Merchant Transmission Investment Using Generalized Financial Transmission Rights

Darryl R. Biggar and Mohammad Reza Hesamzadeh

1 Introduction

The liberalization of wholesale power markets of the last few decades introduced competition into the generation sector, thereby introducing strong private, commercial incentives for efficient generation investment and operation. But the same reforms left responsibility for network operation and investment on regulated or government-owned transmission businesses. This gives rise to a somewhat awkward boundary between the private, commercial decisions of generators and the regulated, muted incentives of network operators. A key question for researchers has been whether or not it is possible to develop a mechanism which would provide efficient private, commercial decisions for network operation and investment.

It has long been observed that it is possible to allow for private, commercial investment in DC transmission links. Such links act like a combination of a generator and a load, arbitraging across differently priced locations. Merchant DC transmission investment was historically allowed in a few countries, including Australia.[1] But DC links are expensive and tend to be niche services. A more important question is

[1] Joskow et al. (2005).

The views expressed in this chapter reflect those of the authors and not the views of the ACCC or KTH.

D. R. Biggar (✉)
Australian Competition and Consumer Commission, Canberra, Australia
e-mail: darryl.biggar@accc.gov.au

M. R. Hesamzadeh
KTH Royal Institute of Technology, Stockholm, Sweden
e-mail: mrhesamzadeh@ee.kth.se

M. R. Hesamzadeh et al. (eds.), *Transmission Network Investment in Liberalized Power Markets*, Lecture Notes in Energy 79,
https://doi.org/10.1007/978-3-030-47929-9_11

whether or not it is possible to develop a mechanism which yields the correct incentives for private investment and operation in regulated AC transmission networks.

The possibility of such a mechanism has been attractive for generations of researchers and policy-makers. If such a mechanism existed, it would, in principle, allow private, commercial operators to make key transmission operation or investment decisions in a decentralized, for-profit manner, improving the efficiency of the transmission network and overcoming many of the drawbacks of regulation. But, to date, no effective mechanism has been developed.

Part of the problem is that a transmission network augmentation gives rise to both winners and losers, benefiting generators in an exporting region, and loads in an importing region, while harming generators in an importing region and loads in an exporting region. Transmission augmentations which are highly valuable for one market participant may be quite harmful to social welfare overall. Conversely, transmission augmentations may provide limited benefits to any one market participant, while producing substantial social benefits overall. Any mechanism for private transmission investment must overcome this mis-match between private and social incentives.

Fairly soon after mechanisms for efficiently pricing electricity transmission networks were proposed, it was recognised that market participants would require instruments for hedging the inter-nodal pricing risks that result. Hogan (1992) proposed the use of a now-conventional fixed-volume hedging instrument (known as a Financial Transmission Right or FTR). Almost immediately researchers explored whether FTRs could be used to signal and incentivize private or merchant transmission investment. Unfortunately, this research program achieved only limited success. In our view, the primary problem with that literature was the focus on only a limited form of inter-nodal hedging instrument—specifically, a fixed volume financial transmission right. We argue below that fixed volume financial transmission rights are inadequate as an instrument for hedging inter-nodal pricing risk, primarily because almost all market participants routinely transact electricity volumes which vary with market conditions. Instead, we have proposed a range of more general financial transmission rights which allow for hedging transactions with a variable volume of production or consumption (including a volume which may vary with the spot price). These instruments allow generators and loads at differently priced locations to achieve the same level of risk management as would arise as if they were at the same pricing node.[2]

Extending this work, in this chapter we show how the proposed generalized financial transmission rights naturally give rise to a mechanism which may allow for private incentives for operation and investment in transmission networks. Specifically, we show that a market participant (which we refer to as a 'trader') may simultaneously (a) provide hedge contracts to generators and loads, allowing them to perfectly hedge the risks they face; and (b) provide hedge contracts, in the form of generalized FTRs to the system operator, perfectly hedging the risks it faces, In doing so, the trader takes on all of the remaining risk in the market on itself. The total payoff faced

[2] Biggar et al. (2019).

by this trader is equal to the total economic welfare created in the sector. This has direct implications for the design of a merchant transmission investment mechanism.

We imagine that, prior to the augmentation, the network is in a state where the trader has provided contracts to all the generators and loads which eliminate their risk. In addition, for each of these contracts, the trader is assumed to acquire a corresponding generalized financial transmission right (defined below). This also eliminates the risk on the system operator.

We then imagine that the trader considers an upgrade to the transmission network. This may allow new players to enter the market (in which case the trader provides new hedge contracts, offset by new generalized FTRs). Overall, we show below that the change in the net payoff to the trader is equal to the change in social welfare. The trader will fund the upgrade if and only if it is socially beneficial.

In some respects, this result is striking. It comes close to the long-sought holy grail of privately funded transmission augmentation. Questions remain as to how this mechanism could be made practical. Nevertheless, we consider this an important first step, and further support for the proposed generalized financial transmission rights.

This chapter has three main sections. In the first section, we introduce the various forms of hedging instruments and the concept of the corresponding generalized financial transmission right. In the second section, we show how these generalized FTRs can place market participants (including the 'trader') in the same position as if all transactions were occurring at the same pricing node. This section also proves that the trader faces a net position equal to the total economic welfare created in the market. The third section illustrates how these principles can be used to yield efficient transmission upgrade decisions in simple networks. The final section concludes.

2 Introduction to Hedging and Generalized FTRs

Let us consider a simple wholesale electricity market comprising generators, loads, and a physical network connecting generators and loads. Without loss of generality, each generator and load can be assumed to be located at its own node in the network. To keep things simple, losses are ignored throughout this paper. In order to create a motivation for hedging, we must introduce some uncertainty into the model. Let us assume that there are different uncertain future states of the market, which we will label s.[3]

[3] Although much of the analysis that follows will depend on the state of the world s, and the point in time t, for simplicity, we will suppress the dependent on s and t in the formulae that follow. We consider that, on balance, this makes the presentation clearer but throughout the paper, this dependence on s should be kept in mind. We will have in mind a world in which all of the physical market participants (generators, loads, and the system operator) are relatively risk averse, while the financial market participants (which we refer to as traders) are close to risk-neutral. This is a special case of a more general framework in which all market participants are risk averse. However, we consider this to be a realistic starting point for electricity markets in practice.

2.1 Supply and Demand Curves

Assume we have a set of n generator pricing nodes and m load nodes. All generators and loads are assumed to be price takers. The spot price for electricity at node i is labelled p_i (these prices vary with the state s). As is conventional, we will assume that generators and loads choose a rate of production or consumption which maximizes their profit or utility.

The generator at node i is assumed to be described by a cost function $c_i(q_i)$ reflecting the rate at which costs are incurred (\$/h) when producing at the rate q_i (MW). The cost function may depend on the state s, according to changes in, say, wind strength, input prices, or outages. The cost function is assumed to be upward sloping $c_i'(\cdot) > 0$ and strictly convex $c_i''(\cdot) > 0$.

When producing at rate q_i^S, the generator at node i receives profit at the rate $\pi_i(q_i^S) = p_i q_i^S - c_i(q_i^S)$ (\$/h). For each value of the spot price, there is a corresponding profit-maximizing rate of production $q_i^S(p_i)$ which, by the assumptions above, is strictly increasing in the spot price. This function reflects the **supply curve** of the generator in state of the world s. We can then express the profit of the generator when facing spot price p_i (and state s) as follows:

$$\pi_i(p_i) = p_i q_i^S(p_i) - c_i(q_i^S(p_i)) \tag{1}$$

In general, the profit π_i varies with the state of the world s, so the generator is exposed to some risk.

Similarly, the load at node j is assumed to be described by a utility function $v_j(q_j)$ reflecting the rate at which utility is received (\$/h) when consuming at the rate q_j (MW). This load may depend on the state s according to factors such as ambient temperature (in Australia, temperature is a major driver of air-conditioning load, a primary source of demand on hot days). The utility function is assumed to be upward sloping $v_j'(\cdot) > 0$ and concave $v_j''(\cdot) < 0$.

The rate at which the load receives utility when consuming at rate q_j^D is given by the expression $u_j(q_j^D) = v_j(q_j^D) - p_j q_j^D$ (\$/h). Maximizing this expression for a given value of the spot price gives the (downward sloping) **demand curve** $q_j^D(p_j)$ in state of the world s. The utility of the load at node j facing spot price p_j can then be written:

$$u_j(p_j) = v_j(q_j^D(p_j)) - p_j q_j^D(p_j) \tag{2}$$

As is conventional, from the overall energy balance equation, the total amount of electricity produced is equal to the total amount consumed, at each point in time and in each state of the world:

$$\sum_i q_i^S = \sum_j q_j^D \tag{3}$$

2.2 *The Design of Typical Hedge Contracts*

As we will see, the form of effective inter-nodal hedging instruments depends in turn on the form of the instruments that generators and loads need in order to hedge their risk. So, let us first consider what forms typical hedging instruments might take.

