is beyond costs efficiency, the regulator can increase the cap, or remove the regulatory restriction, for a limited period on the basis of the successful deployment or commercialisation of the technology/process.

Finally, when the size of innovation projects is large, the incentives can be provided through a competitive mechanism.[9] This is specifically relevant to distribution network companies, given that the number of these grids is sufficiently high to make such competition feasible (in some places such the UK both transmission and distribution companies compete in a single competition for innovation fund). As discussed in the previous section, one challenge of competitive schemes is that they expose the network firms to the risk of not recovering their initial investment in the preparation of innovation proposals, as the outcome of competition is uncertain. This risk can discourage firms from engaging in large innovation projects. One approach to dealing with this issue is that the cost of preparing innovation proposals, including the initial technical, economic, and feasibility studies, is covered by a separate input-based mechanism. This means that the regulator can introduce small-scale funds for small-scale projects (whose costs can be recovered through the network tariff), and their results can be used in the bidding process for large complex funds in the competitive scheme.

4. Innovation incentive in practice: case studies of the UK and Italy

4.1 UK

UK is a pioneering country in the incentive regulation of electricity networks. Since the beginning of liberalisation, it was applying RPI-X model to regulate electricity network. However, in 2013, the UK government introduced a new performance based regulatory model known as RIIO (Revenue=Incentives+ Innovation+Outputs) with an eight years regulatory period. According to the regulator, RIIO model is designed to incentivise the network companies to (i) place stakeholder at the centre of their decision-making process (ii) make efficient investment in order to ensure the continuity and reliability of the network services (iii) innovate with the aim to reduce the cost of network services for the current and future customers and (iv) play a complete role in realising the objective of low carbon economy and wider environmental goals (Ofgem, 2017).

The RIIO model incentivises network companies to undertake innovation through two mechanisms: (a) incentive as part of the price control review (b) specific innovation stimulus package (Eurelectric, 2016). Innovation as part of price control review is promoted through long-term ex-ante output oriented regulatory model where companies benefit from successful innovation. Innovation stimulus package, on the other hand, is designed to facilitate achieving a sustainable energy sector. It includes three different schemes: the network innovation competition (NIC), the network innovation allowance (NIA) and the innovation roll out mechanism (IRM). The NIA and NIC are successors to Low Carbon Networks Fund (LCNF), the scheme which was previously in place to encourage innovation in network companies. The costs of incentives under innovation stimulus package is recovered through network tariffs and companies will lose it if they do not use this fund.

As a form of incentive regulation, RIIO incentivises innovation as part of the price control review by defining a set of outputs and targets. The regulatory model is such that the firm has both financial and reputational motive in order to outperform these targets. The network companies need to report their performance to the regulator for each category of output and their revenue will be adjusted upward when they exceed the target and downward when they fail to meet the target. These rewards and

[9] These projects are usually in the form of a consortium of multiple organisations including: network companies, universities, and private firms.

penalties are not fixed but vary depending on case that incentives is provided for and reflect the marginal value to the consumer. An example of these incentives is the use of non-network solutions in distribution network congestion management which allows companies to retain a percentage of their costs savings.

A specific feature of RIIO model is that it applies a total costs approach and this directs the attention of firm to innovation rather than capital expenditure because network utilities are always entitled to a percentage of costs savings. The totex approach always treats a fixed percentage of total cost as capital expenditure and the rest as operational expenditure regardless of their actual share. This is to prevent the firm from only focusing on capital expenditure and widen the choice of firm for innovation as many of latest innovations in the network companies are not asset based (like for example the use of demand response as alternative to grid capacity upgrade).

Although price control review provides innovation incentive for network companies however, most research, development and demonstration projects have uncertain outcomes and return (Ofgem, 2017b). Furthermore, shareholders are often unwilling to fund speculative projects. In addition, commercialisation of projects that their benefits is linked to the decarbonisation of networks is often difficult. Therefore, the UK regulator has offered a time-limited stimulus package in order to help network companies to establish a culture, internal structures and third party contracts to facilitate innovation.

The innovation stimulus package covers eight years (2015-2023) and provides innovation-specific incentive mechanism for network companies. One of the most important schemes in this package is network innovation competition (NIC). Under this scheme, network companies compete annually, in a two-stage competition process, for fund which allows them to develop and demonstrate new technologies or implement innovative commercial and operational arrangements.

