SOLVING THE PRICING AND HEDGING PROBLEMS IN THE NEM USING "CONSTRAINT-BASED RESIDUES"

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Abstract

The Australian National Electricity Market ("NEM") currently suffers from several problems. Current market rules force all generators and loads in the same region to receive the same price, even in the presence of transmission constraints between locations in the same region. This mis-pricing gives rise to distorted bidding behaviour, leading to inefficient dispatch, and distorted generator and load location decisions. At the same time, the inter-regional settlement residues ("IRSRs") – the primary instrument in the NEM for hedging inter-regional trading risk – are not a "firm" instrument for hedging trading risk in the presence of network outages; loop-flow between regions; or the distorted bidding brought about by the mis-pricing mentioned above.

Several solutions to these problems have been proposed, of which the most prominent is the CSC/CSP mechanism proposed by Charles River Associates. However, this approach does not completely solve the problems identified above. In particular, it is not always possible to design a CSP/CSC mechanism which solves the hedging problem – for certain types of constraints, such as outage constraints, it is not possible to design the CSP/CSC mechanism in such a way as to allow for firm inter-regional hedges without the system operator incurring a surplus or deficit.

This paper sets out the theory of an alternative, known as the "constraint-based residues" approach. I demonstrate that the constraint-based residues approach can solve the problems of mis-pricing and hedging – of both intra-regional and inter-regional price risk, in the presence of both outages and loop-flow. The constraint-based residues approach is also a natural "evolution" or "extension" rather than a radical overhaul of the current market design, and involves no risk of accumulation of surpluses or deficits by the system operator. This paper provides a detailed worked example, using actual market data of how the constraint-based residues approach would solve the problem of mis-pricing and negative settlement residues arising from the Murray-Tumut constraint in the Snowy region. This paper argues that the constraint-based residue approach offers promise as a medium or long-term solution to the mis-pricing and hedging problems in the NEM.

1. Introduction

1. As is widely known, Australia's National Electricity Market ("NEM") uses a "regional" or "zonal" pricing approach. The price paid for the production or consumption of electricity is the same at all geographic locations in the same region, regardless of the number or location of transmission constraints in that region.

2. It is now clearly established that this gives rise to two fundamental problems in the NEM:

(a) First, there is the "mis-pricing" problem. Generators and scheduled loads are dispatched according to the (hypothetical) local price for their connection point, but are only paid the regional reference price. This mismatch (or "inconsistency") between pricing and dispatch induces these generators or loads to bid in a way which does not reflect their underlying cost. These generators or loads can bid as low as $-1000/MWh or as high as $10,000/MWh, in an attempt to increase the amount for which they are dispatched, with little or no impact on the price they receive. This distorted bidding, in turn, leads to inefficient dispatch – more expensive generation is turned on while less expensive generation remains available to produce.

In the longer run, the mis-pricing will affect generator and load location decisions – generators and loads will have too strong an incentive to locate or expand in regions which exacerbate transmission congestion and loads will have too little incentive to locate or expand in regions which alleviate congestion.

(b) Second, there is the "hedging" problem. At present in the NEM, the merchandising surplus is divided up into streams known as inter-regional settlement residues ("IRSRs"), which are auctioned back to market participants as a tool for arbitrage of inter-regional differences in the prices of hedge contracts. But these inter-regional settlement residues are not fully effective at this task – that is, they do not allow for perfect arbitrage of inter-regional differences in hedge prices, and in some cases these inter-regional settlement residues may be negative. This problem of lack of firmness[1] partly arises as a result of the "mis-pricing" problem above but it is not solely a result of mis-pricing. In the event of loop-flows between regions the current IRSRs are not a firm hedging instrument, even in the absence of any intra-regional constraints.

3. Solving the "mis-pricing" problem requires a move towards finer geographic differentiation of prices (at least for generators) in the NEM. This could be achieved through the dividing up of existing regions into smaller regions. If these regions are made small enough this would eliminate the mis-pricing problem. However, it would not solve the hedging problem. As long as there remain loops between regions (and the smaller the regions the more likely it is that there will be numerous loops) the inter-regional settlement residues will remain non-firm.

4. Some commentators have argued for a move to financial transmission rights ("FTRs") to solve the hedging problem. FTRs have a solid theoretical foundation and would, in principle,

[1] In this paper, when discussing the "firmness" of a hedging instrument I will be referring to the ability to use that instrument to hedge a given transaction. The total quantity of transactions that can be hedged depends on the physical limits of the transmission network, as reflected in the right-hand side of the constraint equations. The "firmness" of an interconnector is sometimes also used to refer to the level and certainty surrounding these physical limits on the interconnector. For the purposes of this paper I will put this latter concept of firmness to one side. In this paper I will say that a hedging instrument is firm if it allows a perfect hedge up to the physical limits of the transmission network.

solve the hedging problems in the NEM. However, the introduction of FTRs would be a radical step in the NEM which is not yet being seriously considered. I will put this option to one side.

5. This leaves us with two proposals for solving the mis-pricing and hedging problems in the NEM:

(a) The CSP/CSC mechanism proposed by Charles River Associates. CRA describe this approach in a series of papers produced for the Ministerial Council on Energy[2]; and

(b) The "constraint-based residues" approach set out in this document.

6. The CSP/CSC mechanism and the constraint-based residues approach have elements in common. Both can be adopted in a "progressive" manner – that is, individual constraints could be selected for handling under either mechanism, and other constraints added as they emerge over time. Both approaches solve the mis-pricing problem (at least for those constraints which are included in either regime) – in fact both approaches solve the mis-pricing problem in exactly the same manner: through a system of explicit or implicit payments to generators.

7. However, these approaches differ in their handling of the residues that arise. Under the CSP/CSC mechanism these residues are passed back to the existing market participants and to and from the existing inter-regional settlement residues.

8. In contrast, the constraint-based residues approach creates new residue "funds" or "streams" – closely analogous to the existing inter-regional settlement residues – which are then auctioned, as at present. Under the constraint-based residues approach there could be many new residue funds available – one for each of the constraints which might bind which are covered by the constraint-based residues regime.

9. CRA appear to claim that the CSP/CSC mechanism can be designed in way which makes the inter-regional settlement residues firm. In fact, it is not always possible to design the CSP/CSC mechanism so as to obtain a firm hedge while ensuring that the mechanism is "revenue neutral" overall – that is, without imposing a surplus or a deficit on the system operator.

10. In addition, CRA do not (to my knowledge) make any claims about the ability of market participants to hedge their intra-regional trading risks under the CSP/CSC mechanism. I show that firm intra-regional hedging is possible under the CSP/CSC scheme but only if market participants have access to trade a large number of individual residue funds – more in fact than is required under the constraint-based residues approach.

11. In contrast, in this paper I show that under the constraint-based residues approach, market participants can, by obtaining access to the constraint-based residue funds, perfectly hedge their inter-regional and intra-regional trading risk, in a natural way.

11. In addition, I demonstrate below that the constraint-based residues funds will (under certain assumptions) always be positive and therefore can be auctioned as a stream of one-way payments, with no risk of negative residues and no deficit or surplus incurred by the system operator.. Finally, I show that constraint-based residues are a natural generalization of the existing arrangements in the NEM and can be introduced on a progressive, gradual basis with no disruption to existing inter-regional arbitrage arrangements.

[2] See, particularly, CRA (2004a), CRA (2004b) and CRA (2005).

12. I conclude that the constraint-based residues approach offers the most promise for an evolutionary, yet effective, revenue neutral, solution to the mis-pricing and hedging problems that arise in the current NEM.

13. This paper is divided into seven sections. The first section provides the intuition and motivation for the constraint-based residues approach using simple network models with only a few nodes and ignoring losses. The second section demonstrates how constraint-based residues would work to facilitate inter-regional arbitrage in the context of the NEM itself, using as an example the events on 1 December 2004. The third section introduces the theoretical framework with a number of key definitions and introduces the notion of intra-regional and inter-regional hedging in the NEM. The fourth section considers the status quo arrangements in the NEM and formalizes the mis-pricing and hedging problems. The fifth section defines the constraint-based residues concept and demonstrates how it solves the mis-pricing and hedging problems. The sixth section formally defines the CSP/CSC concept and considers the conditions under which the CSP/CSC approach solves the hedging problems. The seventh section concludes.

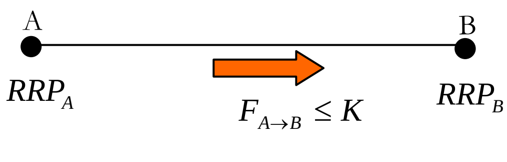
2. Constraint-Based Residues: An Introduction

14. In order to develop some intuition as to the problems with the existing arrangements in the NEM, and how these problems are addressed by constraint-based residues, let's consider some simple network models. This section shows that under the current arrangements in the NEM, the existing inter-regional settlement residues are not a firm hedging instrument in the presence of loop-flows. I go on to demonstrate how access to constraint-based residues allows all generators to obtain a firm hedge.

15. In these examples, we will ignore losses –both static intra-regional losses and dynamic inter-regional losses. As we will see later, this assumption is more than a mere convenience, but it greatly simplifies the presentation and therefore is useful at this stage.

16. Let's start first with a simple network without loop-flow. The following simple two-node network will show, first, how inter-regional settlement residues are used as a hedging device, in a network without intra-regional constraints or loop-flow. In the next examples we will see how inter-regional settlement residues are not effective at hedging in the presence of intra-regional constraints or loop-flow.

17. In this network there are just two regions, labeled region A and region B. The regional reference price in each of these regions is RRP_A and RRP_B. The flow on the line between these two regions is denoted $F_{A\to B}$. The physical limit on the flow on this line is denoted *K*. The inter-regional settlement residues on the interconnector between the regions is equal to the price difference between the regions times the flow $IRSR_{A\to B} = (RRP_B - RRP_A)F_{A\to B}$.



18. Now suppose that a trader wishes to perfectly hedge a transaction which involves purchasing a swap contract in region A and selling a swap contract in region B (a "swap contract" is the simplest form of hedging arrangement under which the buyer agrees to pay the seller the difference between the spot and a pre-determined price at a point in time in the future). In order

to perfectly hedge this transaction the trader needs an instrument which has a pay-off equal to the price difference between the regions times a fixed quantity.

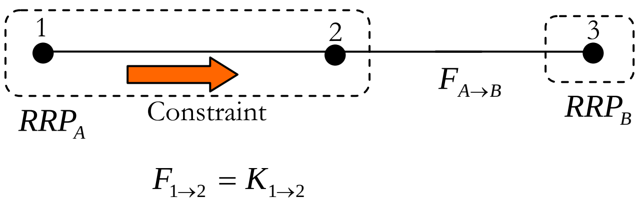
19. Let's suppose that the trader buys a 100 MW swap in region A and sells a 100 MW swap in region B. The trader then needs a hedge instrument which has the pay-off equal to 100 times the price difference – that is, $100 \times (RRP_B - RRP_A)$.

20. Suppose that this trader purchases a share equal to $100/K$ of the inter-regional settlement residues. This has the pay-off equal to:

$$\frac{100}{K} \times IRSR_{A\to B} = 100(RRP_B - RRP_A)\frac{F_{A\to B}}{K}$$

21. Now, in this simple network we know that the price difference between the two regions must be zero unless the flow on the interconnector is at its limit. So the pay-out on the inter-regional settlement residue is equal to zero unless the flow is equal to the limit *K*. Mathematically, this implies that $IRSR_{A\to B} = (RRP_B - RRP_A)K$. Therefore, the payout from purchasing this share $100/K$ of the inter-regional settlement residues is just $100 \times (RRP_B - RRP_A)$, as required. In other words, in this simple network with no loop flow and no intra-regional constraints, the inter-regional settlement residues allow for perfect arbitrage of the differences in hedge prices in each region.[3]

22. Let's now consider a slightly more complicated network with an intra-regional constraint. In the following network there are three nodes, with the first two nodes in region A and the third node in region B. There is an intra-regional constraint between nodes 1 and 2, but no constraint on the inter-regional interconnector between nodes 2 and 3.