2.2.1 Hedging for Generators

Let us start by focusing on the question of how to hedge the profit of a conventional, reliable dispatchable (e.g., thermal) generator. The profit function of a conventional generator is given in Eq. 1. Let us suppose that the generator sells a hedge contract (possibly consisting of a portfolio of hedge contracts) with the payout given by H_i^S, so that the hedged profit of the generator is:

$$\pi_i(p_i) = p_i q_i^S(p_i) - c_i(q_i^S(p_i)) - H_i^S \tag{4}$$

We will define the **implicit volume** V_i^S of the hedge contract to be the rate of change of the hedge payout with respect to the market price:

$$V_i^S(p_i) = \frac{\partial H_i^S}{\partial p_i}(p_i) \tag{5}$$

If this generator is reliable (so that its cost function is independent of the state of the world s), it only faces risk arising from variation in the spot price p_i. It can eliminate this risk by choosing a hedge contract with an implicit volume which matches its supply curve[4]:

$$\frac{\partial \pi_i}{\partial p_i} = q_i^S(p_i) - \frac{\partial H_i^S}{\partial p_i} = 0 \iff \frac{\partial H_i^S}{\partial p_i}(p_i) = q_i^S(p_i) \tag{6}$$

At this point, we can introduce one typical form of hedge contract known as a cap contract. By definition, a **cap contract** with a strike price S and a volume V pays out the difference between the spot price p and the strike price multiplied by the volume when the spot price exceeds the strike price.[5]

$$\text{Cap}(p|S, V) = (p - S)VI(p \geq S) \tag{7}$$

[4]It is important to note—here and elsewhere throughout this chapter—that this theoretical ideal hedge contract matches the forecast supply curve of the generator not the actual output. If the hedge contract paid the generator an implicit volume based on its actual output, the generator would face a moral hazard problem: it would not have an incentive to produce anything at all.

[5]Note that a swap contract is a special case of a cap contract where the strike price is below any possible realization of the spot price.

Here, $I(\cdot)$ is the indicator function[6] which takes the value one when the expression in brackets is true and zero otherwise.

Biggar et al. (2019) show that given a set of cap contracts with strike prices which are reasonably 'dense' (in the sense that, for any given price there is a cap contract in the range with a strike price close to that price), any generator with a fixed, upward-sloping marginal cost curve can construct a hedge contract with an implicit volume which approximates its supply curve. This approximation can be made arbitrarily close to the true supply curve as the strike prices of the cap contracts become arbitrarily dense (in the sense that the smallest distance between a strike price in the range and any given price tends to zero). In other words, given a dense set of cap contracts, any reliable generator with an upward-sloping marginal cost curve can come arbitrarily close eliminating all of the risk that it faces. This result is demonstrated formally in the appendix.

It is worth mentioning that, in practice, even if the portfolio of hedge contracts perfectly matches the supply curve of the generator, such a hedging strategy typically does not eliminate *all* of the risk faced by the generator. A generator may also face risks associated with changes in its cost function $c_i(\cdot)$. For example, a generator might be exposed to risk arising from plant outages (such as the loss of a generating unit) or the risk arising from variation in input-fuel cost. Hedging these risks requires additional hedging instruments, such as input-fuel price contracts.

Let us focus on a special case of a hedging contract faced by a special type of generator with a constant marginal cost, but an uncertain production capacity. We will refer to this as an **intermittent** generator. In particular, let us suppose that the cost function of the intermittent generator can be represented as a variable cost c_i (\$/MWh) up to some production capacity K_i (MW), which is uncertain (e.g., varies with the wind strength). Such a generator will produce at capacity $q_i^S = K_i$ whenever the spot price p_i exceeds the variable cost c_i. The raw or unhedged profit of the generator is therefore:

$$\pi_i(p_i) = (p_i - c_i)K_i I(p_i \geq c_i) \tag{8}$$

As before, this generator can hedge its pricing risk with a hedge contract with an implicit volume equal to its supply curve $q_i^S(p_i) = K_i I(p_i \geq c_i)$. For example, this generator could be perfectly hedged with a hedge contract which resembles a cap contract, but which has a volume whose variation matches the variation in the output of the generator:

$$H_i^S(p_i) = (p_i - c_i)K_i I(p_i \geq c_i) = \text{Cap}(p_i|c_i, K_i) \tag{9}$$

[6] Also known as the Iverson Bracket.

For example, in the case of a wind generator, the hedge contract would have a volume which is designed to reflect the forecast output of a wind farm, based on the measured wind speed. Such hedge products have recently been offered in Australia for wind and solar generators and are known as 'proxy revenue swaps.'[7] A related, more common form of hedge contract of this kind is the **Power-Purchase Agreement** or PPA.[8]

2.2.2 Hedging for Loads

Let us now consider what might be a typical hedge contract for a load. Let us suppose that the load purchases a hedge contract with a payout H_j^D so that its hedged payout is:

$$u_j(p_j) = v_j(q_j^D(p_j)) - p_j q_j^D(p_j) + H_j^D \tag{10}$$

As before, it turns out that a load can perfectly hedge the pricing risk it faces with a hedge contract with an implicit volume equal to the demand curve of the load.

$$\frac{\partial u_j}{\partial p_j} = -q_j^D(p_j) + \frac{\partial H_j^D}{\partial p_j} = 0 \iff \frac{\partial H_j^D}{\partial p_j}(p_j) = q_j^D(p_j) \tag{11}$$

Let us introduce the concept of the floor contract (which is the flip side of the cap contract). A **floor contract** with a strike price S and a volume V pays out the difference between the spot price p and the strike price multiplied by the volume when the spot price is below the strike price:

$$\text{Floor}(p|S, V) = (S - p)VI(p \leq S) \tag{12}$$

As an aside, we note that in the analogue of the well-known put-call parity result, there is a corresponding cap-floor parity, which allows a floor contract to be constructed out of a cap and a swap contract.

[7] These are described as follows: 'The project company pays the hedge provider a fixed percentage of 'proxy revenue', which is equal to the hub price multiplied by the 'proxy generation' for that settlement period. 'Proxy generation' is calculated under the hedge as the power that would have been produced by the project based on measured wind speeds and assuming pre-agreed fixed operational inefficiencies. The assumed operational inefficiencies include availability, performance and electrical losses.' https://www.projectfinance.law/publications/2017/June/hedges-for-wind-projects-evaluating-the-options.

[8] A PPA, which is based on the firm's actual output suffers from the moral hazard problem noted above.

As before, for any given supply curve, given a set of floor contracts with a sufficiently dense set of strike prices, it is possible to construct a portfolio with an implicit volume which approximates the demand curve of the load arbitrarily closely. In particular, in the case of a load which a fixed utility function $v_j(p_j)$, as the density of the set of floor contracts increases the load can create a portfolio of floor contracts which reduces the risk it faces arbitrarily close to zero.

In the literature on wholesale power markets, it is common to model loads as having a utility function which varies with factors such as the ambient temperature. One common assumption is to assume that the load has a fixed utility from consumption (which we will label M_j ($/MWh) – M_j is sometimes referred to as the 'Value of Lost Load' or VOLL) up to a varying level K_j (MW). Such a load will consume quantity K_j provided the spot price is less than M_j. The demand curve is therefore: $q_j^D(p_j) = K_j I(p_j \leq M_j)$.

Such a load can perfectly hedge the risk it faces with a variant of the floor contract which has a volume which varies with the maximum load:

$$H_j^D(p_j) = (M_j - p_j)K_j I(p_j \leq M_j) = \text{Floor}(p_j|M_j, K_j) \tag{13}$$

Such a contract is typically known as a **load-following hedge** or LFH. More generally, if the load has a downward sloping demand curve up to some maximum K_j, we need a more general form of the floor contract, which we will refer to as the FloorLFH, with a payout as follows. There is an example of the use of the FloorLFH in Sect. 4.2 below.

$$\text{FloorLFH}(p|S, V, L, K) = (S - p)VI(p \leq S, L \leq K) \tag{14}$$

2.3 *The Design of Inter-nodal Hedging Instruments*

At this point, we will introduce generalized Financial Transmission Rights. The reason for this design choice will become apparent below.