NIC began in April 2013 and will run until March 2023. A total of £70 million per year is available in this scheme and transmission and distribution companies need to compete against each other in a single competition (Ofgem, 2017b). Funding for this scheme is recovered through transmission network tariff where each transmission user contributes an equal share and the learning from the project is shared among all network companies. In this way, end users will benefit from their funding of these projects through implementation of successful project across whole networks. This scheme assumes that even unsuccessful projects lead to learning with potential costs saving for future consumers.

NIC is designed for large and complex project under which all types of projects including technical, commercial and operational are eligible for funding if bidders can demonstrate their benefits to the network and its customers. In order to be called for submission of full proposals, projects need to pass the initial screening process (ISP). Both network and non-network licensees can participate in this scheme however, non-network licensees need develop their project in partnership with a network company.

The criteria used to evaluate projects in the initial screening process is multiple (Ofgem, 2017b). The project needs to show that it

- provides carbon and environmental benefits to the power system,
- delivers value for money,
- creates knowledge and best practices that can be shared,
- is not part of the business as usual activity of the firm (is really innovative) and
- it requires small scale demonstration to test its effectiveness given the risk involved in the full scale implementation.

These criterions also will be used in the final selection process along with some other indicators such as the project external funding level and partners' expertise, the project relevance and timing as well as the robustness of methodology.

As mentioned in the previous section, competition for innovation fund can expose network companies to the risk of losing their initial investment. The NIC addresses the risk of unrecoverable investments in

two ways. First through initial screening process and second through allowing network firms to recover their bid preparation and submission costs up to a certain level. The ISP provides an early indication of which project might be eligible for funding and thus reduces the risk that network companies spending resources and time to develop ineligible projects . In addition, for the projects that pass ISP stage, the network companies can use up to £175000 or 5 per cent of outstanding fund required (whichever is smaller) from their network innovation allowance (NIA) in order cover costs of preparation and submission of bid (Ofgem, 2017b).

The network innovation allowance (NIA), which is another scheme in the innovation stimulus package, is however not competitive and each company receives this fund as part of its price control review. This fund, which is equal to 0.5% of allowed revenue of the company, is awarded for two main purposes: to fund smaller scale projects with value for network and its customers and to fund the proposal preparation for NIC scheme. The difference between NIA and NIC is that NIA is for smaller size projects as part of the price control settlement. Unlike the NIC, NIA is not limited to innovative project with environmental and decarbonisation benefit (ofgem, 2013). In addition, NIA is only available for network companies, whereas NIC is also available to non-network licensees in a partnership with network utilities. In order to receive NIA fund, network companies need to submit their innovation strategy along with their business plan at the outset of the regulatory period.

NIA is awarded based on the quality and content of innovation strategy and can be extended to the maximum of 1% of company's allowed revenue, if the network firm can put forward a high quality innovation plan. There are two sets of criteria that a project needs to meet in order become eligible for funding under NIA. First, the proposal needs to have a direct improving effect on the operation of network licensees or the system operator and where feasible should involve RD&D in the area of product and process developments or adoption of new technologies and arrangement. Second, it needs to result in learning adoptable by all network licensees, have the potential of financial benefits to the network customers and must not lead to unnecessary duplication of existing registered projects (Ofgem, 2013).

The third incentive scheme under innovation stimulus package is innovation rollout mechanism (IRM) whereby a network company can receive further fund to undertake innovation within the regulatory period. This fund facilitates deployments of proven technologies. In order to receive this fund, companies need to submit a business case to the regulator that demonstrates the value of the project and benefit to the customers.

4.2 Italy

Since 2000, an incentive regulation regime, in the form of price cap, was being applied by the Italian Regulatory Authority for Electricity Gas and Water (AEEGSI) which over time evolved into a hybrid model. In the hybrid model an incentive scheme applied to tariffs components covering operational expenditures (Opex) and a cost of service scheme was applied to the tariffs covering capital expenditures (Capex). In 2010, AEEGSI started to incentivise deployment of pilot smart grid projects through an input-based incentive regulation model (Eurelectric, 2016). This was done by allowing an increase of 2% on the weighted average costs of capital for 12 years on investments made on smart grid projects (i.e., increase in the revenue cap). The smart grid projects eligible for a higher rate of return are selected by AEEGSI. Along with smart grid projects, storage on distribution and transmission electricity networks are also eligible for a higher return incentive. These projects are selected by a commission that is appointed by AEEGSI.