23. As before, we will ask whether the inter-regional settlement residues allow for the perfect arbitrage of swap prices across the two regions. The inter-regional settlement residues are, in this network, equal to $IRSR_{A\to B} = (RRP_B - RRP_A)F_{A\to B}$. In other words, the inter-regional settlement residues are equal to the price difference between node 3 and node 1 times the flow on the line between node 3 and node 2.

24. The trader could still perfectly arbitrage 100 MW of swaps in each region, by purchasing the share $100/F_{A\to B}$ of the inter-regional settlement residues. This yields a payout of precisely $100 \times (RRP_B - RRP_A)$, as required.

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[3] As an aside, note that "perfect" arbitrage does not mean that the swap prices in each region have exactly the same price, rather that the difference in the swap prices is precisely equal to the forecast future average difference in the spot prices.

25. But there is a potential problem: In the previous example we saw that the flow on the interconnector was always equal to the physical limit at times of binding constraint (and therefore at times of large price differences). But in this network *there is no necessary relationship between the flow on the interconnector and any of the network's physical limits* at times of a binding intra-regional constraint.

26. This poses a problem for the trader who is seeking to arbitrage hedge prices. How does the trader know the flow on the line between node 2 and node 3 at times of binding intra-regional constraint? The flow on the line between node 2 and node 3 could be positive, zero or even negative (giving rise to negative settlement residues) at times when the intra-regional constraint is binding. If the trader cannot perfectly forecast the flow on the interconnector at times of binding constraint the trader cannot obtain a perfect hedge – the trader is left bearing some risk.

27. This problem is known as the "lack of firmness" issue. In the presence of intra-regional constraints, price differences between regions can arise whether or not the flow on the interconnector between regions is at its physical limit. Since traders cannot easily forecast the flow on the interconnector at times of binding intra-regional constraint, traders cannot obtain an instrument which allows for perfect hedge with no residual risk.

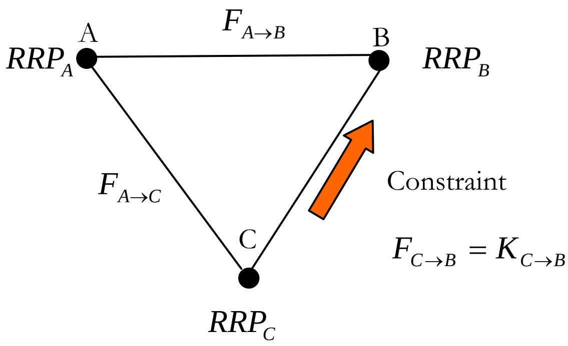
28. This problem could be solved if traders had access to another source of residues. Let's suppose that the trader has access to the "constraint-based residues" for the constraint on the line between node 1 and node 2. In this simple network the constraint-based residues for this constraint are equal to the price difference between node 1 and node 2 times the physical limit between node 1 and node 2. In other words, the constraint-based residues for the constraint between node 1 and node 2 are: $CBR_{1\to 2} = (P_2 - P_1)K_{1\to 2}$.

29. Now, suppose the trader purchases a share $100/K_{1\to 2}$ of these constraint-based residues. Since the price at node 1 is equal to the regional reference price for region A and since the price at node 2 is equal to the regional reference price for region B (assuming, as above, no binding constraints on the interconnector) we have demonstrated that this share of the constraint-based residue allows for perfect arbitrage:

$$\frac{100}{K_{1\to 2}} \times CBR_{1\to 2} = \frac{100}{K_{1\to 2}}(P_2 - P_1)K_{1\to 2} = 100(RRP_B - RRP_A)$$

30. More generally, in the network above, the trader could buy the required share of the inter-regional settlement residues and the required share of the constraint-based residues and would have a perfect hedging instrument, whether there was a binding constraint on either line. We can conclude that allowing a trader access to the constraint-based residues improves the effectiveness of inter-regional arbitrage of hedge contracts. Constraint-based residues solve the problem of lack of firmness of the inter-regional settlement residues in the presence of intra-regional constraints.

31. Let's now consider a network with loop flow. The following network has three nodes, joined by three interconnectors. The flow on the line from C to B is assumed to be at its limit.



32. As always in the NEM, the pricing outcomes which arise when a constraint is binding depend on the precise form of the constraint equation. In this case, the binding constraint equation might take the form:

$$\beta_{A\to B}F_{A\to B} + \beta_{A\to C}F_{A\to C} \le K_{C\to B}$$

Where $\beta_{A\to B}$ and $\beta_{A\to C}$ are constants.

33. The mathematics of constrained optimisation then tells us that the price differences between the various nodes in this simple network are equal to the "marginal value" of the binding constraint equation times the coefficient on the relevant interconnector in that constraint equation:

$$RRP_B - RRP_A = \lambda \times \beta_{A\to B} \text{ and}$$

$$RRP_C - RRP_A = \lambda \times \beta_{A\to C}$$

34. If we assume that all three of these lines have identical electrical impedance, it turns out that the coefficient on the flow from A to B must be the negative of the flow from A to C ($\alpha_{A\to B} + \beta_{A\to C} = 0$). This implies that the price at node A must be equal to the average of the price at node B and the price at node C.

$$RRP_A = \tfrac{1}{2}RRP_B + \tfrac{1}{2}RRP_C$$

35. This in turn implies, of course, that if the flow on the line from A to C is in the direction of node C, there will be negative settlement residues accumulating on the interconnector from A to C. This is, of course, the underlying reason why negative settlement residues accrue on the VIC-Snowy interconnector at times of binding Murray-Tumut constraint.

36. Let's ask whether the inter-regional settlement residues allow for the perfect arbitrage of swaps between any pair of regions. Let's start with arbitrage between node A and node C. The inter-regional settlement residues are equal to $IRSR_{A\to C} = (RRP_C - RRP_A)F_{A\to C}$. As before, a trader could perfectly arbitrage 100 MW of swaps between A and C, by purchasing the share $100/F_{A\to C}$ of the inter-regional settlement residues. But, as before, how does the trader know the flow on the line between node A and node C at times of a binding constraint between nodes C and B? The flow on the line between node A and node C could be negative, zero or positive (giving rise to negative settlement residues) at times when the C-B constraint is binding. As before, the A-C inter-regional settlement residue is no longer a firm instrument for arbitraging swaps between A and C.

37. The same is true for the inter-regional settlement residues between node A and node B. Again, these inter-regional settlement residues are not firm – that is, they do not allow for perfect arbitrage of swap prices between A and B.

38. What about the inter-regional settlement residues between node C and B? In this case – and only this case – the inter-regional settlement residues are "firm". The trader could perfectly arbitrage 100 MW of swaps between C and B by purchasing a share $100/K_{C\to B}$ of the C-B inter-regional settlement residues.[4]

39. As before, the problem of lack of firmness can be solved if traders had access to the constraint-based residues for the constraint on the line between node C and node B. Let's define a new residue for this constraint equal to the "marginal value" of the binding C-B constraint times the physical limit between node 1 and node 2: $CBR_{C\to B} = \lambda_{C\to B} K_{C\to B}$.

40. Now, a trader who wishes to perfectly arbitrage 100 MW of swaps between A and B need only purchase the share $100\alpha_{A\to B}/K_{C\to B}$ of this constraint-based residue. The resulting payoff is: $\dfrac{100\beta_{A\to B}}{K_{C\to B}} CBR_{C\to B} = 1000\lambda_{C\to B}\beta_{A\to B} = 100(RRP_B - RRP_A)$ as required.

41. Similarly, a trader who wishes to perfectly arbitrage 100 MW of swaps between A and C need only purchase the share $100\beta_{A\to C}/K_{C\to B}$ of this constraint-based residue. The resulting payoff is: $\dfrac{100\beta_{A\to C}}{K_{C\to B}} CBR_{C\to B} = 100\lambda_{C\to B}\beta_{A\to C} = 100(RRP_C - RRP_A)$ as required.

42. Finally, a trader who wishes to perfectly arbitrage 100 MW of swaps between C and B need only purchase the share $100(\beta_{A\to B} - \beta_{A\to C})/K_{C\to B}$ of this constraint-based residue. The resulting payoff is: $\dfrac{100(\beta_{A\to B} - \beta_{A\to C})}{K_{C\to B}} CBR_{C\to B} = 100\lambda_{C\to B}(\beta_{A\to B} - \beta_{A\to C})$ $= 100(RRP_B - RRP_C)$ as required.

43. In other words, whereas the inter-regional settlement residues are not firm and do not allow for perfect arbitrage of hedge prices in this simple network, the constraint-based residues are fully firm and allow for perfect arbitrage of swap prices across any pair of nodes. As before, allowing a trader access to the constraint-based residues improves the effectiveness of inter-regional arbitrage of hedge contracts. Constraint-based residues solve the problem of lack of firmness of the inter-regional settlement residues in the presence of loop flow in the network.

44. These examples have illustrated the constraint-based residues approach in the context of simple network models and ignoring losses. When losses are taken into account the problem is slightly more complex. The next section illustrates the use of constraint based residues for inter-regional arbitrage in the context of the events in the NEM on 1 December 2004.

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[4] In this network there are defined to be three interconnectors. In the Snowy region there are only two interconnectors, neither of which is useful for obtaining perfect arbitrage.

3. Constraint-based residues: An illustration of their operation in the NEM

45. This section demonstrates how constraint-based residues would be used to improve inter-regional arbitrage in the context of the NEM itself.

46. In the examples above, we ignored losses. Now, as we move to apply these ideas to the NEM we can no longer simply ignore losses. The NEM models losses on interconnectors using dynamic inter-regional loss equations. Losses within each region are modeled using static marginal loss factors. The presence of losses on interconnectors implies that price differences can and regularly do arise between regions even in the absence of binding constraints. These price differences from losses give rise to inter-regional settlement residues in exactly the same manner as price differences from binding constraints give rise to settlement residues. As a consequence, the total merchandising surplus is larger than just the sum of all the constraint based residues. So, we need to define one more category of residues – those residues which arise due to losses between regions.

47. In the theory sections below I define "inter-regional loss residues" for each interconnector. As we will see, to perfectly arbitrage inter-regional differences in the prices of hedge contracts between two adjacent regions, a trader needs access to two sources of residues – the inter-regional loss residues for the interconnector between those regions and the constraint-based residues for each binding constraint affecting that interconnector. More precisely, to perfectly arbitrage inter-regional hedge prices, the trader needs to purchase both (a) a share of the inter-regional loss residues which is inversely proportional to the flow on the interconnector and (b) for each binding constraint, a share of the constraint-based residues equal to the coefficient of that interconnector in the binding constraint equation divided by that constraint equation's "right hand side".

48. Precisely how this would work in the NEM can be illustrated using the events in the NEM of 1 December 2004. This was a relatively "busy" day in the market. In particular, on this day a binding constraint due to the network limitation between Murray and Tumut produced negative settlement residues on the VIC-Snowy interconnector, inducing NEMMCO to "clamp" the flows on the VIC-Snowy interconnector.

49. Table 1 (at the end of this section) highlights the events that occurred during a couple of hours in the morning of this day – starting at the dispatch interval ending 9:25 am, through to the dispatch interval ending 11:15 am.