We propose that: (a) a node in the network is chosen and designated the reference node (labelled node N); and (b) for each node in the network other than the reference node, and for each hedge contract chosen by a generator or load at that node, the system operator makes available to the market a **corresponding FTR** from that node to the reference node. For each hedge contract H_i, the corresponding FTR is an FTR from node i to the reference node with the same implicit volume.

In the previous section, we introduced cap contracts, floor contracts, PPAs, and LFHs. We propose that, for each of these hedge contract types, there is made available a corresponding financial transmission right.

For example, in the previous section, we introduced the concept of the cap contract. A cap contract with a strike price S and volume V has an implicit volume equal to $VI(p \geq S)$. In exactly the same way, we propose the creation of an FTR contract which takes the form of a cap contract (which we will refer to as a CapFTR) with the same implicit volume. Specifically, a CapFTR from node i to node N, with a strike price S and a volume V pays out the following:

$$\text{CapFTR}(p_i, p_N|S, V) = (p_N - p_i)VI(p_i \geq S) \tag{15}$$

In exactly the same manner as with cap contracts, CapFTRs can be combined to form an instrument with an implicit volume which matches the supply curve of any generator with an upward-sloping supply curve. Specifically, given a set of CapFTRs with different strike prices, as the density of those strike prices increases, it is possible to form a set of CapFTRs with an implicit volume which approximates a given supply curve arbitrarily closely.

Analogously, we propose the creation of FloorFTRs, PPAFTRs, and LFHFTRs. The payout on a FloorFTR from node i to node j, with a strike price S and a volume V is as follows:

$$\text{FloorFTR}(p_i, p_N|S, V) = (p_N - p_i)VI(p_i \leq S) \tag{16}$$

The other generalized FTRs are defined in a similar way.

3 Hedging Using Generalized FTRs

To understand why these generalized FTRs might be valuable, let us first clarify the task to be solved. We will show that hedging between market participants cannot eliminate all risk. There remains a residual risk which must be borne by some party. Our objective with inter-nodal hedging, therefore, is not to enable the parties to eliminate all risk, but merely to allow them to reduce the risk down to the level that would arise if all generators and loads traded at the same pricing node.

3.1 The Theoretical Minimum Level of Risk

But what is this theoretical minimum level of risk? Let us suppose that each generator or load enters into a portfolio of financial hedge contracts which, in total, oblige the generator to pay the amount H_i^S and the load to receive the amount H_j^D in state s. In addition, we will suppose that the system operator enters into hedge contracts to hedge the risk that it faces (from variation in the merchandising surplus). In total these hedge contracts oblige the system operator to pay the amount H^{SO}. Let us define the amount H to be the total net payments made between generators, loads and the system operator. This net amount reflects the extent to which, for hedging purposes, there are payments to or from *other, outside* sources or parties (other than generators, loads, or the system operator).

$$H = \sum_i H_i^S - \sum_j H_j^D + H^{SO} \tag{17}$$

In sum, the total collective risk faced all the market participants (after hedging) is equal to the variation in the sum of the hedged profit for each generator plus the sum of the hedged utility of load plus the hedged position of the system operator. This can be written as follows:

$$\begin{aligned} W &= \sum_i \pi_i(p_i) + \sum_j u_j(p_j) + MS + H^{SO} \\ &= \sum_i (p_i q_i - c_i(q_i) - H_i) + \sum_j (v_j(q_j) - p_j q_j + H_j) + MS + H^{SO} \\ &= R + H \end{aligned} \tag{18}$$

Here $R = \sum_j v_j(p_j) - \sum_i c_i(p_i)$ is the total economic welfare of the participants in the market, H is the net payments under the hedge contracts as defined in Eq. 17, and MS is the **merchandising surplus** (also known as congestion rent) which is conventionally defined as the value of the net withdrawal of power at each node:

$$MS = -\sum_a p_a z_a \tag{19}$$

where $z_a = \sum_{i \in a} q_i^S - \sum_{j \in a} q_j^D$ is the net injection at pricing node a ($i \in a$ and $j \in a$ refers to the set of generation nodes and load nodes in pricing region a, respectively).

We will also assume that market participants do not trade hedge contracts with any other entities outside the electricity market, so that $H = 0$. Then, from Eq. 18 it follows that, no matter what hedge contracts are written, the total payoff of all the market participants is just equal to the total economic welfare $W = R$. This makes clear that although hedge contracts can shift risk around within the industry, there is a minimum economic risk which cannot be eliminated by trading in hedge contracts between generators and loads alone. That minimum risk is equal to the variation in the total economic welfare $\mathrm{Var}(R)$.[9]

[9]There is a corollary of this result which is interesting. This corollary is a parallel to the well-known Modigliani-Miller Theorem: The total value of the generators and loads in the market is independent of the trade in hedge contracts. To see this, let $V(X)$ be the present value of the uncertain future cash-flow X. This function is linear $V(X + Y) = V(X) + V(Y)$. From Eq. 18, we have that

This result is important because it establishes the theoretical minimum level of risk which must be borne in the market. The question for us now is how to package the merchandising surplus in a way which allows market participants to easily form the portfolios they need to hedge the risks they face.

3.2 Are Fixed-Volume FTRs an Effective Inter-nodal Hedging Instrument?

In practice, many liberalized wholesale electricity markets make available to market participants an instrument known as a fixed volume financial transmission right (FFTR). These are also known as FTR obligations to distinguish them from FTR options. A fixed-volume FTR between two locations on the network at a given point in time pays out a flow of funds equal to the difference in the nodal prices in those locations at that time multiplied by a *fixed* quantity. An FFTR of volume f_{ij} from node i to node j pays out the following amount in state s:

$$F_{i \to j} = (p_j - p_i) f_{ij} \tag{20}$$

But are fixed-volume FTRs a useful inter-nodal hedging instrument? The answer is no: A firm FTR is a hedging instrument with a fixed volume. It is therefore a useful instrument for hedging transactions which feature a *fixed volume* of production and consumption. But most conventional generators in the wholesale market have an output which varies with the state of the world, such as with changes in the wind speed, or the spot price. Such generators would prefer a hedging instrument with a hedging volume which varies with the wind speed or the spot price in a manner which mimics the production of the generator.

For example, consider the problem of hedging the output of a generic price-taking generator with a cost function $c_i(q_i)$. As noted earlier, this generator has a supply function $q_i(p_i)$ which is determined by the marginal cost function of the generator: $c_i'(q_i(p_i)) = p_i$. As the spot price p_i varies, the output of the generator $q_i(p_i)$ varies, potentially over a wide range, or the generator might shut down entirely. The risk associated with this pattern of production cannot be hedged with a *fixed volume* hedging instrument. The same, of course, applies to a wind generator. Such a generator has a pattern of production which cannot be hedged with a *fixed volume* hedging instrument.

$V(W) = \sum_i V(\pi_i) + \sum_j V(u_j) = V(R)$. The total value of the market participants is constant and independent of the trade in hedge contracts.

In our view, fixed-volume FTRs are not a satisfactory instrument for hedging inter-nodal pricing risks. The lack of effective inter-nodal hedging instruments has hindered the development of wholesale electricity markets.[10] We turn now to explain how the generalised FTRs introduced above may be used to hedge inter-nodal pricing risk.

3.3 Hedging Inter-nodal Pricing Risk Using Generalized FTRs

As we have seen, hedging between generators and loads alone cannot eliminate all risks. The remaining risks must be borne by at least one other party. For this reason, following Biggar et al. (2019), we introduce a new market participant, which we will refer to as the **trader**. The trader(s) are financial intermediaries who are assumed to behave in a manner which is close to risk neutral. The trader plays the risk-taking role, taking these residual or remaining risks on itself. Specifically, we will assume that through a process of trade and exchange in hedge contracts between generators, loads, and the trader, each generator and each load reaches a position where, due to the portfolio of hedge contracts it has acquired, it is perfectly hedged from risk. The trader takes on all of the remaining or residual risk.

Without loss of generality we can ignore trade directly between generators and loads. We therefore assume that, for each generator i, the trader purchases a hedge contract from the generator $H_i^S(p_i)$ which reduces the risk faced by the generator to zero, i.e., $\mathrm{Var}(\pi_i + H_i^S) = 0$. This implies $H_i^S(p_i) = \pi_i(p_i) + k_i$, for some constant k_i. As we have seen, this also implies that the implicit volume in the hedge contract is equal to the supply curve of the generator.

Similarly, for each load, the trader sells a contract to the load which reduces the risk faced by the load to zero, i.e., $H_j^D(p_j) = u_j(p_j) + k_j$, for some constant k_j. Again, the implicit volume in the hedge contract is equal to the demand curve of the load.