Since 2015, the Italian regulator (AEEGSI) introduced a new regulatory model in which the incentive for innovation is provided in an output-based fashion. The shift from input-based to an output-based incentive model is implemented in order to streamline the process and allow the network companies to evaluate and quantify the benefits of projects when targets are achieved. Currently, the application of output-based regulation is limited to two types of technologies: network observability and voltage control

on medium voltage networks. The network observability technologies allow for data exchange between distribution and transmission networks. They also facilitate a precise estimation of generation and demand. Voltage control technologies allow for an increase in the capacity of electricity network in order to connect distributed generations without further grid reinforcement.

The Italian regulator also incentivises implementation of smart city projects with the aim to integrate demand response, increase customer awareness and implement innovative non-network solution at the level of distribution network. The incentive for these projects are provided through a one-off payment along with an annual payment for two years.

The Italian regulator is planning to move towards a TOTEX approach from 2020. This is because the current approach that allows for higher rate of return can incentivise inefficient capitalisation strategies by network companies with the aim to maximise their profit. It is also not neutral between different innovation solutions that can be implemented by the firm. The TOTEX approach will be implemented in combination with the incentive menus and output based schemes.

5. Conclusions

In order to facilitate decarbonisation, digitalisation, and decentralisation of the electricity industry along with electrification of other sectors, the power networks require significant innovation not only in their technological dimensions but also in aspects of their organisational and business models. The results of our review of innovations in the electricity grid show that while both transmission and distribution networks need technological modernisation, most commercial and process innovations are needed at the level of the low-voltage grid. This is mainly because of the rapid transformation of grid edge technologies, which necessitates different modes of operation for electricity distribution networks.

However, network companies are regulated natural monopolies; this means that they hardly ever undertake innovation activities in the absence of sufficient incentives. Traditional regulatory models of network utilities are designed to incentivise cost efficiency, with the assumption that network business is costly and the task of regulation is to lower these costs, subject to achieving a certain level of reliability. The main challenge of incentivising innovation is that it is not only costly but also risky. Therefore, an innovation-oriented regulatory model needs to factor in uncertainty in the outcome of innovation efforts.

The costs and risks of innovation effort can be borne by firms, be passed to consumers, or shared between these two. If the regulator were able to observe the firm's effort, incentivising innovation would be simple because the regulator could set the remuneration at a level equal to the cost of the efficient level of effort. However, in practice there is information asymmetry between the regulator and the firm, which means that the remuneration of firms needs to be linked to the performance of the firm. But this is not straightforward. On the one hand, the regulator wants the firm to undertake innovation, but for this to happen he needs to remunerate the firm for its costs when undertaking risky activity. On the other hand, the regulator does not want to distort the firm's incentives by giving it full insurance for activities whose risks are actually manageable by the firm. The task of regulation is, therefore, to devise a scheme which balances risk sharing with incentives.

We show that incentive mechanisms that do not take into account the risk profile of innovation activities divert the attention of the network utilities from innovation to normal efficiency gain. This indicates the importance of differentiating between cost efficiency and innovation in designing the regulation of electricity networks. A shift from traditional models of network regulation to new models – where innovation is the key part of the incentive structure – is crucial to facilitate the transition of the power sector. In relation to the design of an innovation-friendly regulatory scheme, the regulator needs to

differentiate between types of innovation activities, as there is a different level of risk involved at each stage of innovation. When network companies engage in R&D and piloting, an input-based regulation (whereby the costs of these activities are transferred to consumers) has proved to be an effective approach. For less risky activities, such as the introduction of established technologies and processes, an output-based regulation that uses costs sharing or revenue cap adjustment leads to a more efficient risk-sharing mechanism.