50. As can be seen in Table 1, the prices in VIC, Snowy and NSW were initially similar, and around $100 (the differences in these prices are due entirely to losses on the interconnectors). Then, in the interval ending 9:35 am, the Murray-Tumut constraint limit (here, the H>>H-64_B constraint) started to bind. Immediately the price in Snowy dropped significantly, to close to $0, the price in VIC dropped to around $55 and the price in the NSW increased to $300. This resulted in substantial negative settlement residues on the VIC-Snowy interconnector.

51. NEMMCO responded by clamping the VIC-Snowy interconnector – first with a 350 MW flow limit (reflected in the VH_0350 constraint), dropping to 200 MW at 10:10 am and finally down to 100 MW at 10:30 am. By 10:35 am the Murray-Tumut constraint had been relieved and the Snowy price jumped up to $800, reflecting the NSW price (which by this time was at $930).

52. In a network without losses (as in the examples in the previous section), a flow of residues can be used to perfectly arbitrage hedge prices if it has a pay-out equal to the price difference between two regions. This is no longer the case in a network with losses. In a network with losses, in order to sell 100 MW of electricity in the importing region, the trader must purchase more than 100 MW of electricity in the exporting region. In fact, if the quantity of electricity imported at the importing region regional reference node is F and the losses on the interconnector are L, (so that the quantity of electricity exported from the exporting region is

$F+L$), the trader must purchase precisely $100 \times (1+L/F)$ MW in the exporting region to obtain 100 MW of electricity in the importing region.

53. As a consequence, in order to perfectly arbitrage the hedge prices between two regions where all the losses are attributed to the exporting region, the trader must obtain a flow of residues with a pay-out not simply equal to the price difference between the two regions $(RRP_B - RRP_A)$, but equal to the price difference adjusted for losses: $RRP_B - RRP_A \times (1+L/F)$.

54. To make matters slightly more complicated, the NEM does not always attribute losses entirely to the exporting region. Instead, losses are shared between regions in fixed proportions in an amount given by the "loss share". The loss share is a constant which specifies the share of the losses which are attributed to the exporting region. Therefore, in the NEM, in order to perfectly arbitrage the hedge prices between two regions, the trader must obtain a flow of residues with a pay-out equal to:

$$RRP_B \times (1-(1-loss\_share) \times L/F) - RRP_A \times (1-loss\_share \times L/F)$$

55. Let's call this amount the "Adjusted Price Difference". I demonstrate below how the various sources of residue can be combined to yield a pay-out precisely equal to the Adjusted Price Difference.

56. Table 2 sets out the inter-regional settlement residues and the inter-regional loss-residues for the VIC-Snowy interconnector and all the constraint-based residues affecting the VIC-Snowy interconnector for the relevant time period on 1 December 2004.

57. It is immediately apparent that the inter-regional settlement residues become large and negative as soon as the Murray-Tumut constraint binds and do not become positive again until this constraint is relieved at 10:30 am. In contrast, note that *all* of the inter-regional loss residues and the constraint-based residues are positive. These streams can therefore be auctioned in the usual NEMMCO process, with no need for intervention to prevent negative residues streams as at present.[5]

58. We saw above that inter-regional settlement residues are a useful source of residues for perfectly arbitraging inter-regional hedge price differences, but only when the trader can perfectly forecast the flow on the interconnector. This remains true even though the inter-regional settlement residues are negative. As table 3 shows, provided the trader can perfectly forecast the flow on the interconnector at each point in time, a trader could use the inter-regional settlement residues (even though they are negative) to perfectly arbitrage inter-regional hedge price differences.

59. Specifically, in table 3, the 4th column represents the share of the VIC-Snowy inter-regional settlement residues that the hypothetical trader would need to purchase (which is, recall, inversely proportional to the flow on the interconnector). The 5th column, labeled "IRSR pay-out" is the resulting pay-out each interval to a trader purchasing exactly this share. By comparing this 5th column with the 3rd column labeled "Adjusted Price Difference" we can see that, if we could purchase the correct share of the inter-regional settlement residues, the inter-regional settlement residues would allow for perfect inter-regional hedging. In fact, as Table 3 shows, the inter-regional settlement residues allow for perfect hedge even in the presence of NEMMCO clamping of the VIC-Snowy interconnector.

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[5] In this next section I set-out the conditions under which the inter-regional loss residues and the constraint-based residues are positive.

60. However, in practice it is likely to be extremely difficult for a trader to know the flow on the VIC-Snowy interconnector at every point in time, especially at those times when the Murray-Tumut constraint is binding (whether or not NEMMCO intervenes through clamping). As a result, the trader is not likely to be able to forecast precisely how much of Vic-Snowy inter-regional settlement residues to purchase. Instead the trader would be forced to forecast some "average" level which would leave it exposed to some risk. This is, of course, precisely the "firmness" issue discussed above. In any case, as we already noted, the inter-regional settlement residues throughout most of this period are negative.

61. Let's now explore hedging using inter-regional loss residues and constraint-based residues. Since there are four constraints which bind (and which affect the VIC-Snowy interconnector) during this period, there are four constraint-based residues. In order to obtain a flow of residues which is equal to the Adjusted Price Difference, the trader must purchase a share of the inter-regional loss residues which is inversely proportional to the flow (this is the share set out in the 6th column of table 3) and a share of each of the constraint-based residues equal to the coefficient in the constraint equation divided by the constraint right-hand side. In the case of each of the NEMMCO "clamp" constraints, the coefficient in the constraint equation is one, and the right-hand-side is simply a constant and equal to the clamped limit. In the case of the H>>H-64_B constraint, the coefficient in the constraint equation for the VIC-Snowy interconnector is -0.164. As we can see in table 1, the constraint right-hand-side for the H>>H-64_B constraint is not perfectly constant but varies between 930 and 940. I will assume that the trader can perfectly forecast this constraint right-hand-side.[6] As can be seen in table 3, when the trader forms the resulting portfolio of residues, the pay-out (the 11th column in table 3) is precisely equal to the Adjusted Price Difference. The conclusion is that the loss residues and the constraint-based residues (a) are positive; and (b) allow for perfect arbitrage of the inter-regional price differences.

62. The examples in this section have focused on hedging the VIC-Snowy price differences. However exactly the same analysis applies to hedging the Snowy-NSW interconnector. Combining these two instruments would allow a trader to hedge across the entire Snowy region between VIC and NSW.

[6] Even if the trader could not perfectly forecast this value, the risk the trader would have to bear simply by forecasting the average value is relatively small.

Table 1: Pricing and Constraint Outcomes 1 December 2004 9:25 am – 11:15 am

Dispatch Interval	RRP Vic	RRP Snowy	RRP NSW	Flow VIC-Snowy	H>>H-64_B		VH_0350		VH_0200		VH_0100	
					MV	RHS	MV	RHS	MV	RHS	MV	RHS
2004/12/01 09:25	$89.23	$95.90	$108.79	753.7	0	929.61	0	0	0	0	0	0
2004/12/01 09:30	$89.82	$96.10	$109.75	697.9	0	942.51	0	0	0	0	0	0
2004/12/01 09:35	$54.97	$0.04	$305.86	370.3	345.63	936.34	0	0	0	0	0	0
2004/12/01 09:40	$54.74	$0.04	$309.84	417.5	345.63	936.07	0	0	0	0	0	0
2004/12/01 09:45	$54.08	$0.04	$311.84	552.1	345.63	949.24	0	0	0	0	0	0
2004/12/01 09:50	$44.15	$0.04	$313.86	350.0	345.63	937.23	11.19	350	0	0	0	0
2004/12/01 09:55	$40.50	$0.04	$902.11	350.0	993.78	942.12	121.24	350	0	0	0	0
2004/12/01 10:00	$44.15	$0.04	$907.96	350.0	993.78	928.73	117.49	350	0	0	0	0
2004/12/01 10:05	$40.50	$0.04	$299.65	350.0	340.86	945.96	14.17	350	0	0	0	0
2004/12/01 10:10	$27.70	$0.04	$305.80	200.0	345.63	933.31	0	350	28.51	200	0	0
2004/12/01 10:15	$27.70	$0.04	$307.79	200.0	345.63	947.2	0	0	28.52	200	0	0
2004/12/01 10:20	$32.70	$0.04	$309.75	200.0	345.63	938.11	0	0	23.43	200	0	0
2004/12/01 10:25	$40.50	$0.04	$309.52	200.0	345.63	940.53	0	0	15.49	200	0	0
2004/12/01 10:30	$35.08	$280.00	$319.26	100.0	0	948.82	0	0	0	0	244.3	100
2004/12/01 10:35	$27.70	$805.00	$930.44	100.0	0	946.79	0	0	0	0	776.21	100
2004/12/01 10:40	$30.10	$805.00	$930.34	100.0	0	928.42	0	0	0	0	773.8	100
2004/12/01 10:45	$29.70	$805.00	$936.59	100.0	0	946	0	0	0	0	774.22	100
2004/12/01 10:50	$27.70	$805.00	$936.62	100.0	0	932.7	0	0	0	0	776.24	100
2004/12/01 10:55	$32.70	$805.00	$930.32	100.0	0	947.53	0	0	0	0	771.19	100
2004/12/01 11:00	$32.70	$805.00	$936.93	100.0	0	940.92	0	0	0	0	771.2	100
2004/12/01 11:05	$30.59	$805.00	$949.78	100.0	0	933.35	0	0	0	0	773.34	100
2004/12/01 11:10	$32.70	$805.00	$943.21	100.0	0	939.05	0	0	0	0	771.22	100
2004/12/01 11:15	$32.70	$805.00	$943.24	100.0	0	932.91	0	0	0	0	771.2	100

Table 2: VIC-Snowy inter-regional Settlement Residues, VIC-Snowy inter-regional Loss Residues, Constraint-Based Residues

Dispatch Interval	Flow Vic-Snowy	Adjusted Price Difference	Inter-regional Settlement Residues	Inter-regional Loss Residues	CB residues H>>H-64_B	CB residues VH_0350	CB residues VH_0200	CB residues VH_0100
2004/12/01 09:25	753.7	$3.22	$2,429.73	$2,429.73	$0.00	$0.00	$0.00	$0.00
2004/12/01 09:30	697.9	$3.04	$2,122.20	$2,122.20	$0.00	$0.00	$0.00	$0.00
2004/12/01 09:35	370.3	-$55.94	-$20,711.79	$275.21	$323,627.47	$0.00	$0.00	$0.00
2004/12/01 09:40	417.5	-$55.82	-$23,304.40	$362.59	$323,531.63	$0.00	$0.00	$0.00
2004/12/01 09:45	552.1	-$55.42	-$30,599.85	$695.01	$328,084.16	$0.00	$0.00	$0.00
2004/12/01 09:50	350.0	-$44.87	-$15,702.76	$219.90	$323,935.94	$3,916.50	$0.00	$0.00
2004/12/01 09:55	350.0	-$41.16	-$14,404.51	$204.47	$936,260.25	$42,434.00	$0.00	$0.00
2004/12/01 10:00	350.0	-$44.86	-$15,699.98	$221.49	$922,954.69	$41,121.50	$0.00	$0.00
2004/12/01 10:05	350.0	-$41.15	-$14,401.96	$203.90	$322,438.41	$4,959.50	$0.00	$0.00
2004/12/01 10:10	200.0	-$27.96	-$5,592.59	$42.08	$322,576.41	$0.00	$5,702.00	$0.00
2004/12/01 10:15	200.0	-$27.96	-$5,591.09	$41.57	$327,380.31	$0.00	$5,704.00	$0.00
2004/12/01 10:20	200.0	-$33.01	-$6,601.76	$48.91	$324,241.84	$0.00	$4,686.00	$0.00
2004/12/01 10:25	200.0	-$40.89	-$8,177.30	$61.36	$325,074.69	$0.00	$3,098.00	$0.00
2004/12/01 10:30	100.0	$244.50	$24,450.30	$20.30	$0.00	$0.00	$0.00	$24,430.00
2004/12/01 10:35	100.0	$776.55	$77,655.15	$34.15	$0.00	$0.00	$0.00	$77,621.00
2004/12/01 10:40	100.0	$774.15	$77,414.69	$34.69	$0.00	$0.00	$0.00	$77,380.00
2004/12/01 10:45	100.0	$774.57	$77,457.09	$35.09	$0.00	$0.00	$0.00	$77,422.00
2004/12/01 10:50	100.0	$776.58	$77,658.30	$34.31	$0.00	$0.00	$0.00	$77,624.00
2004/12/01 10:55	100.0	$771.55	$77,155.25	$36.25	$0.00	$0.00	$0.00	$77,119.00
2004/12/01 11:00	100.0	$771.56	$77,156.34	$36.34	$0.00	$0.00	$0.00	$77,120.00
2004/12/01 11:05	100.0	$773.69	$77,369.10	$35.10	$0.00	$0.00	$0.00	$77,334.00
2004/12/01 11:10	100.0	$771.59	$77,158.55	$36.55	$0.00	$0.00	$0.00	$77,122.00
2004/12/01 11:15	100.0	$771.56	$77,156.34	$36.34	$0.00	$0.00	$0.00	$77,120.00