In addition, for each hedge contract held by the trader (that is, for each hedge contract purchased from a generator or sold to a load), the trader is assumed to acquire the corresponding generalized financial transmission right from the system operator. Let us assume that node N is the reference node. For each generator at node i and load at node j, the trader acquires the corresponding generalized FTR $H_{i\to N}^S$ and $H_{j\to N}^D$.

[10] Some markets also make available FTR *options*. However this does not solve the problem identified above. FTR options payout the price difference between two nodes, but only when that price difference is positive. We have seen above that a generator or load would like an instrument which depends only on the price at one location, not on the sign of the price difference.

As we noted earlier, the corresponding generalized financial transmission right has an implicit volume which matches the implicit volume of the hedge contract.[11]

In other words, in addition to the hedge contracts H_i^S and H_j^D purchased from generators or sold to loads, the trader also acquires a portfolio of generalised FTRs with the following payoffs:

$$H^S_{i\to N} = (p_N - p_i)q_i^S(p_i) \tag{21}$$

$$H^D_{j\to N} = (p_N - p_j)q_j^D(p_j) \tag{22}$$

Immediately, we can observe that the total payoff of these generalized FTRs is equal to the merchandising surplus, eliminating the risk faced by the system operator:

$$\begin{aligned}\sum_i H^S_{i\to N} - \sum_j H^D_{j\to N} &= \sum_j p_j q_j^D - \sum_i p_i q_i^S + p_N(\sum_i q_i^S - \sum_j q_j^D)\\ &= -\sum_a p_a z_a = MS \end{aligned}\tag{23}$$

Now, let us examine the characteristics of the total hedge position of the trader. Let H^T be the total financial position of the trader. Using the results above:

$$\begin{aligned} H^T &= \sum_i H_i^S - \sum_j H_j^D + \sum_i H^S_{i\to N} - \sum_j H^D_{j\to N}\\ &= \sum_i [p_i q_i^S(p_i) - c_i(q_i^S(p_i)) + k_i] + \sum_j [v_j(q_j^D(p_j)) - p_j q_j^D(p_j) + k_j]\\ &\quad \sum_i (p_N - p_i)q_i^S(p_i) + \sum_j (p_j - p_N)q_j^D(p_j)\\ &= \sum_j v_j(q_j^D(p_j)) - \sum_i c_i(q_i^S(p_i)) + k\\ &= R + k \end{aligned}\tag{24}$$

Here, $k = \sum_i k_i + \sum_j k_j$. We conclude that $\mathrm{Var}(H^T) = \mathrm{Var}(R)$. The risk has been reduced to the minimum possible level. Market participants are placed in the same position as if there was only one pricing node.

In Sect. 4 we demonstrate how this might work in practice, but first we show how this theory has a direct application in the context of merchant transmission investment

[11] As noted earlier, this does not necessarily imply that the generalised FTR is some form of bespoke arrangement—as we noted earlier, the hedge contract required by the generator or load could consist of a portfolio of cap or floor contracts. The corresponding generalised FTRs would itself be a portfolio of the corresponding capFTR or floorFTR contracts.

3.4 Merchant Transmission Investment Using Generalised FTRs

As noted in the introduction, economists have long been interested in the possibility that locational marginal prices might, somehow, provide the correct signals for electricity network investment. If this could be achieved, private commercial incentives for network investment could improve or replace the weak, imperfect or muted incentives for investment that arise under regulatory frameworks. This is an attractive possibility.

In particular, we wish to design a mechanism under which the change in the value of the payoff to a market participant aligns with the overall economic welfare. Formally, let us suppose that the uncertain future welfare of the power system is initially R^0. A market participant (who will be the trader) is considering whether or not to make a change to power system (in this case an augmentation to the network) with an associated incremental cost C. The new uncertain future welfare of the power system after the change is assumed to be R^1. It is socially efficient for the network augmentation to be carried out if and only if

$$V(R^1) - C > V(R^0) \tag{25}$$

Here, $V(X)$ is the valuation function: For any uncertain cash-flow X, $V(X)$ reflects the present discounted value of the cash-flow.

But how can we design a mechanism in such a way that a market participant faces the change in total economic welfare following a change in the market?

The discussion above suggests that such a mechanism might be possible. The broad outline of the mechanism is as follows: The trader offers hedge contracts to generators and loads which perfectly insulate them from risk. The trader then combines those contracts with the matching generalized FTR, thereby perfectly insulating the system operator from risk. As we have seen (from Eq. 24), the trader then faces a total payoff which is equal to the total social welfare (up to a constant). Therefore, provided these hedge contracts continue to perfectly insulate the generators and loads (and any new generators and loads that enter the market), following any change in the market, the trader will face the total change in welfare following the change in the market. In particular, if the trader incurs the cost of a network augmentation, the trader will choose to augment the network if and only if the network augmentation is in the public interest.

Let us look more closely at how this might work. As noted above, we have assumed that all market participants are risk averse, except for one market participant, which we will refer to as the trader, who is risk neutral. The market participants are assumed to trade in hedge contracts. As we have seen, for each generator, the trader is assumed to purchase hedge contracts from that generator, referenced to the generator's local node, which collectively match (in volume) the supply curve of the generator (including any shifts in that supply curve resulting from factors such as changes in the wind speed). This insulates the generator from all risk. At the same time, the trader is assumed to obtain the matching or corresponding generalised FTR from that local node to the reference node. Similarly, the trader sells hedge contracts to loads, referenced to the load's local node, which match (in volume) the demand curve of the load. Again, this perfectly insulates the load from all risk. As before, the trader obtains the matching or corresponding generalised FTR from that local node to the reference node. As we have seen, (from Eq. 24) the total payoff facing the trader then matches the total welfare of the power system (up to a constant).

Now imagine that, the trader has the potential to make a change to the power system, such as a network upgrade. For the mechanism outlined above to work, it must be that the trader continues to face a payoff equal to the total welfare after the change. In the short run, the network upgrade will cause a change in prices, leading to a change in dispatch outcomes and, in the longer term, may change the entry and exit decisions of generators.

Let us start with the short-run changes. As just noted, the network upgrade will bring about a change in dispatch outcomes. This may result in generators and loads exploring new regions of their supply and demand curves, which were not previously reached. We will address this by assuming that, nevertheless the hedge contracts of the generators and loads accurately reflect these regions of the supply and demand curves (even though there were not reached before).[12] With this assumption, it follows that the generators and loads continue to be perfectly hedged after the network augmentation. This implies, in turn, that the trader continues to a cash-flow stream which matches the total welfare of the power system. The trader has an incentive to upgrade the network if and only if it is efficient to do so.

In the longer term, the network upgrade may induce generators and loads to enter or exit the market. For the mechanism to work, the change in welfare brought about by this entry and exit must be reflected back to the trader. To bring this about, we will introduce a new category of hedge contract, which we will refer to as an 'entry-contingent hedge option'.

An entry-contingent hedge call option gives the holder (in this case the trader) the right to purchase a hedge option in the future on payment of a pre-determined price f. This contract would be sold by a potential-entrant generator with the pre-determined price set equal to the fixed cost of operation of the generator f. If the call option is not exercised, the generator does not enter the market and no payments are made. If the call option is exercised the generator enters the market, incurring the fixed cost f, which is paid by the trader in exchange for exercising the call option. The generator also receives an uncertain future payment stream, which is perfectly hedged by the hedge option, passing the risk on to the trader. The call option will only be exercised if the value of the uncertain payment stream exceeds the fixed cost, which is exactly the condition for entry in an efficient, competitive market.[13]

---

[12]We do not consider this assumption to be unreasonable as we conjecture that it should not cost any more to provide hedge contracts to reflect parts of the supply and demand curves which are not actually reached ex ante.

[13]There is an analogous result for loads.

To be a little more precise, let us suppose that H_i is a perfect hedge for a potential-entrant generator with an uncertain future profit π_i. In a competitive market for hedge contracts, the current price for the hedge is $V(H_i)$ (where $V(\cdot)$ is the value function described above). Let us suppose the fixed cost of the generator is f_i. This generator will enter the market and sell a hedge contract if and only if $V(H_i) > f_i$. This generator may then sell an entry-contingent call option with the strike price f_i, giving the trader the right to purchase the hedge contract at the price f_i. After the trader purchases the call option, if the trader augments the network, the trader will exercise the option if and only if $V(H_i) > f_i$, which is the condition for efficient entry. In addition, the trader receives the payoff $V(H_i) - f_i$, which is the total social welfare created by the entry.