The issue of risk in regulating innovation is not confined to the actual risk of outcome. The risk attitude of network companies is also decisive. If the scheme does not take this into account, a heterogeneous risk attitude among bidders can distort the outcome of a competitive allocation of innovation funds. We demonstrate that a firm with a greater level of risk tolerance but a less valuable project can win a contest for innovation funds in competition with a risk averse firm which has a more valuable innovation project. The risk of losing their initial investment because of the uncertain outcome of competition can discourage network companies from entering into competition or spending resources to make a case for their project. An approach to address this issue is to adopt a two-stage competition process in which an initial evaluation provides an early indication of eligible projects before companies are invited for full submission. Regulator can also offer smaller funds to be used for projects whose technical/economic results can then be used in larger-scale innovation proposals. This eliminates the risk of losing the upfront capital and puts network companies with different levels of risk tolerance on the same level in the competition process.

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Appendix

The optimal share and effort for the regulatory model presented in (1):

Owing to the uncertain nature of efficiency gain and innovation activities, the compensation plan of the firm has some degree of uncertainty. Given the normal distribution of random signal and the shape of the utility function, the certainty equivalent (CE) of allowed revenue for the firm is:

$$CE = \beta + \alpha^T e - c(e) - \tfrac{1}{2} r\alpha^T \Sigma \alpha \qquad \text{(A1)}$$

The certainly equivalent of a lottery z is a certain payment that makes an individual indifferent between lottery z and its certainty equivalent CE as each gives the same level of utility

$$u(CE) = E[u(z)]$$

$$E[u(z)] = E\{-\exp[-rz - c(e)]\}$$

$$E[u(z)] = E\{-\exp[-r(\beta + \alpha^T x) - c(e)]\} \qquad \text{(A2)}$$

The moment generating function for a multivariate normal variate of $X \sim N(\mu, \Sigma)$

$$M(t) = \exp\{\mu' t + \tfrac{1}{2} t' \Sigma t\} \qquad \text{(A3)}$$

and defining property of moment generating function is $E[e^{tx}] = M(t)$.

$$E[u(z)] = E\{-\exp[-r((\beta + \alpha^T x) - c(e))]\} = \exp(-r\beta + rc(e)) E(-r\alpha^T \varepsilon)$$

$$E[u(z)] = \exp\left(-r\beta - r\alpha^T e + rc(e)\right) \exp(-\frac{1}{2} r^2 \alpha^T \Sigma \alpha)$$

$$E[u(z)] = \exp\left(-r\beta - r\alpha^T e + rc(e) - \frac{1}{2} r^2 \alpha^T \Sigma \alpha\right)$$

$$E[u(z)] = \exp\left(-r\left(\beta + \alpha^T e - c(e) + \tfrac{1}{2} r\alpha^T \Sigma \alpha\right)\right) \qquad \text{(A4)}$$

As we know that:

$$u(CE) = E[u(z)] \qquad \text{(A5)}$$

$$\text{Thus } CE = \beta + \alpha^T e - c(e) + \tfrac{1}{2} r\alpha^T \Sigma \alpha$$

and for the principal (regulator) the CE gain is $e - \alpha^T e - \beta$. Following Holmstrom and Milgrom (1991) we assume the principal maximises the total certainty equivalent:

$$Max_{e,\alpha}\{\, e - c(e) - \tfrac{1}{2} r\alpha^T \Sigma \alpha\} \qquad \text{(A6)}$$

subject to the firm's incentive compatibility constraint as follows:

$$Max_{e^*}\{\, \alpha^T e - c(e)\} \qquad \text{(A7)}$$

and its individual rationality constraint as in (A8).

$$\beta = CE - \alpha^T e + c(e) + \tfrac{1}{2} r\alpha^T \Sigma \alpha \qquad \text{(A8)}$$

The first order condition of (A7) yields: $\alpha_i = c_i(e)\ \forall\, i$ where the subscript i on C represents a partial derivative with respect to elements of vector e. Differentiating the former equation will lead to:

$$\frac{\partial \alpha}{\partial e} = C_{ij} \text{ and thus } \frac{\partial e}{\partial \alpha} = [C_{ij}]^{-1} \qquad \text{(A9)}$$

The first order condition for $\alpha^T e - c(e)$ is $\alpha^T - c_i(e)$ which appears as a constraint in the Lagrangian function of principal maximisation problem.

$$\mathcal{L} = e - c(e) - \tfrac{1}{2} r\alpha^T \Sigma \alpha + \mu(\alpha^T - c_i(e)) \tag{A10}$$

$\frac{\partial \mathcal{L}}{\partial \alpha} = 0$ $\quad -r\alpha^T \Sigma + \mu = 0$