Table 3: Hedging using Inter-regional Settlement Residues and Constraint-Based Residues

Dispatch Interval	Flow Vic-Snowy	Adjusted Price Difference	Share of IRSRs	IRSR Pay-out	Share of IRLRs	Share of H>>H-64_B	Share of VH_0350	Share of VH_0200	Share of VH_0100	IRLR/CBR Pay-out
2004/12/01 09:25	753.69	$3.22	0.1327%	$3.22	0.1327%	-0.0176%	0.2857%	0.5000%	1.0000%	$3.22
2004/12/01 09:30	697.86	$3.04	0.1433%	$3.04	0.1433%	-0.0174%	0.2857%	0.5000%	1.0000%	$3.04
2004/12/01 09:35	370.25	-$55.94	0.2701%	-$55.94	0.2701%	-0.0175%	0.2857%	0.5000%	1.0000%	-$55.94
2004/12/01 09:40	417.53	-$55.82	0.2395%	-$55.81	0.2395%	-0.0175%	0.2857%	0.5000%	1.0000%	-$55.81
2004/12/01 09:45	552.1	-$55.42	0.1811%	-$55.42	0.1811%	-0.0173%	0.2857%	0.5000%	1.0000%	-$55.42
2004/12/01 09:50	350	-$44.87	0.2857%	-$44.87	0.2857%	-0.0175%	0.2857%	0.5000%	1.0000%	-$44.87
2004/12/01 09:55	350	-$41.16	0.2857%	-$41.16	0.2857%	-0.0174%	0.2857%	0.5000%	1.0000%	-$41.16
2004/12/01 10:00	350	-$44.86	0.2857%	-$44.86	0.2857%	-0.0177%	0.2857%	0.5000%	1.0000%	-$44.86
2004/12/01 10:05	350	-$41.15	0.2857%	-$41.15	0.2857%	-0.0173%	0.2857%	0.5000%	1.0000%	-$41.15
2004/12/01 10:10	200	-$27.96	0.5000%	-$27.96	0.5000%	-0.0176%	0.2857%	0.5000%	1.0000%	-$27.96
2004/12/01 10:15	200	-$27.96	0.5000%	-$27.96	0.5000%	-0.0173%	0.2857%	0.5000%	1.0000%	-$27.96
2004/12/01 10:20	200	-$33.01	0.5000%	-$33.01	0.5000%	-0.0175%	0.2857%	0.5000%	1.0000%	-$33.01
2004/12/01 10:25	200	-$40.89	0.5000%	-$40.89	0.5000%	-0.0174%	0.2857%	0.5000%	1.0000%	-$40.89
2004/12/01 10:30	100	$244.50	1.0000%	$244.50	1.0000%	-0.0173%	0.2857%	0.5000%	1.0000%	$244.50
2004/12/01 10:35	100	$776.55	1.0000%	$776.55	1.0000%	-0.0173%	0.2857%	0.5000%	1.0000%	$776.55
2004/12/01 10:40	100	$774.15	1.0000%	$774.15	1.0000%	-0.0177%	0.2857%	0.5000%	1.0000%	$774.15
2004/12/01 10:45	100	$774.57	1.0000%	$774.57	1.0000%	-0.0173%	0.2857%	0.5000%	1.0000%	$774.57
2004/12/01 10:50	100	$776.58	1.0000%	$776.58	1.0000%	-0.0176%	0.2857%	0.5000%	1.0000%	$776.58
2004/12/01 10:55	100	$771.55	1.0000%	$771.55	1.0000%	-0.0173%	0.2857%	0.5000%	1.0000%	$771.55
2004/12/01 11:00	100	$771.56	1.0000%	$771.56	1.0000%	-0.0174%	0.2857%	0.5000%	1.0000%	$771.56
2004/12/01 11:05	100	$773.69	1.0000%	$773.69	1.0000%	-0.0176%	0.2857%	0.5000%	1.0000%	$773.69
2004/12/01 11:10	100	$771.59	1.0000%	$771.59	1.0000%	-0.0175%	0.2857%	0.5000%	1.0000%	$771.59
2004/12/01 11:15	100	$771.56	1.0000%	$771.56	1.0000%	-0.0176%	0.2857%	0.5000%	1.0000%	$771.56

3. The Theoretical Framework

63. The subsequent sections of this paper formally demonstrate the results presented informally in the previous sections. This first section sets up the basic framework and defines a number of key terms. Section 4 then looks at the current arrangements in the market and formally identifies the problems that arise. Section 5 looks at constraint-based residues and how they solve the basic problems identified in section 4. Section 6 examines the CSP/CSC approach and examines whether or not this approach also solves the basic problems set out in section 4.

64. The theory in this section is based on a model of the NEM which approximates as closely as possible the actual current implementation of the NEM as set out in the NEM dispatch engine documentation. The primary difference here is that I ignore FCAS (frequency control and ancillary services) markets. The theory in this section allows for locationally-differentiated prices. In the next section we will see how the current zonal pricing arrangements in the NEM differ from this benchmark.

65. This section defines a large number of terms. Power is injected or withdrawn from the NEM at **connection points**. Let *CP* be the set of connection points. For each connection point $i \in CP$, the net injection of power at that connection point will be denoted z_i. Similarly, the (nodal) price for electricity at that connection point will be denoted p_i. This is the price paid to generators for the energy they produce and the price paid by scheduled and non-scheduled load for the energy they consume.

66. For each connection point $i \in CP$ it is possible to define a function $B_i(z_i)$ which reflects the total economic welfare or surplus from the production and consumption of electricity at that node, when the net injection is z_i. This function depends on the demand and supply conditions at that connection point, as reflected in the bids and offers of the generators and loads connected to that connection point. This function has the important property that the derivative of this function with respect to the injection is the nodal price at that injection point: $\forall i \in CP$, $\frac{\partial B_i}{\partial z_i}(z_i) = -p_i(z_i)$.

67. Each connection point is assigned to one and only one **region**. Let *R* denote the set of regions. For each connection point $i \in CP$, let $region(i) \in R$ be the corresponding region. For each region there is a single connection point which is denoted the **regional reference node**. For each region $r \in R$, let $RRN(r) \in CP$ denote the regional reference node. For each region $r \in R$, the **regional reference price** will be denoted P_r.

68. Within each region, losses between each connection point and the regional reference node are modeled through static marginal loss factors. For each connection point $i \in CP$ the loss factor *i* is denoted LF_i. This is interpreted as follows: If there is a net injection of 1 MW of energy at the regional reference node, the total quantity of energy that must be withdrawn at the connection point is: LF_i. For each region, the loss factor for the regional reference node is, of course, exactly one $LF_{RRN(r)} = 1$.

69. Regions are joined by directional **interconnectors**. Let *L* be the set of interconnectors. Each interconnector $l \in L$ carries electric power between an originating region known as the "from region" or $fr(l) \in R$ and a terminating region known as the "to region" or $tr(l) \in R$. The **flow** on an interconnector is denoted F_l (of course, the flow could be positive or negative).

70. For each interconnector $l \in L$ there is an associated function which reflects the electrical **losses** on the interconnector as a function of the flow $L_l(F_l)$. In the NEM, this function is required to be a simple quadratic and to be zero when the flow is zero (in other words, this function takes the form $L_l(F_l) = \frac{1}{2} a_l F_l^2 + b_l F_l$ where a_l and b_l are fixed constants and $a_l > 0$).[7]

71. These losses are assumed to be shared between the from-region $fr(l)$ and the to-region $tr(l)$. The share of the losses which is attributed to the from-region $fr(l)$ is called the **loss share** and is given by a fixed constant denoted s_l (and therefore the share of the losses attributed to the to-region $tr(l)$ is $1 - s_l$).

72. There are two types of interconnectors – regulated interconnectors and market network service providers or **MNSPs.** Let $MNSP \subset L$ be the set of interconnectors which are MNSPs. MNSPs differ from regulated interconnectors in two respects. One is that MNSPs are not assumed to connect at the regional reference node. Instead, MNSPs may connect at some other connection point in a region. A static marginal loss factor is then used to adjust for losses between the regional reference node and the MNSP connection point.

73. For a given interconnector $l \in L$, let $frcp(l) \in CP$ be the connection point in the from-region and $trcp(l) \in CP$ be the connection point in the to-region. For an additional 1 MW of energy at the regional reference node in the from-region, there is an additional $LF_{frcp(l)}$ MW of electricity at the from-region connection point. Similarly, for each additional 1 MW of energy at the to-region regional reference node, there is an additional $LF_{trcp(l)}$ MW of electricity at the to-region connection point. For regulated interconnectors (which are assumed to connect at the regional reference node) the from-region loss factor and the to-region loss factor is exactly one $LF_{trcp(l)} = LF_{frcp(l)} = 1$.

74. The second difference between MNSPs and other interconnectors is that MNSPs submit an offer curve reflecting their willingness to transport power in response to a price difference between two regions. We can summarize that offer curve in the form of a function $B_l(F_l)$. This function has the property that the derivative of this function with respect to the flow on the MNSP is equal to the bid price difference for that flow: $\forall l \in MNSP$, $\frac{\partial B_l}{\partial F_l}(F_l) = -D_l(F_l)$ where $D_l(F_l)$ is the offer function of the MNSP (i.e., the price difference the MNSP requires to accept a flow target of F_l).

75. The NEM dispatch engine solves a constrained optimisation problem. The dispatch engine chooses the injection at each connection point z_i, $\forall i \in CP$ and the flow on each interconnector F_l, $\forall l \in L$ to maximise the objective function: $\sum_{i \in CP} B_i(z_i) + \sum_{l \in MNSP} B_l(F_l)$ subject to certain constraints. There are two important types of constraints:

[7] Actually, the NEM dispatch engine uses a "linearised" version of this equation, but this is not strictly important for the results here.