We will assume that the trader purchases such entry-contingent call options from all generators which may enter or exit the market. After the network upgrade is made, the trader invokes the call options for generators which now become profitable, bringing about new entry. At the same time, the trader does not invoke the call option for generators which now become loss-making, resulting in their exit from the market. In either case, the trader is left with a payoff which reflects the change in total economic welfare arising from the entry and/or exit decision.

In summary, the risk averse generators, loads and the system operator pass the risk they face to this central agent, referred to as the trader. The trader, making use of the generalized FTRs described above, and, if necessary, the entry-contingent hedge options described above, faces a payoff which perfectly reflects the changes in total economic welfare arising from changes in the market. The trader therefore has an incentive to upgrade the network if and only if it is efficient to do so.

4 Simple Network Examples

Let us turn now to explore how generalized FTRs might facilitate inter-locational hedging and merchant investment in practice.

4.1 Two-Node Network Example

The first network we consider has just two nodes, labelled A and B. Each node has both generators and load, as illustrated in Fig. 1.

Fig. 1 Simple two-node network

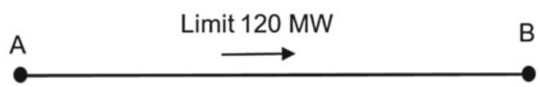


Table 1 Optimal dispatch outcomes in each scenario in the network of Fig. 1. Here MS= merchandising surplus, SWF = total welfare

State	Load		Flow	Price		MS	SWF
	L_A	L_B	$A \to B$	A	B	MS	R
1	50	200	100	$50	$50	$0	$242,500
2	50	250	120	$50	$300	$30,000	$282,500
3	50	300	120	$50	$300	$30,000	$317,500
4	50	350	120	$50	$1000	$114,000	$331,500
5	85	200	100	$50	$50	$0	$275,750
6	85	250	120	$100	$300	$24,000	$315,500
7	85	300	120	$100	$300	$24,000	$350,500
8	85	350	120	$100	$1000	$104,000	$364,500

There are assumed to be three generators at node A and two at node B. Each generator is perfectly reliable and has a constant marginal cost up to a maximum capacity of 100 MW. The marginal costs (c_i) of the generators at node A are G1:$10/MWh, G2:$50/MWh, and G3:$100/MWh. The marginal costs of the generators at node B are G4:$40/MWh, G5:$300/MWh.

There are two sources of uncertainty in the model, corresponding to uncertainty in the maximum load L_A and L_B at nodes A and B, respectively. The load at node A can take two values: $L_A = 50$ or 85. The load at node B can take four values: $L_B = 200$, 250, 300 or 350, for a total of eight different scenarios. The maximum value of consumption (sometimes referred to as the Value of Lost Load or VoLL) is assumed to be $1000/MWh. The link $A \to B$ initially has a fixed capacity of 120 MW, but there is potential to upgrade this link to 160 MW. No generators or loads enter or exit the market following the upgrade.

The optimal dispatch outcomes (prices, flows, merchandising surplus, and overall total welfare) under each of the different load scenarios are set out in Table 1.

We will assume that each generator and load seeks to eliminate all of the risk that it faces. For the generators, this can be achieved if the trader purchases from the generator a cap contract with a strike price equal to the marginal cost of each generator and a volume of 100 MW. In the case of the loads, the elimination of risk can be achieved with a load-following floor contract, with a volume equal to the realization of the maximum load (L_A and L_B). The full list of hedge contracts is set out in Table 2. These hedge contracts completely eliminate the risk faced by the generators and loads.

Let us designate node B as the reference node. Let us suppose that, in addition, the trader acquires generalized FTRs for each generator at node A to node B. Since each generator at node A can be hedged with a cap contract, the corresponding generalized

Table 2 Hedge contracts to eliminate the risks of the market participants in the network of Fig. 1

Gen/Load	Hedge contract
G1	Cap(p_1|\$10, 100)
G2	Cap(p_1|\$50, 100)
G3	Cap(p_1|\$100, 100)
G4	Cap(p_2|\$40, 100)
G5	Cap(p_2|\$300, 100)
L1	Floor(p_1|\$1000, L_A)
L2	Floor(p_2|\$1000, L_B)

Table 3 Trader net position in the network of Fig. 1

State	Gen hedging $\sum_i H_i^S$	Load hedging $\sum_j H_j^D$	FTR Payout	Total Payoff	SWF R
1	\$5000	\$237,500	\$0	\$242,500	\$242,500
2	\$30,000	\$222,500	\$30,000	\$282,500	\$282,500
3	\$30,000	\$257,500	\$30,000	\$317,500	\$317,500
4	\$170,000	\$47,500	\$114,000	\$331,500	\$331,500
5	\$5000	\$270,750	\$0	\$275,750	\$275,750
6	\$40,000	\$251,500	\$24,000	\$315,500	\$315,500
7	\$40,000	\$286,500	\$24,000	\$350,500	\$350,500
8	\$180,000	\$76,500	\$108,000	\$364,500	\$364,500

FTR is a CapFTR contract.[14] Similarly, the trader is assumed to acquire a generalized FTR for the load at A. Since the load at A can be hedged with a load-following floor contract, we assume the trader can acquire the corresponding LfhFTR.

Now, let us consider the net position of the trader. Table 3 sets out the total hedge payout to generators, the total hedge payout to loads, and the total payout on the generalised FTRs. As table 3 shows, the total net payout on the FTRs is equal to the merchandising surplus (as shown in table 1). Importantly, the total net position of the trader matches the total welfare created in this market.

Now, let us suppose that the trader considers upgrading the link to a capacity of 160 MW. This results in a new optimal dispatch with new pricing outcomes in each scenario. It also results in a higher overall social welfare. The outcomes under optimal dispatch following the upgrade are set out in Table 9.

We will assume that the same players continue in the market, with no new entry. Moreover, the trader does not need to offer any new hedge contracts or retire any old hedge contracts. All the generators and loads can be perfectly hedged using the

[14] We will assume that the CapFTR contract pays out $H_{i,A\to B} = (P_B - P_A)V_i$ where $V_i = 100$ if $P_A > c_i$, $V_i = 0$ if $P_A < c_i$ and $V_i = Q_i^S$ if $P_A = c_i$. This last condition is required since we have violated the assumption that the supply curve is strictly upward sloping.

Table 4 Optimal dispatch outcomes in each scenario in the network of Fig. 1 with link $A \rightarrow B$ upgraded to 160 MW

State	Load		Flow	Price		MS	SWF
	L_A	L_B	$A \rightarrow B$	A	B	MS	R
1	50	200	100	\$50	\$50	\$0	\$242,500
2	50	250	150	\$50	\$50	\$0	\$290,000
3	50	300	160	\$100	\$300	\$32,000	\$327,000
4	50	350	160	\$100	\$300	\$32,000	\$362,000
5	85	200	100	\$50	\$50	\$0	\$275,750
6	85	250	150	\$50	\$50	\$0	\$312,500
7	85	300	160	\$100	\$300	\$32,000	\$358,500
8	85	350	160	\$100	\$300	\$32,000	\$393,500

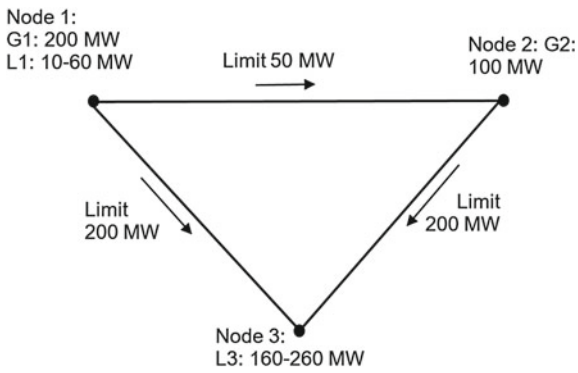
Table 5 Trader net position in the network of Fig. 1, with the link $A \rightarrow B$ upgraded to 160 MW

State	Gen hedging $\sum_i H^S_{Gi}$	Load hedging $\sum_j H^D_{Lj}$	FTRs Payout	Total Payoff	SWF R
1	\$5000	\$237,500	\$0	\$242,500	\$242,500
2	\$5000	\$285,000	\$0	\$290,000	\$290,000
3	\$40,000	\$255,000	\$32,000	\$327,000	\$327,000
4	\$40,000	\$290,000	\$32,000	\$362,000	\$362,000
5	\$5000	\$270,750	\$0	\$275,000	\$275,750
6	\$20,000	\$301,500	\$0	\$321,500	\$321,500
7	\$40,000	\$286,500	\$32,000	\$358,500	\$358,500
8	\$40,000	\$321,500	\$32,000	\$393,500	\$393,500

contracts set out in Table 3. In addition, the set of FTRs need not change. The resulting net position of the trader after the upgrade is set out in Table 5. As before, the total net position of the trader matches the total economic welfare created in this market.