$\frac{\partial \mathcal{L}}{\partial e} = 0$ $\quad e' - c_i(e) - \mu C_{ij}(e) = 0$

$\frac{\partial \mathcal{L}}{\partial \mu} = 0$ $\quad \alpha^T - c_i(e) = 0$

$$e' - c_i(e) - r\alpha^T C_{ij}(e^*)\Sigma = 0$$

$$e' - \alpha^T - r\alpha^T C_{ij}(e^*)\Sigma = 0$$

$$e' = \alpha^T [I + rC_{ij}(e^*)\Sigma]$$

$$\alpha^* = (I + r[C_{ij}(e^*)]\Sigma)^{-1} e' \tag{A11}$$

Given the shape of the cost function:

$$c(e_1, e_2) = \tfrac{1}{2}\rho(e_1^2 + e_2^2) + \theta e_1 e_2 \tag{A12}$$

We can write:

$$C_{ij}(e^*) = \begin{bmatrix} \rho & \theta \\ \theta & \rho \end{bmatrix}$$

$$I + r[C_{ij}(e^*)]\Sigma = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + \begin{bmatrix} r\rho & r\theta \\ r\theta & r\rho \end{bmatrix} \begin{bmatrix} \sigma_1^2 & \sigma_{12} \\ \sigma_{12} & \sigma_2^2 \end{bmatrix} = \begin{bmatrix} 1 + r(\rho\sigma_1^2 + \theta\sigma_{12}) & r(\rho\sigma_{12} + \theta\sigma_2^2) \\ r(\theta\sigma_1^2 + \rho\sigma_{12}) & 1 + r(\theta\sigma_{12} + \rho\sigma_2^2) \end{bmatrix}$$

$$\begin{bmatrix} \alpha_1^* \\ \alpha_2^* \end{bmatrix} = \begin{bmatrix} 1 + r(\rho\sigma_1^2 + \theta\sigma_{12}) & r(\rho\sigma_{12} + \theta\sigma_2^2) \\ r(\theta\sigma_1^2 + \rho\sigma_{12}) & 1 + r(\theta\sigma_{12} + \rho\sigma_2^2) \end{bmatrix}^{-1} \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} \alpha_1^* \\ \alpha_2^* \end{bmatrix} = \frac{1}{1 + r(2\theta\sigma_{12} + \rho\sigma_1^2 + \rho\sigma_2^2) + r^2(\rho^2 - \theta^2)(\sigma_1^2\sigma_2^2 - \sigma_{12}^2)} \begin{bmatrix} 1 + r(\theta\sigma_{12} + \rho\sigma_2^2) & -r(\rho\sigma_{12} + \theta\sigma_2^2) \\ -r(\theta\sigma_1^2 + \rho\sigma_{12}) & 1 + r(\rho\sigma_1^2 + \theta\sigma_{12}) \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} \alpha_1^* \\ \alpha_2^* \end{bmatrix} = \frac{1}{1 + r(2\theta\sigma_{12} + \rho\sigma_1^2 + \rho\sigma_2^2) + r^2(\rho^2 - \theta^2)(\sigma_1^2\sigma_2^2 - \sigma_{12}^2)} \begin{bmatrix} 1 + r(\sigma_2^2 - \sigma_{12})(\rho - \theta) \\ 1 + (\sigma_1^2 - \sigma_{12})(\rho - \theta) \end{bmatrix} \tag{A13}$$

Optimum effort:

Focusing on the interior solution, from the incentive compatibility constraint (ICCs) for the two efforts one can derive the agent's decision regarding $(e_1,\ e_2)$:

$$\begin{bmatrix} \rho & \theta \\ \theta & \rho \end{bmatrix}$$

$$\frac{\partial e}{\partial \alpha} = [C_{ij}]^{-1} = \frac{1}{\rho^2 - \theta^2} \begin{bmatrix} \rho & -\theta \\ -\theta & \rho \end{bmatrix}$$

$$\begin{bmatrix} e_1^* \\ e_2^* \end{bmatrix} = \frac{1}{\rho^2 - \theta^2} \begin{bmatrix} \rho & -\theta \\ -\theta & \rho \end{bmatrix} \begin{bmatrix} \alpha_1^* \\ \alpha_2^* \end{bmatrix}$$

$$\begin{bmatrix} e_1^* \\ e_2^* \end{bmatrix} = \frac{1}{\rho^2 - \theta^2} \begin{bmatrix} \rho\alpha_1^* - \theta\alpha_2^* \\ \rho\alpha_2^* - \theta\alpha_1^* \end{bmatrix} \tag{A14}$$