(a) First, there are constraints which ensure the **energy balance** in each region. These ensure that the sum of the injections in each region less the flow out of the region (plus attributed losses) plus the flow into the region (plus attributed losses) is zero:

$$\forall r \in R, \quad \sum_{i:region(i)=r} z_i LF_i - \sum_{l:fr(l)=r} (F_l + s_l L_l) LF_{frcp(l)} + \sum_{l:tr(l)=r} (F_l - (1-s_l) L_l) LF_{trcp(l)} = 0$$

(b) The second set of constraints are referred to as **generic constraints**. Let *GC* be the set of generic constraints. These constraints are all *linear*, but otherwise there is a great deal of flexibility over their form. These constraints must all be either "less than", "greater than" or "equality" constraints. The *n*th generic constraint takes the form:

$$\sum_{i \in CP} \alpha_i^n z_i + \sum_{l \in L} \beta_l^n F_l \text{ "}\leq, \geq, =\text{" } RHS^n$$

76. Of course, a linear constraint is unchanged if it is re-scaled by any constant factor. In particular, we can divide each constraint equation through by the right hand side to obtain a constraint of the form: $\sum_{i \in CP} \frac{\alpha_i^n}{RHS^n} z_i + \sum_{l \in L} \frac{\beta_l^n}{RHS^n} F_l \leq 1$. We could, without loss of generality, assume that all the generic constraints take this standardised form. However, this is not strictly necessary for what follows. However, none of the key results that should depend on the absolute level of the coefficients, α_i^n and β_l^n, but should only depend on the ratio of these coefficients and the constraint right-hand-side: $\frac{\alpha_i^n}{RHS^n}$ and $\frac{\beta_l^n}{RHS^n}$.

77. We will say that a generator $i \in CP$ or an interconnector $l \in L$ is **affected** by a constraint if $\alpha_i^n \neq 0$ or $\beta_l^n \neq 0$, respectively.

78. We can say that a constraint is a **pure inter-regional** constraint if the constraint contains no terms relating to an individual connection point. That is, a constraint $n \in GC$ is a pure inter-regional constraint if $\forall i \in CP$, $\alpha_i^n = 0$. Similarly, a constraint could be said to be a **pure intra-regional** constraint if the constraint contains no terms relating to an interconnector. That is, a constraint $n \in GC$ is a pure intra-regional constraint if $\forall l \in L$, $\beta_l^n = 0$. A mixed constraint is a constraint which is neither a pure inter-regional constraint nor a pure intra-regional constraint.

79. We will say that a pure inter-regional constraint is a **pure radial** constraint if there is only one term (which must be an interconnector term) on the left-hand-side. In other words, a pure-inter-regional constraint $n \in GC$ is a radial constraint if $\beta_k^n = 0$ for all $k \in L$ except $k = l$.

80. We will say that a network is a **pure radial** network if the only generic constraints are pure radial generic constraints.

81. The problem solved by the NEM dispatch engine can be written:

$$\max_{z_i, F_l} \sum_{i \in CP} B_i(z_i) + \sum_{l \in MNSP} B_l(F_l) \text{ subject to:}$$

$$\forall r \in R, \quad \sum_{i:region(i)=r} z_i LF_i - \sum_{l:fr(l)=r} (F_l + s_l L_l) LF_{frcp(l)} + \sum_{l:tr(l)=r} (F_l - (1-s_l) L_l) LF_{trcp(l)} = 0$$

And $\forall n \in GC$, $\sum_{i \in CP} \alpha_i^n z_i + \sum_{l \in L} \beta_l^n F_l \leq or \geq or = RHS^n$

82. We may choose μ_r to be the Lagrange-multiplier on the region-energy-balance constraint and λ_n to be the Lagrange-multiplier on the *n*th generic constraint. The Lagrangian for this maximisation problem can therefore be written:

$$\begin{aligned}L = &\sum_{i \in CP} B_i(z_i) + \sum_{l \in MNSP} B_l(F_l) \\ &- \sum_{r \in R} \mu_r \Big(\sum_{i:region(i)=r} z_i LF_i - \sum_{l:fr(l)=r} (F_l + s_l L_l) LF_{frcp(l)} + \sum_{l:tr(l)=r} (F_l - (1-s_l)L_l) LF_{trcp(l)} \Big) \\ &- \sum_{n \in GC} \lambda_n \Big(\sum_{i \in CP} \alpha_i^n z_i + \sum_{l \in L} \beta_l^n F_l - RHS^n \Big)\end{aligned}$$

83. Using this formulation, we know from the theory of constrained optimisation that the Lagrange-multiplier on the *n*th generic constraint (also known as the constraint **marginal value**) must be positive when the constraint is of the "less than" form, must be negative when the constraint is of the "greater than" form, and has an indeterminate sign when the constraint is of the "equality" form.

84. At this point it is useful to define several new terms:

(a) The **merchandising surplus** is equal to the total revenue to the system operator from the purchase and sale of electricity to generators and loads. The merchandising surplus is therefore:

$$MS = -\sum_{i \in CP} p_i z_i$$

(b) For a given interconnector, the **inter-regional settlement residues** on that interconnector are equal to the surplus accruing from purchasing a volume of electricity in the from region (including a share of losses) transporting it and selling it in the to region:

$$\forall l \in L,\ IRSR_l = P_{tr(l)}(F_l - (1-s_l)L_l) LF_{trcp(l)} - P_{fr(l)}(F_l + s_l L_l) LF_{frcp(l)}$$

(c) For a given region, the **region surplus** is the residues that accrue to the system operator as a result of geographic differentiation of pricing within the region:

$$\forall r \in R,\ RS_r = \sum_{i:region(i)=r} (P_r LF_i - p_i) z_i$$

(e) For a given interconnector, the **inter-regional loss residues** are equal to the difference in the marginal and average losses on the interconnector, valued at a weighted average price:

$$\forall l \in L,\ IRLR_l = (F_l L_l' - L_l)(P_{fr(l)} s_l LF_{frcp(l)} + P_{tr(l)}(1-s_l) LF_{trcp(l)})$$

(f) For a given constraint equation, the **constraint-based residues** are equal to the constraint marginal value multiplied by the constraint right-hand-side.

$$\forall n \in GC,\ CBR^n = \lambda^n RHS^n$$

85. It is perhaps worth noting that if we ignore losses, the inter-regional settlement residues on a given interconnector are just equal to the price-difference across the inter-connector times

the flow on the interconnector. In the case of a regulated interconnector this reduces to: $\forall l \in L$, $IRSR_l = (P_{tr(l)} - P_{fr(l)})F_l$. The inter-regional loss residues are equal to zero.

First order conditions related to each connection point

86. The first-order-condition with respect to the injection at connection point *i* yields the following set of equations:

$$\forall i \in CP,\ -p_i(z_i) - \mu_{region(i)} LF_i - \sum_{n \in GC} \lambda_n \alpha_i^n = 0$$

87. Under the current approach in the NEM, the regional reference price in each region is defined to be equal to the (negative of the) Lagrange multiplier on the energy balance equation. Therefore, let's define the regional reference price in each region as follows:

$$\forall r \in R,\ P_r = -\mu_r$$

88. Under normal operations of the NEM, the regional reference price is also supposed to be equal to the nodal price at the regional reference node. In other words, $\forall r \in R$, $P_r = p_{RRN(r)}$.

89. We will say that the constraint equations are **correctly oriented** if and only if there are no terms involving the regional reference node in any region in any constraint equation (i.e., if $\forall n \in GC, r \in R$, $\alpha_{RRN(r)}^n = 0$). Using the first order condition above we see that provided all the constraint equations are correctly oriented, the regional reference price in each region is just equal to the nodal price at the regional reference node.

$$\forall r \in R,\ -p_{RRN(r)} + P_r LF_{RRN(r)} = -p_{RRN(r)} + P_r = 0$$

90. Under the assumption that all the constraint equations are correctly oriented, the first-order condition above implies the following relationship between the spot price at each connection point and the regional reference price:[8]

$$\forall i \in CP,\ p_i = P_{region(i)} LF_i - \sum_{n \in GC} \lambda_n \alpha_i^n$$

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[8] Exactly the same equation can be found in other documents. For example, the part of the National Electricity Rules which deals with the Snowy CSP/CSC trial (Part 8(j)) defines the "substitute price" SPd_p (for p = the power stations: Lower Tumut and Upper Tumut) as follows: $SPd_p = DP_{Snowy} \times TLF_p - \sum_k CSP_{ak} \times Coeff_{p,k}$, where: DP_{Snowy} is the dispatch price that applies to the Snowy region for the relevant dispatch interval; TLF_p is the transmission loss factor for power station "p"; CSP_{ak} is the constraint marginal value (\$/MWh) as determined by the dispatch engine for each dispatch interval of relieving binding constraint "k" by a marginal amount; and $Coeff_{p,k}$ is the coefficient assigned to element "p" in constraint "k" from the Murray/Tumut constraint list.

91. If we multiply the first first-order-condition by z_i and sum over $i \in CP$, we obtain the following:

$$-\sum_{i \in CP} p_i z_i - \sum_{r \in R} \mu_r \sum_{i:region(i)=r} z_i LF_i - \sum_{n \in GC, i \in CP} \lambda_n \alpha_i^n z_i = 0$$

92. Now, using the regional energy balance for each region, we can write the above expression as:

$$-\sum_{i \in CP} p_i z_i - \sum_{r \in R} \mu_r \Big(\sum_{l:fr(l)=r} (F_l + s_l L_l) LF_{frcp(l)} - \sum_{l:tr(l)=r} (F_l - (1-s_l) L_l) LF_{trcp(l)} \Big) - \sum_{n \in GC, i \in CP} \lambda_n \alpha_i^n z_i$$
$$= -\sum_{i \in CP} p_i z_i - \sum_{l \in L} \mu_{fr(l)} (F_l + s_l L_l) LF_{frcp(l)} + \sum_{l \in L} \mu_{tr(l)} (F_l - (1-s_l) L_l) LF_{trcp(l)} - \sum_{n \in GC, i \in CP} \lambda_n \alpha_i^n z_i = 0$$

93. Using the fact that $\forall r \in R$, $RS_r = \sum_{i:region(i)=r} (P_r LF_i - p_i) z_i$, the first order equation above yields, $\sum_{r \in R} RS_r = \sum_{r \in R} \sum_{i:region(i)=r} (P_r LF_i - p_i) z_i = \sum_{n \in GC, i \in CP} \lambda_n \alpha_i^n z_i$. Similarly, using the fact that $IRSR_l = P_{tr(l)} (F_l - (1-s_l) L_l) LF_{trcp(l)} - P_{fr(l)} (F_l + s_l L_l) LF_{frcp(l)}$ we can conclude that the merchandising surplus is equal to the sum of the inter-regional settlement residues plus the region surplus.

$$MS = \sum_{l \in L} IRSR_l + \sum_{r \in R} RS_r$$

94. If the only constraints which are binding are pure inter-regional constraints it follows that the region surplus is zero for each region. $\sum_{r \in R} RS_r = \sum_{n \in GC, i \in CP} \lambda_n \alpha_i^n z_i = 0$. In this case the total merchandising surplus is just equal to the sum of the inter-regional settlement residues.

First order conditions related to each interconnector

95. The first-order-condition with respect to the flow on the interconnector *l* yields the following set of equations:

$$\forall l \in L,\ -D_l(F_l) + \mu_{fr(l)} (1 + s_l L_l') LF_{frcp(l)} - \mu_{tr(l)} (1 - (1-s_l) L_l') LF_{trcp(l)} - \sum_{n \in GC} \lambda^n \beta_l^n = 0$$

96. From the first-order condition above, using the assumption that all the constraints are correctly oriented, we have the result the inter-regional settlement residues on an interconnector is equal to the inter-regional loss residues on an interconnector, plus an amount which reflects the binding constraints affecting that interconnector:

$$\forall l \in L,\ IRSR_l = IRLR_l + \sum_{n \in GC} \lambda^n \beta_l^n F_l$$

97. We can immediately conclude that, as long as there are no binding constraints which affect this interconnector, the inter-regional settlement residues for that interconnector are precisely equal to the inter-regional loss residues.