It follows immediately that the trader faces exactly the right economic incentives to upgrade this link. For example, if all of the scenarios are equally likely, the expected net position of the trader before the upgrade is \$310,031 per hour and after the upgrade is \$321,344 per hour—a difference of \$11,313. The trader will make the upgrade if and only if the (amortized) cost per hour of the upgrade is less than \$11,313, as required.

Fig. 2 Simple three-node network



4.2 Three-Node Network Example

Now, let us illustrate how the proposals might work with a simple meshed network with just three nodes.[15] This network is illustrated in Fig. 2. Each link is assumed to have identical electrical characteristics. We will also assume that the generators have quadratic cost functions up to the maximum capacity, requiring a larger portfolio of cap contracts for effective hedging.

This network features two generators and two loads. Generator G1, located at node 1, has a marginal cost function given by $c_1'(q_1^S) = 10 + 0.02 \times q_1^S$ up to a capacity of 200 MW. Generator G2, located at node 2, has a cost function given by $c\prime_2(q_2^S) = 30 + 0.04 \times q_2^S$ up to a capacity of 100 MW. Load L1 is located at node 1 and has a utility function $v\prime(q_2^D) = 1000 - 0.02 \times q_2^D$ up to a maximum load which can take values 10, 20, 30, 40, or 50 MW. Load L2 is located at node 3 and has a utility function $v\prime(q_3^D) = 5000 - 0.08 \times q_3^D$ up to a maximum load of 160, 210 or 260 MW. There are, therefore, 15 states of the world to consider. Node 3 is the reference node.

The link $1 \to 2$ initially has a fixed capacity of 30 MW, but there is potential to upgrade this link to 50 MW. Any limits on the other two links are not binding.

The optimal dispatch outcomes (prices, flows, merchandising surplus, and overall total welfare) under each of the different load scenarios are set out in Table 6.

What portfolio of hedge contracts might hedge the positions of the generators and the loads? For the generators, the risk they face can be reduced to a very low level with a portfolio of around a dozen cap cap contracts with varying strike prices contracts, as set out in Table 7. Similarly, the load utility can be effectively hedged with a set of FloorLFH contracts, as set out in Table 7.

As before, for each of the contracts set out in Table 7, the trader is assumed to acquire the corresponding generalised FTR. That is, for each cap contract purchased from generators G1 and G2 the trader acquires the corresponding CapFTR, and

[15] Biggar et al. (2019) illustrate how this might work in networks with 6 and 24 buses.

Table 6 Optimal dispatch outcomes in each scenario in the network of Fig. 2

State	Load		Flow			Price			MS	SWF
	L_1	L_2	$1 \to 2$	$1 \to 3$	$2 \to 3$	1	2	3	MS	R
1	160	10	29.9	94.1	64.3	\$12.7	\$31.2	\$22.0	\$837.9	\$807329.9
2	160	20	30.0	94.2	64.2	\$12.9	\$31.4	\$22.1	\$837.4	\$817212.7
3	160	30	30.0	94.2	64.2	\$13.1	\$31.4	\$22.2	\$828.6	\$827077.6
4	160	40	30.0	94.2	64.2	\$13.3	\$31.4	\$22.3	\$819.8	\$836938.5
5	160	50	30.0	94.2	64.2	\$13.5	\$31.4	\$22.4	\$810.5	\$846794.4
6	210	10	30.0	118.9	89.0	\$13.2	\$32.4	\$22.8	\$871.0	\$1055482.8
7	210	20	30.0	118.9	89.0	\$13.4	\$32.4	\$22.9	\$862.7	\$1065346.5
8	210	30	30.0	118.9	89.0	\$13.6	\$32.4	\$23.0	\$853.4	\$1075206.5
9	210	40	30.0	118.9	89.0	\$13.8	\$32.4	\$23.1	\$843.6	\$1085061.9
10	210	50	29.6	118.7	89.2	\$23.7	\$32.4	\$28.4	\$465.2	\$1094900.8
11	260	10	30.0	143.7	113.7	\$13.7	\$33.4	\$23.6	\$893.3	\$1303384.2
12	260	20	30.0	143.7	113.7	\$13.9	\$33.4	\$23.7	\$884.8	\$1313243.1
13	260	30	26.4	141.9	115.5	\$33.6	\$33.6	\$33.6	\$0.4	\$1322991.9
14	260	40	19.8	138.6	118.8	\$197.4	\$197.4	\$197.4	\$0.0	\$1332647.1
15	260	50	19.8	138.6	118.8	\$998.9	\$998.9	\$999.0	\$9.1	\$1332645.2

Table 7 Hedge contract portfolios to approximately eliminate the risks of the market participants in the network of Fig. 2

Gen/Load	Hedge contract portfolio
G1	Cap(p_1|10.07, 135), Cap(p_1|12.77, 5), Cap(p_1|12.87, 5), Cap(p_1|12.97, 5), Cap(p_1|13.07, 5), Cap(p_1|13.17, 5), Cap(p_1|13.27, 5), Cap(p_1|13.37, 5), Cap(p_1|13.47, 5), Cap(p_1|13.57, 5), Cap(p_1|13.67, 5), Cap(p_1|13.77, 5), Cap(p_1|13.87, 5), Cap(p_1|13.97, 5)
G2	Cap(p_2|30.21, 10), Cap(p_2|30.61, 10), Cap(p_2|31.01, 10), Cap(p_2|31.41, 10), Cap(p_2|31.81, 10), Cap(p_2|32.21, 10), Cap(p_2|32.61, 10), Cap(p_2|33.01, 10), Cap(p_2|33.41, 10), Cap(p_2|33.81, 10)
L1	FloorLFH(p_1|\$999.9, 10, 10), FloorLFH(p_1|\$999.7, 10, 20), FloorLFH(p_1|\$999.5, 10, 30), FloorLFH(p_1|\$999.3, 10, 30), FloorLFH(p_1|\$999.1, 10, 40), FloorLFH(p_1|\$998.9, 10, 60)
L2	FloorLFH(p_3|\$4998, 160, 160), FloorLFH(p_3|\$4995.2, 50, 210), FloorLFH(p_3|\$4991.2, 50, 260)

for each load-following floor contract sold to L1 and L2 the trader acquires the corresponding FloorLFHFTR.

The resulting net position of the trader is set out in Table 8. We observe as before that the total net payout on the FTRs is close to the merchandising surplus in Table 6. The remaining difference is due to the approximation of the supply and demand curves implicit in the portfolio of CapFTRs and FloorFTRs we have chosen. This difference could be made smaller by choosing a portfolio with a denser set of strike

Table 8 Trader net position in the network of Fig. 1

State	Gen hedging $\sum_i H_i^S$	Load hedging $\sum_j H_j^D$	FTR Payout	Total Payoff	SWF R
1	\$376.7	\$806,036.3	\$925.0	\$807,338	\$807,330
2	\$408.8	\$815,876.2	\$875.1	\$817,160	\$817,213
3	\$438.9	\$825,720.1	\$865.9	\$827,025	\$827,028
4	\$470.7	\$835,558.1	\$856.7	\$836,886	\$836,939
5	\$505.1	\$845,389.1	\$758.8	\$846,653	\$846,794
6	\$500.5	\$1,054,020.3	\$862.3	\$1,055,383	\$1,055,483
7	\$532.7	\$1,063,860.3	\$854.3	\$1,065,247	\$1,065,347
8	\$568.3	\$1,073,694.1	\$798.1	\$1,075,061	\$1,075,206
9	\$609.7	\$1,083,518.3	\$696.5	\$1,084,824	\$1,085,062
10	\$2582.2	\$1,091,767.0	\$372.6	\$1,094,722	\$1,094,901
11	\$661.3	\$1,301,737.6	\$737.0	\$1,303,136	\$1,303,384
12	\$697.2	\$1,311,569.2	\$632.7	\$1,312,899	\$1,313,243
13	\$4655.0	\$1,318,245.5	\$0.3	\$1,322,901	\$1,322,992
14	\$53787.8	\$1,278,768.3	\$-0.1	\$1,332,556	\$1,332,647
15	\$294260.6	\$1,038,291.8	\$4.0	\$1,332,556	\$1,332,645

prices. In addition, Table 8 shows that the total net position of the trader is very close to the total welfare created in this market. The difference between the position of the trader and the total social welfare is less than 0.03% in each scenario.