Solving the model presented in Section 3.2:

Given the setting of the model in Section 3.2, the expected utility of player i:

$$E(u_i) = p_i u_i(I_i + w_i - e_i) + (1 - p_i) u_i(I_i - e_i) \quad \text{(A15)}$$

$$E(u_i) = -[p_i \exp\big(-r_i(I_i + w_i - e_i)\big) + (1 - p_i) \exp\big(-r_i(I_i - e_i)\big)] \quad \text{(A16)}$$

$$i, j \in \{1,2\}$$

The first order condition for the firm would yield:

$$p_i' = \frac{r_i}{1-e^{-r_i w}} (p_i e^{-r_i w} + 1 - p_i) \quad \text{(A17)}$$

where $p_i' = \frac{\partial p_i}{\partial e_i} \geq 0$.

$$p_i = \frac{\lambda_i e_i}{\lambda_1 e_1 + \lambda_2 e_2}$$

$$\frac{\partial p_1}{\partial e_1} = \frac{\lambda_1 \lambda_2 e_2}{(\lambda_1 e_1 + \lambda_2 e_2)^2}$$

$$\frac{\partial p_2}{\partial e_2} = \frac{\lambda_1 \lambda_2 e_1}{(\lambda_1 e_1 + \lambda_2 e_2)^2}$$

Setting $s(r_i) = \frac{r_i}{1-e^{-r_i w}}$, the ratio of first order condition for two firms leads to the following equation:

$$\frac{\frac{\partial p_1}{\partial e_1}}{\frac{\partial p_2}{\partial e_2}} = \frac{\frac{r_1}{1-e^{-r_1 w}}}{\frac{r_2}{1-e^{-r_2 w}}} \frac{(p_1 e^{-r_1 w} + 1 - p_1)}{(p_2 e^{-r_2 w} + 1 - p_2)}$$

$$\frac{e_2}{e_1} = \frac{\frac{r_1}{1-e^{-r_1 w}}}{\frac{r_2}{1-e^{-r_2 w}}} \frac{(p_1 e^{-r_1 w} + 1 - p_1)}{(p_2 e^{-r_2 w} + 1 - p_2)} \quad \text{(A18)}$$

On the other hand, we know that:

$$\frac{p_2}{p_1} = \frac{\lambda_2}{\lambda_1} (\frac{e_2}{e_1})$$

And by substituting for $\frac{e_2}{e_1}$ in (A18) we can write:

$$\frac{\lambda_1 q}{\lambda_2} = \frac{s(r_1)}{s(r_2)} \frac{(e^{-r_1 w} + q)}{(q e^{-r_2 w} + 1)} \quad \text{(A19)}$$

where $q = \frac{p_2}{p_1}$ is the competitive balance of the competition, and depending whether $q < 1$, $q > 1$, or $q = 1$, the wining probability of firm one is higher than two, lower than two, or the contest is even. Solving (A19) for q leads to the following:

$$q = \sqrt{\frac{\lambda_2 s(r_1) e^{-r_1 w}}{\lambda_1 s(r_2) e^{-r_2 w}} + (\frac{\lambda_1 s(r_2) - \lambda_2 s(r_1)}{2 s(r_2) e^{-r_2 w}})^2} - (\frac{\lambda_1 s(r_2) - \lambda_2 s(r_1)}{2 \lambda_1 s(r_2) e^{-r_2 w}}) \quad \text{(A20)}$$

The ratio of optimum effort for two firms can be presented as in (A21).

$$\frac{e_2}{e_1} = \frac{s(r_1)}{s(r_2)} \frac{(p_1 e^{-r_1 w} + 1 - p_1)}{(p_2 e^{-r_2 w} + 1 - p_2)}$$

$$\frac{e_2}{e_1} = \frac{s(r_1)}{s(r_2)} \frac{(e^{-r_1 w} + q)}{(q e^{-r_2 w} + 1)} \tag{A21}$$