98. In addition, we have the "complementary slackness" conditions:

$$\forall n \in GC\,,\ \lambda^n\left(\sum_{i\in CP}\alpha_i^n z_i + \sum_{l\in L}\beta_l^n F_l - RHS^n\right) = 0$$

99. This condition can be re-written as follows:

$$\forall n \in GC\,,\ \sum_{i\in CP}\lambda^n\alpha_i^n z_i + \sum_{l\in L}\lambda^n\beta_l^n F_l = CBR^n$$

100. This first proposition below shows that it is possible to divide up the total settlement residues into streams which are positive under certain conditions. In the next section we will demonstrate that these streams are useful for hedging.

Proposition 1: The merchandising surplus is equal to the sum of the inter-regional loss residues for each interconnector and the constraint-based residues for each generic constraint.

$$MS = \sum_{l\in L} IRLR_l + \sum_{n\in GC} CBR_n$$

In addition:

(a) for a given interconnector, the inter-regional loss residues are zero when there is no flow on the interconnector, are zero when the interconnector is lossless, and are positive when both the from-region reference price and the to-region reference price are positive;

(b) for a given generic constraint, the constraint based residues are zero when the constraint is not binding, and are positive provided the constraint is a less-than constraint and has a positive right-hand-side or is a greater-than constraint and has a negative right-hand-side.

Proof of Proposition 1: From the above analysis we have that:

$MS = \sum_{l\in L} IRSR_l + \sum_{n\in GC, i\in CP}\lambda^n\alpha_i^n z_i$ and $\sum_{l\in L} IRSR_l = \sum_{l\in L} IRLR_l + \sum_{n\in GC, l\in L}\lambda^n\beta_l^n F_l$. Adding these two equations together and using the complementary slackness condition we get the required result.

Recall that losses are modelled in the dispatch engine as $L_l(F_l) = \frac{1}{2}a_l F_l^2 + b_l F_l$ where a_l and b_l are fixed constants (and $a_l > 0$). Therefore $F_l L_l' - L_l = \frac{1}{2}a_l F_l^2 \geq 0$. If there are no losses on the interconnector (so that $a_l = 0$), this expression is zero. As long as the regional reference price in both the from region and to region is positive the expression $(P_{fr(l)} s_l LF_{fr(l)}^l + P_{tr(l)}(1-s_l)LF_{tr(l)}^l)$ must be positive, and therefore the inter-regional loss residues must be positive.

The constraint based residues are positive provided the constraint marginal value λ_n and the constraint right-hand-side RHS^n have the same sign. In other words, in the case of a less-than constraint, the right-hand-side must be positive. In the case of a greater-than constraint, the right-hand-side must be negative.

101. We will say that there is **consistency between pricing and dispatch** at a connection point if the marginal price paid at a connection point is equal to the nodal price. p_i . Conversely we will say that a connection point is **mis-priced** if this relationship does not hold. When there is

consistency between pricing and dispatch a market participant is always dispatched for a price-quantity combination which lies on its bid or offer curve.

102. When the price-quantity combination offered to a generator is above that generator's offer curve, that generator is said to be **constrained off**. A generator which is constrained off has an incentive to lower its offer curve in order to increase the amount for which it is dispatched. When the price-quantity combination offered to a generator is below that generator's offer curve, that generator is said to be **constrained on**. A generator which is constrained off has an incentive to raise its offer curve in order to reduce the amount for which it is dispatched.

103. Let's now turn to look at the problem of arbitrage of hedging instruments across regions. The arbitrage problem of a trader in this market can be broken down into two problems:

(a) The problem of arbitraging hedge price differences between any given connection point and the regional reference node in that connection point's region; and

(b) The problem of arbitraging hedge price differences between any two regional reference nodes. This last problem can, itself, be further broken down into the problem of arbitraging between any two adjacent[9] regional reference nodes.

104. Let's focus first on the problem of hedging between any given connection point and the regional reference node in that connection point's region.[10] Consider the problem of a trader which purchases a swap contract for a fixed quantity *X* MW of electricity at a fixed price $\overline{p}_i$ at connection point *i* and sells a swap contract for the fixed quantity $X \times LF_i$ MW of electricity at the regional reference node at the fixed price $\overline{P}_r$. This trader hedges this transaction by purchasing *X* units of a hedge instrument which has a pay-off equal to $H_{ir}X$. The total revenue of the trader is then:

$$\overline{P}_r LF_i X - P_r LF_i X - \overline{p}_i X + p_i X + H_{ir} X - \overline{H}_{ir} X$$

105. This trader will be able to achieve a perfect hedge (that is, to completely eliminate its risk) if and only if:

$$-P_r LF_i X + p_i X + H_{ir} X = \text{constant}$$

106. Since this must be true for whatever quantity of electricity is transacted by this trader, we have that the hedge instrument H_{ir} must have the following payout: $H_{ir} = P_r LF_i - p_i$.

107. Let's now look at the problem of hedging between two regional reference nodes which are joined by a regulated interconnector $l \in L$. Let's suppose that a trader purchases a swap contract for a fixed quantity *X* of electricity in the from-region, sells a swap contract for a (different) quantity of electricity in the to-region, and hedges this transaction using a hedging instrument.

[9] Two regional reference nodes are "adjacent" if there exists an interconnector between the two relevant regions.

[10] Under the current NEM arrangements (with uniform regional pricing) a generator faces no price risk for its dispatch to the regional reference node but it may face some "dispatch risk" (that is, the risk that it will not be able to be dispatched up to the level it is willing to be dispatched at the regional reference price). This dispatch risk cannot, to my knowledge, currently be effectively hedged.

108. Let's suppose that the flow on the interconnector at the relevant point in time is F_l. Let's define the amount $Y = \dfrac{X}{(1-(1-s_l)(L_l / F_l)}$. The trader then sells a swap contract for the quantity of electricity $(1-(1-s_l)(L_l / F_l)Y$ at the fixed price of $\overline{P}_{tr(l)}$ in the to-region. Since some electricity is lost in the transmission process, the amount of the swap contract that the firm purchases in the from-region must be adjusted for losses. In fact, the trader must purchase $(1+s_l)(L_l / F_l)Y$ in the from-region, at the fixed price of, say, $\overline{P}_{fr(l)}$.

109. The trader is then exposed to the risk of price movement in both regions. Let's suppose that this trader hedges this risk by purchasing a hedging instrument which has a payout of H_l per MW of the hedging instrument purchased. Let's suppose that this hedging instrument has a fixed price of $\overline{H}$. The total revenue of this trader is then:

$$(\overline{P}_{tr(l)} - P_{tr(l)})(1-(1-s_l)(L_l / F_l))Y - (\overline{P}_{fr(l)} - P_{fr(l)})(1+s_l(L_l / F_l))Y + H_l Y - \overline{H}Y$$

110. This trader will be able to achieve a perfect hedge (that is, to completely eliminate its risk) if and only if:

$$H_l Y - P_{tr(l)}(1-(1-s_l)(L_l / F_l))Y + P_{fr(l)}(1+s_l(L_l / F_l))Y = \text{constant}$$

111. Since this must be true no matter what volume of trade the trader chooses to engage in, we need a hedging instrument which has the following payout per MW of hedge purchased:

$$H = P_{tr(l)}(1-(1-s_l)(L_l / F_l)) - P_{fr(l)}(1+s_l(L_l / F_l))$$

112. The following proposition shows that inter-regional settlement residues can be used to obtain a perfect hedge, *provided that the trader can forecast the flow on the interconnector*, especially at times of large price differences. The trader obtains this hedge by purchasing a share of the interconnector proportional to the inverse of the flow on the interconnector at the future point in time.

113. This result is intuitively clear if we ignore losses – in this case the inter-regional settlement residues are just equal to the price-difference between the regions times the flow. A share of this residue which is proportional to the inverse of the flow is therefore just proportional to the price difference. The next proposition shows that this intuition remains precisely correct even in the case where losses are taken into account.

Proposition 2: Suppose that a trader is trading a fixed quantity of electricity between the regional reference nodes of two adjacent regions connected by a regulated interconnector. This trader can obtain a perfect hedge for its trade between those regions at some future time provided that:

(a) the trader can obtain its desired share of the inter-regional settlement residues; and

(b) the trader can perfectly forecast the flow on the interconnector at the future time.

The total volume of such hedges available is equal to the flow on the interconnector at that point in time.

Proof of Proposition 2:

Let's suppose that the trader purchases a share $\frac{1}{F_l}$ of the inter-regional settlement residues for this interconnector. The resulting hedge payoff is:

$$\begin{aligned} H_l &= \frac{1}{F_l} IRSR_l \\ &= P_{tr(l)}(1-(1-s_l)(L_l / F_l)) - P_{fr(l)}(1+s_l(L_l / F_l)) \end{aligned}$$

This demonstrates that a share of the inter-regional settlement residues is, in fact, a perfect hedge for hedging inter-regional trading risk. The total volume of such hedges which can be written is equal to the flow on the interconnector.

114. There are, of course, several problems with the use of inter-regional settlement residues to hedge inter-regional trading risk:

(a) First, the trader must be able to forecast the level of flow which will arise on the interconnector in advance – especially at times of large inter-regional price differences. Importantly, this flow is not necessarily related to the physical limits on the transmission network. As I showed earlier, in the presence of intra-regional constraints or loop-flow, the price-difference between regions can be completely unrelated to the flow on the interconnector. In addition, for the same reasons, the total volume of such hedges which can be simultaneously written may be much less than the physical limits on the transmission network.

(b) Second, the inter-regional settlement residues may be negative and therefore are incompatible with the current arrangements for auctioning settlement residues in the NEM. In instances where large negative residues threaten to accumulate, NEMMCO is forced to intervene to limit counter-price flows.

115. What does it mean for a given hedging instrument to be "firm"? As we will see, in general, obtaining a perfect hedge will require access to two instruments: (a) the "inter-regional loss residues" for hedging against that component of residues which is due to losses and (b) another instrument for hedging that component of residues which arises from network congestion. In general the inter-regional loss residues are not "firm". The concept of "firmness" relates primarily to the hedging of that component of residues which arises from network congestion.

116. We will say that a given hedging instrument H_l for hedging 1 MW of a firm transaction between two adjacent regions joined by interconnector $l \in L$ is **firm** if it is possible to obtain a perfect hedge by constructing a portfolio consisting of H_l and the inter-regional loss residues: $IRLR_l$. Specifically, H_l will be said to be firm if it is possible to obtain a perfect hedge by purchasing:

(a) a share of the inter-regional loss residues inversely proportional to the flow on the interconnector at that point in time: $\frac{IRLR_l}{F_l}$; and

(b) a fixed share of the instrument H_l.

117. We saw earlier that the inter-regional settlement residues can be expressed as the sum of the inter-regional loss residues and another term:

$$\forall l \in L,\ IRSR_l = IRLR_l + \sum_{n \in GC} \lambda^n \beta_l^n F_l$$

118. Let's suppose that these settlement residues are separated into two components – the inter-regional loss residues $IRLR_l$ and the remainder $IRSR_l - IRLR_l$. We saw earlier that it is possible to form a perfect hedge using the inter-regional loss residues and the hedge instrument $\frac{IRSR_l - IRLR_l}{F_l} = \sum_{n \in GC} \lambda^n \beta_l^n$. It therefore follows that a given hedging instrument is firm if and only if the purchase of a fixed share of H_l is equal to $\sum_{n \in GC} \lambda^n \beta_l^n$ for all possible realizations of λ^n.