Now, let us suppose that the trader considers upgrading the link to a capacity of 50 MW. This results in a new optimal dispatch with new pricing outcomes in each scenario. It also results in a higher overall social welfare. The outcomes under optimal dispatch following the upgrade are set out in Table 9.

As before, let us assume that the set of generators and loads remains the same. As we have seen, the generators and loads can continue to be effectively (to a close approximation) hedged using the contracts set out in table 7. As before, the set of FTRs also can remain the same. Therefore the trader can reduce its risk down to the theoretical minimum using the set of FTRs described above. The resulting net position of the trader after the upgrade is set out in Table 10. As before, the total net position of the trader closely matches the total economic welfare created in this market. The difference between the net position of the trader and the total economic welfare is less than 0.05%.

As before, we find the trader has the right incentives to fund the upgrade if and only if it is socially beneficial to do so. Specifically, if all 15 scenarios are equally likely, the trader receives a payout equal to \$1,074,290 per hour, on average, when the link has a capacity of 30 MW. When the link is upgraded, the trader receives a payout equal to \$1,074,590 per hour. The difference is \$300 per hour, which is very close to the total economic welfare generated by the upgrade of \$303 per hour. This

Table 9 Optimal dispatch outcomes in each scenario in the network of Fig. 2 with link 1 → 2 upgraded from 30 to 50 MW

State	Load		Flow			Price			MS	SWF
	L_1	L_2	1 → 2	1 → 3	2 → 3	1	2	3	MS	R
1	160	10	50.0	104.2	54.2	$13.3	$30.2	$21.7	$1276.8	$807882.1
2	160	20	50.0	104.2	54.2	$13.5	$30.2	$21.8	$1261.7	$817745.0
3	160	30	50.0	104.2	54.2	$13.7	$30.2	$21.9	$1246.5	$827603.8
4	160	40	50.0	104.2	54.2	$13.9	$30.2	$22.0	$1231.4	$837458.7
5	160	50	46.2	102.3	56.1	$30.4	$30.4	$30.4	$0.0	$847216.1
6	210	10	50.0	129.0	78.9	$13.8	$31.2	$22.5	$1314.7	$1056036.2
7	210	20	49.5	128.7	79.2	$31.2	$31.2	$31.2	$0.0	$1065881.1
8	210	30	42.9	125.4	82.5	$31.6	$31.6	$31.6	$0.0	$1075562.1
9	210	40	36.3	122.1	85.8	$32.0	$32.0	$32.0	$0.0	$1085237.1
10	210	50	29.7	118.8	89.1	$32.4	$32.4	$32.4	$0.0	$1094906.1
11	260	10	39.6	148.5	108.9	$32.8	$32.8	$32.8	$0.0	$1303664.1
12	260	20	33.0	145.2	112.2	$33.2	$33.2	$33.2	$0.0	$1313331.1
13	260	30	26.4	141.9	115.5	$33.6	$33.6	$33.6	$0.0	$1322992.1
14	260	40	19.8	138.6	118.8	$460.2	$460.2	$460.2	$0.0	$1332647.1
15	260	50	19.8	138.6	118.8	$999.2	$998.9	$999.2	$0.0	$1332647.1

Table 10 Trader net position in the network of Fig. 2, with the link 1 → 2 upgraded from 30 to 50 MW

State	Gen hedging $\sum_i H_i^S$	Load hedging $\sum_j H_j^D$	FTR Payout	Total Payoff	SWF R
1	$446.9	$806,067.5	$1221.9	$807,736	$807,882
2	$480.9	$815,911.8	$1207.4	$817,600	$817,745
3	$516.8	$825,750.0	$1110.6	$827,377	$827,604
4	$554.8	$835,582.3	$1015.9	$837,153	$837,459
5	$3853.4	$843,273.0	$0.0	$847,126	$847,216
6	$552.4	$1,054,077.9	$1171.4	$1,055,802	$1,056,036
7	$4029.2	$1,061,760.8	$0.0	$1,065,790	$1,065,881
8	$4123.1	$1,071,348.2	$0.0	$1,075,471	$1,075,562
9	$4221.0	$1,080,925.6	$0.0	$1,085,147	$1,085,237
10	$4322.9	$1,090,493.0	$0.0	$1,094,816	$1,094,906
11	$4428.8	$1,299,143.4	$0.0	$1,303,572	$1,303,664
12	$4538.7	$1,308,700.8	$0.0	$1,313,240	$1,313,331
13	$4652.6	$1,318,248.2	$0.0	$1,322,901	$1,322,992
14	$132622.7	$1,119,933.4	$0.0	$1,332,556	$1,332,647
15	$294330.5	$1,038,225.6	$0.0	$1,332,556	$1,332,647

remaining difference could be reduced through consideration of a larger set of hedge contracts and generalised FTRs in the trader's portfolio.

5 Discussion

It is worthwhile to explore the relationship between the proposal set out in this chapter, and some of the literature on merchant investment, such as the HRGV mechanism set out in Hesamzadeh et al. (2018).

Under the HRGV mechanism, an outside party (the 'regulator') allows the transmission company (referred to as a Transco) to change the fixed component of the two-part transmission tariff by an amount which does not exceed the change in total economic welfare from one period to the next. As a consequence, by construction, if the Transco upgrades the network, it receives the full change in total economic welfare in return. The Transco has the incentive to upgrade the network if and only if it is efficient to do so.

The HRGV mechanism is similar to the approach set out in this chapter. In the HRGV mechanism, the regulator ensures that the Transco receives the full gain from any change in welfare. In contrast, under the proposal in this chapter, it is the desire of generators, loads, and the system operator to be hedged which leads them to transact in hedge contracts with the trader which has the effect of leaving the trader in a position which faces the full social welfare created by the network.

But there are also key differences between the two proposals. One key difference is that, in the HRGV work, an outside party (the regulator) has to determine the change in total social welfare in order to determine how much the Transco can change the fixed fee. This requires the additional assumption that key demand and supply information is publicly available, which seems unlikely.

In contrast, in the proposal set out in this chapter, the trader is not assumed to necessarily know information about the demand and supply of generators and loads. Instead, the trader merely stands ready to transact in hedge contracts. The desire of generators and loads to hedge their risk leads them to transact in contracts in which all their risk is passed to the trader. The trader(s) then make use of generalised FTRs to trade in those contracts while taking the minimum possible risk on themselves. We have seen that the trader(s) then collectively face a payoff equal to the total social welfare. But this arises as a result of a consequence of a natural process, rather than being assumed at the outset.

There is also a deeper problem. The HRGV mechanism, by design, has the property that it expropriates the value of investments made by market participants. This undermines the incentive for market participants to make those investments in the first place.

The HRGV mechanism allow the Transco to capture the full change in economic welfare arising from any change in the market. In fact the HRGV mechanism is equivalent (in this respect) to a perfectly price discriminating monopolist who is able to extract the full surplus from all market participants. Consider the position of a generator who is considering making an investment to enhance its thermal efficiency (and thereby reduce its costs). Under the HRGV proposal, the generator immediately loses all of the benefits of that investment in the following period. The same applies to a load which is considering upgrading the electrical equipment in a factory. Again, under the HRGV proposal, all of the increase in surplus arising from that upgrade would be taken by the Transco in the following period.

The chapter by Vogelsang in this volume recognises this problem, but views it as a 'fairness' issue:

> Because the HRGV mechanism hands all social surplus increases linked to the transmission system to the Transco it provides no net benefit beyond the status quo the transmission users, which are generators and loads This can be unfair from a distributional perspective Thus the mechanism needs to be augmented by rules that lead to a fairer distribution of the social surplus increase.

We agree that this is an undesirable feature, but not just on fairness grounds. There is a strand of regulatory theory which emphasises that a fundamental objective of public utility regulation is the protection sunk investments by customers— precisely in order to ensure those customers have incentives to make socially desirable investments.[16]

One of the benefits of our proposed mechanism is that, once hedged, any change in the social surplus (e.g., a generator lowering its production cost) accrues to the individual who created that social surplus, and therefore does not undermine incentives for making such investments in the first place.[17] We consider that the approach articulated here, unlike the HRGV mechanism, is consistent with the economic foundation for public utility regulation.

In summary, the approach set out here has some similarities to the HRGV mechanism. However, we consider that the approach set out here makes an interesting and important contribution in establishing a natural link between hedging (including inter-nodal hedging using G-FTRs) and the total economic welfare in the power system. We consider that this link offers substantial promise for developing a mechanism linking private and public incentives for network augmentation in the future.