119. It is worth emphasizing that according to this definition of "firmness", even if a trader has access to a firm hedging instrument, it doesn't automatically follow that the trader will be able to write a perfect hedge. In order to obtain a perfect hedge a trader must have access to a firm hedging instrument *and* access to the inter-regional loss residues (and, in addition, must be able to forecast the flow).

4. The Status Quo: Zonal Pricing in the NEM

120. The foregoing analysis has assumed a form of nodal pricing. Of course, the NEM does not at present use nodal pricing – rather it uses a form of "zonal" or "regional" pricing. This section formally identifies the problems that arise in a zonal or regional pricing approach.

121. Under a zonal pricing scheme each generator is paid the regional reference price (adjusted for static intra-regional marginal losses, i.e., $P_r LF_i$) for its output. Similarly, each load receives the regional reference price for its output.

122. We can express this as an (implicit or explicit) payment from the system operator to each generator or load to compensate them for the difference between the local nodal price and the regional reference price. Specifically, if the output of a given generator is q_i, that generator receives a payment equal to $(P_r LF_i - p_i)q_i$. Similarly, if the consumption of a given load is d_i, that load must make a payment to the system operator equal to $(P_r LF_i - p_i)d_i$.

123. Since this applies to all generators and loads at a connection point, if z_i is the net injection of the market participants for connection point $i \in CP$ (i.e., $z_i = q_i - d_i$), the current zonal or regional pricing arrangements are equivalent to making a transfer from the system operator to these market participants in the amount $(P_r LF_i - p_i)z_i$. The total payment from the system operator to market participants in a given region is $\sum_{i:region(i)=r} (P_r LF_i - p_i)z_i$.

124. In the previous section we defined the region surplus in a region as follows: $RS_r = \sum_{i:region(i)=r} (P_r LF_i - p_i)z_i$. It is clear, therefore, that the current zonal pricing arrangements in the NEM is equivalent to taking an amount equal to the region surplus and paying this amount out to market participants in each region.

125. The total surplus accruing to the system operator is equal to the merchandising surplus, less the payments to each generator. Since the merchandising surplus is equal to the sum of the inter-regional settlement residues and the regions surplus, we can see that the total surplus accruing to the system operator under the status quo is just the inter-regional settlement residues.

$$
\begin{aligned}
&MS - \sum_{i:region(i)=r} (P_r LF_i - p_i)z_i = \sum_{l \in L} IRSR_l + \sum_{r \in R} RS_r - \sum_{i:region(i)=r} (P_r LF_i - p_i)z_i \\
&= \sum_{l \in L} IRSR_l
\end{aligned}
$$

126. Under the status quo do all market participants have an incentive to submit a bid or offer which reflects their true marginal cost? The answer is no.

127. Under a zonal pricing region, a market participant at connection point $i \in CP$ producing the net injection z_i receives a revenue equal to the nodal price times the net injection at that connection point plus the payment from the system operator, giving a total revenue of: $p_i z_i + (P_r LF_i - p_i)z_i = P_r LF_i z_i$. The marginal price is therefore the RRP adjusted for static losses: $P_r LF_i$.

128. In other words, under a zonal pricing regime, a market participant is paid the adjusted RRP ($P_r LF_i$), but is dispatched for a quantity which corresponds to the nodal price p_i . Therefore, if these two prices differ, mis-pricing will arise.

129. From the previous section we know that $\forall i \in CP$, $P_{region(i)} LF_i - p_i = \sum_{n \in GC} \lambda_n \alpha_i^n$. It follows that a connection point will be mis-priced if and only if $\sum_{n \in GC} \lambda_n \alpha_i^n \neq 0$. That is, if and only if there is at least one binding constraints for which that connection point has a non-zero term in the corresponding constraint equation.

130. We can see that under the status quo there will arise mis-pricing at some connection points in the NEM unless all constraints which bind with some positive probability are pure inter-regional constraints.

131. Let's now explore the effectiveness of hedging arrangements under the status quo. As we have seen, under the status quo, all market participants in a region receive the regional reference price. Therefore there is no need for hedging between a participant's connection point and the regional reference node.[11] We can therefore focus on the case of hedging between two regional reference nodes.

132. Let's consider the firmness of the inter-regional settlement residues as a hedging device. Under the status quo, the inter-regional settlement residues are the sum of two components – (a) the inter-regional loss residues and (b) a component reflecting the impact of binding constraints. Since the inter-regional loss residues are not "firm" it follows that the "bundled" inter-regional settlement residues can never be firm either.

133. However, let's make the assumption that somehow a trader can separate out (or doesn't care about) the impact of the inter-regional loss residues. In particular, let's assume that somehow a trader has access to the inter-regional loss residues $IRLR_l$ and the remainder $IRSR_l - IRLR_l$ for each interconnector.

134. The question for us, therefore, is whether or not $IRSR_l - IRLR_l$ is a firm hedging instrument. We saw earlier that $IRSR_l - IRLR_l$ is firm if and only if the purchase of a fixed share of $IRSR_l - IRLR_l$ is equal to $\sum_{n \in GC} \lambda^n \beta_l^n$ for all possible realizations of λ^n .

135. Consider the purchase of a fixed share $\overline{F_l}$ of $IRSR_l - IRLR_l$. From the analysis above, this is equal to $\sum_{n \in GC} \lambda^n \beta_l^n \frac{F_l}{\overline{F_l}}$. We need that $\sum_{n \in GC} \lambda^n \beta_l^n \frac{F_l}{\overline{F_l}} = \sum_{n \in GC} \lambda^n \beta_l^n$ for all possible realisations of λ^n and F_l . This can only be true when there is only one constraint involving the interconnector in question and that constraint is of the form $\beta_l^n F_l \leq RHS^n$. In this case we can choose $\overline{F_l} = \frac{\beta_l^n}{RHS^n}$.

136. In other words, *under the status quo the inter-regional settlement residues are only a firm hedging instrument when the only binding constraints are pure radial constraints*. (And, even in the case where the

[11] At least, there is no need for hedging of price risk. There may still arise some dispatch risk.

only constraints which bind are pure radial constraints, a trader would still need to obtain access to the inter-regional loss residues to obtain a perfect hedge).

137. These results are summarised in the following Proposition:

Proposition 3: Under the current zonal or regional pricing arrangements in the NEM:

(a) The total surplus or residues accruing to the system operator is equal to the sum of the inter-regional settlement residues;

(b) Mis-pricing will arise at some connection points unless all constraints which bind with positive probability are pure inter-regional constraints.

Formally: mis-pricing at a connection point $i \in CP$ will occur if and only if there are exists a constraint $n \in GC$ for which $\lambda^n \alpha_i^n \neq 0$.

(c) The inter-regional residues are not a firm instrument for hedging transactions between regional reference nodes unless all constraints which bind with positive probability are pure radial constraints.

Formally: for an interconnector $l \in L$, the inter-regional settlement residues $IRSR_l$ are firm if and only if there is only one constraint which may bind which affects that interconnector and that constraint has the "pure radial" form $F_l \leq \frac{RHS^n}{\beta_l^n}$.

5. Constraint-Based Residues

138. Let's now consider how the constraint based residues approach addresses the problems identified with the status quo above.

139. The constraint-based residues approach can be defined formally as follows. First, a set of constraints which fall within the constraint-based residues regime is defined. Let's call this set *CBRC*. $CBRC \subset GC$.

140. For each constraint in this set, there is a corresponding set of payments from each generator and each interconnector to the system operator (analogous to the "CSP" payments in the CSP/CSC approach as set out in the next section). These payments could, of course, be negative (in which case they would correspond to a payment from the system operator to the generator or interconnector, respectively). For each constraint $n \in CSPC$:

(a) for each connection point $i \in CP$, a payment is made from each generator to the system operator in the amount $\lambda^n \alpha_i^n q_i$ where q_i is the output of the generator at that connection point. Similarly, for each connection point $i \in CP$, a payment is made to each load in the amount $\lambda^n \alpha_i^n d_i$, so the net payment to all the market participants at a given connection point $i \in CP$ is $\lambda^n \alpha_i^n z_i$ where z_i is the net injection.

(b) for each interconnector $l \in L$, a payment is made from that interconnector to the system operator in the amount $\lambda^n \beta_l^n F_l$ where F_l is the flow on the interconnector.

141. The system operator then gathers these revenues into a fund, known as a constraint based residue fund and then auctions the right to these funds (equal to $CBR^n = \lambda^n RHS^n$) back to the market participants. The inter-regional settlement residues (less any funds siphoned off to the constraint-based residue funds) continue to be auctioned as at present.

142. It is straightforward to check that this constraint based residue scheme is "revenue neutral" in the sense that the total revenue received from market participants and from interconnector is precisely equal to the system operator's obligations to each constraint-based residues fund. For each $n \in CBRC$:

$$\sum_{i \in CP} \lambda^n \alpha_i^n z_i + \sum_{l \in L} \lambda^n \beta_l^n F_l = \lambda^n (\sum_{i \in CP} \alpha_i^n z_i + \sum_{l \in L} \beta_l^n F_l) = \lambda^n RHS^n = CBR^n$$

143. In the light of the two key problems highlighted in the previous section, there are two key questions which we would like to ask of the constraint-based residues approach:

(a) First, does the constraint-based residues approach restore the pricing signals on generators?

(b) Second, does the constraint-based residues approach allow for fully-firm intra-regional and inter-regional hedging?

144. Does the constraint-based residues mechanism restore the incentives on generators and loads to submit bids and offers which reflect their true costs? Under the constraint-based residues mechanism the total payment to a market participant at a connection point $i \in CP$ is as follows:

$$p_i z_i + (P_r LF_i - p_i) z_i - \sum_{n \in CBRC} \lambda^n \alpha_i^n z_i$$

145. As a result, the marginal price is:

$$P_r LF_i - \sum_{n \in CBRC} \lambda^n \alpha_i^n = P_r LF_i - \sum_{n \in GC} \lambda^n \alpha_i^n + \sum_{n \notin CBRC} \lambda^n \alpha_i^n = p_i + \sum_{n \notin CBRC} \lambda^n \alpha_i^n$$

146. It is clear that the constraint-based residues mechanism achieves consistency between pricing and dispatch if and only $\sum_{n \notin CBRC} \lambda^n \alpha_i^n = 0$. That is, if and only if the set of constraints in the constraint-based residues regime includes all those constraints which might bind with positive probability and which affect the given connection point.

147. Now let's examine the hedging implications under a constraint-based residues regime. Consider first the task of a market participant located at a connection point $i \in CP$ which is seeking to obtain a perfect hedge for a transaction of a fixed volume of electricity with the regional reference node. As we saw earlier, this market participant needs to find a perfect hedge for the difference between the regional reference price adjusted for the loss factor $P_r LF_i$ and the local marginal price, which is $P_r LF_i - \sum_{n \in CBRC} \lambda^n \alpha_i^n$. Hence, the market participant must find a hedge instrument with a payoff equal to $H_{ir} = \sum_{n \in CBRC} \lambda^n \alpha_i^n$ for all possible realisations of λ^n.

148. The market participant can achieve this payoff by purchasing a share $\frac{\alpha_i^n}{RHS^n}$ of the constraint-based residue fund CBR^n for each constraint covered by the constraint-based residues regime: $n \in CBRC$. The resulting payoff is $\sum_{n \in CBRC} \frac{\alpha_i^n}{RHS^n} CBR^n = \sum_{n \in CBRC} \lambda^n \alpha_i^n = H_{ir}$ as desired. We can conclude that any market participant can obtain a perfect hedge for a transaction between its connection point and the regional reference node.