6 Conclusion

Almost since the time when locational marginal pricing of electricity networks was first proposed, researchers have explored whether or not it is possible to create a mechanism by which the incentives of private, commercial market players seeking to fund transmission augmentations would align with the overall public benefit. This chapter proposes such a mechanism, drawing on our previous work proposing the development of generalised Financial Transmission Rights.

---

[16] See Biggar (2009, 2012).

[17] The same principle could perhaps be adopted in the HRGV mechanism if the mechanism offered long-term hedge contracts in the same way as suggested here.

We consider that generalized FTRs are worthy of study, in themselves, as effective inter-nodal hedging mechanisms are becoming increasingly important. Around the world increasing penetration of Distributed Energy Resources is leading to pressure to extend current arrangements for locational marginal pricing of wholesale power markets down to lower-voltage levels. It is of critical importance that market participants have access to the tools they need to hedge those risks.

To date, liberalized wholesale power markets have only made available a strictly limited range of instruments to hedge inter-locational pricing risk. In our view this has had the effect of limiting the scope for effective inter-locational hedging. We consider this to be one of the most important weaknesses in what is otherwise one of the most important and successful sectoral liberalizations of the late twentieth century. Generalized FTRs go some way to addressing this gap.

This chapter demonstrates how, in principle, a trader using generalized FTRs faces the correct incentives to upgrade the transmission network, if and only if it is socially beneficial to do so. We envisage that the trader will trade with generators and loads, making available hedge contracts to all generators and loads which eliminate their risk. At the same time, the trader will trade with the system operator, acquiring matching generalized FTRs. We show that, if the trader is able to effectively offset the risks of generators, loads, and the system operator the trader faces a total payoff equal to the total social welfare created in the wholesale market.

Many questions remain, including whether or not the proposed mechanism can be made practical. A key question is whether or not the trader role itself can be decentralized across the market. In this case, the results set out in this chapter refer to the collective interests of the total coalition of traders in the market. The implications of this possibility are left for future research.

7 Appendix

Consider a price-taking generator with a cost function $c(g)$ facing a price p. The profit-maximising level of output of the generator is the level of output g which satisfies $c'(g) = p$ which we will write as $g(p) = (c')^{-1}(p)$. $g(p)$ represents the supply curve of the generator - for any level of the spot price it shows the corresponding profit-maximising level of output.

Up to a constant, the raw or unhedged profit of such a generator can be expressed as an integral:

$$\pi(p) = pg(p) - c(g(p)) = \int_0^{g(p)} (p - c'(g))dg \tag{26}$$

Let's suppose we have a set of cap contracts with strike prices $S_0, S_1, S_2, \ldots$. These are assumed to be ordered so that $S_0 < S_1 < S_2 \ldots$ and are assumed to span the relevant space in the sense that S_0 is below the lowest marginal cost of any generator and the largest strike price is above the largest marginal cost of any generator (or the largest marginal utility of any load). The gap between consecutive strike prices $S_{i+1} - S_i$ is assumed to be less than ΔS.

We can approximate the profit function of the generator with the following step function (here i^* is the largest value of i for which $S_i \leq p$):

$$\sum_{i=0}^{i^*}(p - S_{i+1})(g(S_{i+1}) - g(S_i)) \leq \pi(p) \leq \tag{27}$$

$$\sum_{i=0}^{i^*-1}(p - S_i)(g(S_{i+1}) - g(S_i)) + (p - S_{i^*})(g(p) - g(S_{i^*})) \tag{28}$$

We can write this as:

$$\sum_{i=0} Cap(p|S_{i+1}, g(S_{i+1}) - g(S_i)) \leq \pi(p) \leq \tag{29}$$

$$\sum_{i=0} Cap(p|S_i, g(S_{i+1}) - g(S_i)) \tag{30}$$

$$+ (p - S_{i^*})(g(p) - g(S_{i^*})) \tag{31}$$

As the spacing in the strike prices ΔS tends to zero, the last term in Eq. 31 tends to zero. The upper and lower bounds in Eq. 31 therefore approximate the profit function arbitrarily closely. Using this result we can conclude that we can approximate the optimal hedge contract arbitrarily closely with a set of cap contracts.

Theorem 1 *Given a price-taking generator with a cost function with continuous and upward sloping marginal cost $c'(\cdot)$, and a set of cap contracts with strike prices $S_0, S_1, S_2, \ldots$, as the gaps between the strike prices $S_{i+1} - S_i$ tend to zero, the generator is able to form a portfolio of cap contracts which hedges its exposure to market price risk arbitrarily closely. Specifically, suppose that, given a set of strike prices S_i and a function $g(\cdot)$ we define a hedge contract portfolio $H(g, S|P)$ as follows:*

$$H(p|g, S) = \sum_i Cap(p|S_{i+1}, g(S_{i+1}) - g(S_i)) \tag{32}$$

Then, provided we choose $g(p) = (c')^{-1}(p)$ we have that:

$$H(g, S|P) \approx \pi(p) \ \ as \ \Delta S \to 0 \tag{33}$$

As before, let's suppose we have a generator with an upward sloping supply curve $g(p)$. We can write the supply curve of the generator as follows:

$$g(p) = \sum_{i=1}^{i^*}(g(S_i) - g(S_{i-1})) + g(p) - g(S_{i^*}) \tag{34}$$

Therefore, we can approximate the supply curve as follows:

$$\sum_{i=1}^{i^*}(g(S_i) - g(S_{i-1})) \leq g(p) \leq \tag{35}$$

$$\sum_{i=1}^{i^*+1}(g(S_i) - g(S_{i-1})) \tag{36}$$

This approximation becomes arbitrarily close as $\Delta S \to 0$.

From which it follows that we can approximate, arbitrarily closely, an inter-nodal hedging instrument with the required volume profile using a portfolio of CapFTRs:

$$\sum_{i=1}^{i^*} Cap(p_i, p_j|S_i, g(S_i) - g(S_{i-1})) \leq (p_i - p_j)g(p_i) \leq \tag{37}$$

$$\sum_{i=1}^{i^*+1} Cap(p_i, p_j|S_i, g(S_i) - g(S_{i-1})) \tag{38}$$

This leads to the following theorem:

Theorem 2 *Suppose a generator has an upward sloping supply curve $g(p)$. Given a set of CapFTR contracts from node i to node j with strike prices $S_0, S_1, S_2, \ldots$, it is possible to form a portfolio of CapFTR contracts with the property that, as the gaps between the strike prices $S_{i+1} - S_i$ tend to zero, the portfolio forms an internodal hedging instrument from node i to node j with a volume which matches the supply curve of the generator arbitrarily closely. Specifically, suppose that, given a set of strike prices S_i and an upward-sloping function $g(\cdot)$ we define a hedge contract portfolio $H(p_i, p_j)$ as follows:*

$$H(p_i, p_j) = \sum_{i=1} Cap(p_i, p_j|S_i, g(S_i) - g(S_{i-1})) \tag{39}$$

Then:

$$H(p_i, p_j) \approx (p_i - p_j)g(p_i) \ \ as\ \Delta S \to 0 \tag{40}$$

References

D. Biggar, Is protecting sunk investments by consumers a key rationale for natural monopoly regulation? Rev. Network Econ. **8**(2) (2009)

D. Biggar, Why regulate airports? A re-examination of the rationale for air-port regulation. J. Transp. Econ. Policy (JTEP) **46**(3), 367–380 (2012)

D.R. Biggar, M. Hesamzadeh, Generalized financial transmission rights for hedging inter-nodal pricing risks. IEEE Trans. Power Syst.

J.B. Bushnell, S.E. Stoft, Electric grid investment under a contract network regime. J. Regul. Econ. **10**(1), 61–79 (1996)

J.B. Bushnell, S.E. Stoft, Improving private incentives for electric grid investment. Resour. Energy Econ. **19**(1–2), 85–108 (1997)

M.R. Hesamzadeh et al., A simple regulatory incentive mechanism applied to electricity transmission pricing and investment. Energy Econ. **75**, 423–439 (2018)

W.W. Hogan, Contract networks for electric power transmission. J. Regul. Econ. **4**(3), 211–242 (1992)

W.W Hogan, et al., Financial transmission rights, revenue adequacy and multi-settlement electricity markets [Online]. Available Harvard University web site: http://www.hks.harvard.edu/fs/whogan/HoganFTRRevAdequacy31813

P. Joskow, J. Tirole, Merchant transmission investment. J. Ind. Econ. **53**(2), 233–264 (2005)

J. Rosellón, T. Kristiansen, *Financial Transmission Rights* (Springer, Berlin, 2013)