149. Now consider the task of hedging a transaction between two regional reference nodes. In the previous section we saw that a source of residues is "firm" for hedging an inter-regional transaction if a fixed fraction of that source of residues has a payoff equal to $\sum_{n \in GC} \lambda^n \beta_l^n$ for all possible realisations of λ^n.

150. Consider the portfolio formed by purchasing a share $\frac{\beta_l^n}{RHS^n}$ of the constraint-based residue fund CBR^n for each constraint covered by the constraint-based residues regime: $n \in CBRC$. The resulting payoff is $\sum_{n \in CBRC} \frac{\beta_l^n}{RHS^n} CBR^n = \sum_{n \in CBRC} \lambda^n \beta_l^n$.

151. It is clear that this portfolio is fully firm in the case where all the constraints which bind with positive probability are in the set *CBRC*.

152. But what about the more general case where there are some constraints which bind which are not in the set *CBRC*? As under the status quo, there remains the possibility of hedging using the inter-regional settlement residues. The inter-regional settlement residues under this

approach are equal to the inter-regional settlement residues under the status quo less the payments to the system operator:

$$IRSR_l^{CBR} = IRSR_l^{CBR} - \sum_{n \in CBRC} \lambda^n \beta_l^n F_l = IRLR_l + \sum_{n \notin CBRC} \lambda^n \beta_l^n F_l$$

153. As in the previous section, it follows that $IRSR_l^{CBR} - IRLR_l$ is a firm hedge if and only if the only binding constraint on the interconnector is a constraint which has the pure radial form..

154. We can conclude that it is possible to construct a firm hedge from the constraint-based residues and the inter-regional settlement residues if and only if either $\sum_{n \notin CBRC} \lambda^n \beta_l^n = 0$, or there is only one constraint binding that is not under the constraint-based residues regime and that constraint has the pure radial form.

155. Furthermore, in the case where all constraints which bind are included in the set *CBRC*, the inter-regional settlement residues are equal to the inter-regional loss residues. So, in this case, not only is it possible to construct a hedging instrument which is firm using the constraint-based residues, it is also possible to construct a perfect hedge (provided the trader can forecast the flows on the interconnector at the relevant time).

Proposition 4: Under the constraint-based residues approach:

(a) The total surplus or residues accruing to the system operator is equal to the sum of the inter-regional settlement residues plus the constraint-based residues;

(b) Mis-pricing will arise at some connection points unless all constraints which bind with positive probability, and which are not included in the constraint-based residues mechanism, are pure inter-regional constraints.

Formally: mis-pricing at a connection point $i \in CP$ will occur unless $\sum_{n \notin CBRC} \lambda^n \alpha_i^n = 0$ for all possible realisations of λ^n.

(c) All market participants can form a perfect hedge for transactions between their connection point and the local regional reference node.

(c) The constraint-based residues and the inter-regional settlement residues can be used to construct a firm instrument for hedging an intra-regional transaction provided any constraint which binds with positive probability, and which is not included in the constraint-based residues mechanism, is a pure radial constraints.

Formally: for an interconnector $l \in L$, the constraint-based residues and the inter-regional settlement residues $IRSR_l^{CBR}$ can be used to construct a firm hedge provided that either $\sum_{n \notin CBRC} \lambda^n \beta_l^n = 0$ or there is only one constraint $n \notin CSPC$ which may bind which affects that interconnector and that constraint has the “pure radial” form $F_l \leq RHS^n$.

6. The CSP/CSC proposal

156. In a series of papers, CRA set out a proposal which appears to be designed to address the two problems identified at the outset of this paper, namely (a) the mis-pricing at individual connection points arising from the current zonal or regional approach to pricing and (b) the lack of firmness on the inter-regional settlement residues.

157. CRA's proposal can be described formally as follows. First, a set of constraints which fall within the CSP/CSC regime is defined. Let's call this set CSPC. This set is a subset of all the generic constraints $CSPC \subset GC$. Next, for each constraint $n \in CSPC$ in this set the CSP/CSC mechanism can be represented as two payments: First, a payment is made *from* each generator and each interconnector to the system operator. Second, a payment is made *to* each generator and each interconnector, known as a "CSC" payment. These payments or transfers are defined as follows.[12]

158. First, the payments from the generator to the system operator are defined as follows. CRA sometimes loosely refer to these payments as "CSP payments". However, to be clear, they use the term "CSP" to refer to the constraint "marginal value", here denoted λ^n. For each constraint $n \in CSPC$:

(a) for each connection point $i \in CP$, a payment is made from each generator to the system operator in the amount $\lambda^n \alpha_i^n q_i$ where q_i is the output of the generator at that connection point. Similarly, for each connection point $i \in CP$, a payment is made to each load in the amount $\lambda^n \alpha_i^n d_i$, so the net payment to all the market participants at a given connection point $i \in CP$ is $\lambda^n \alpha_i^n z_i$ where z_i is the net injection.[13]

(b) for each interconnector $l \in L$, a payment is made from that interconnector to the system operator in the amount $\lambda^n \beta_l^n F_l$ where F_l is the flow on the interconnector.

159. Second, the CSC payments are defined as follows. For each constraint $n \in CSPC$ a set of numbers a_i^n for each connection point $i \in CP$, and b_l^n for each interconnector, are chosen. Then:

(a) for each connection point $i \in CP$, a payment is made to each generator or load in the amount $\lambda^n a_i^n RHS^n$.

(b) for each interconnector $l \in L$, a payment is made to that interconnector in the amount $\lambda^n b_l^n RHS^n$.

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[12] As above, these payments could be negative, in which case the revenue flows in the opposite direction. The statement that a given payment is "from A to B" is only a definition of the direction for positive flows.

[13] In the notation of CRA, the payment from each generator to the system operator is equal to: CSP_k*$MWGEN_p$*$COEFF_{kp}$ where $MWGEN_{pp}$ is the generation by participant *p*, CSP_k is the "marginal value" of the *k*th constraint, and $COEFF_{kp}$ is the coefficient of participant *p* in the *k*th constraint equation. See page 12 of CRA (2005)

160. We will say that a CSP/CSC scheme is **revenue neutral** if the total payments to and from the system operator are zero. A CSP/CSC scheme which is revenue neutral does not require any outside source of funding, or generate a surplus for the system operator.

161. It is straightforward to check that the CSP/CSC payments are "revenue neutral" if and only if for each constraint $n \in CSPC$ the numbers a_i^n for each connection point $i \in CP$, and b_l^n for each interconnector, sum to one. That is, if and only if: for all $n \in CSPC$, $\sum_{i \in CP} a_i^n + \sum_{l \in L} b_l^n = 1$.

162. To see this, consider adding up the total payments to and from the system operator associated with a given constraint $n \in CSPC$.

$$\begin{aligned}
&\sum_{i \in CP} \lambda^n \alpha_i^n z_i + \sum_{l \in L} \lambda^n \beta_l^n F_l - \sum_{i \in CP} \lambda^n a_i^n RHS^n - \sum_{l \in L} \lambda^n b_l^n RHS^n \\
&\qquad = \lambda^n \Big(\sum_{i \in CP} \alpha_i^n z_i + \sum_{l \in L} \beta_l^n F_l\Big) - \lambda^n RHS^n \Big(\sum_{i \in CP} a_i^n + \sum_{l \in L} b_l^n\Big) \\
&\qquad = \lambda^n RHS^n - \lambda^n RHS^n = 0
\end{aligned}$$

163. Another condition that might be expected of a CSP/CSC scheme is that it should only involve payments to or from generators or interconnectors which are directly affected by a given set of constraints. In other words, if a generator is not directly affected by a given constraint (perhaps because that generator is located in a different region), that generator should not receive or make any payments under the CSP/CSC scheme. We will say that a CSP/CSC scheme is **narrowly focused** if the scheme only involves payments to or from generators or interconnectors which are directly affected by constraints in the scheme. In other words, a CSP/CSC scheme is narrowly focused if $\forall n \in CSPC$, $\alpha_i^n = 0 \Rightarrow a_i^n = 0$ and $\beta_l^n = 0 \Rightarrow b_l^n = 0$.[14]

164. If a CSP/CSC scheme is "narrowly focused" it can be expressed as a set of numbers $\bar{z}_i^n$ and $\bar{F}_l^n$ which satisfy: $a_i^n = \frac{\alpha_i^n \bar{z}_i^n}{RHS^n}$ and $b_l^n = \frac{\beta_l^n \bar{F}_l^n}{RHS^n}$. The numbers $\bar{z}_i^n$ and $\bar{F}_l^n$ correspond to the "entitlement" or "allocation" of "rights" under the CSP/CSC scheme. At this stage we will allow these allocations to vary with each constraint.[15] A narrowly focused CSP/CSC scheme is revenue neutral if and only if the numbers $\bar{z}_i^n$ and $\bar{F}_l^n$ satisfy the corresponding constraint equation *with equality*. In other words, a narrowly focused CSP/CSC scheme is revenue neutral if and only if $\forall n \in CSPC$, $\sum_{i \in CP} \alpha_i^n \bar{z}_i^n + \sum_{l \in L} \beta_l^n \bar{F}_l^n = RHS^n$.

165. As in the previous section, there are two key questions which we would like to ask of the CSP/CSC scheme:

(a) First, does the CSP/CSC mechanism restore the pricing signals on generators?

[14] CRA do not use the term "narrowly focused". However they do say that "If some participant or interconnector term has a zero coefficient in the constraint, this actually implies zero participant in both CSC and CSP arrangements", which implies the same concept. See page 14, CRA (2005). .

[15] CRA note that "in principle, a different CSC may apply for each different constraint form". See page 15, CRA (2005).

(b) Second, does the CSP/CSC mechanism allow for fully firm intra-regional and inter-regional hedging?[16]

166. Does the CSP/CSC mechanism restore the incentives on generators and loads to submit bids and offers which reflect their true costs? Under the CSP/CSC mechanism the total payment to a market participant at a connection point $i \in CP$ is the nodal price times the output of the generator plus the payment to the generator arising from the zonal pricing regime, less the CSP payment plus the CSC payment:

$$p_i z_i + (P_r LF_i - p_i) z_i - \sum_{n \in CSPC} \lambda^n \alpha_i^n z_i + \sum_{n \in CSPC} \lambda^n a_i^n RHS^n$$

167. As a result, the effective local marginal price is $P_r LF_i - \sum_{n \in CSPC} \lambda^n \alpha_i^n = p_i + \sum_{n \notin CSPC} \lambda^n \alpha_i^n$. In other words, as with the constraint-based residues approach, the CSP/CSC mechanism eliminates mis-pricing if and only if the set of constraints in the CSP/CSC regime includes all those constraints which might bind with positive probability and which affect the given connection point. (In other words, if and only if $\sum_{n \notin CSPC} \lambda^n \alpha_i^n = 0$)

168. CRA make this point themselves, noting that: the "the signals faced by participants will not reflect any effects arising out of constraints which may be binding, but which are not explicitly covered by the proposal".[17]

169. What about hedging? Does a revenue neutral, narrowly focused CSP/CSC mechanism allow for fully firm intra-regional and inter-regional hedging?

Inter-regional hedging

170. Let's start by focusing on inter-regional hedging. In the previous sections we saw that a given inter-regional hedging instrument is firm if and only if a fixed share of the instrument is equal to $\sum_{n \in GC} \lambda^n \beta_l^n$ for all realisations of λ^n. In the CSP/CSC mechanism, the only inter-regional hedging instruments which are available are the inter-regional settlement residues (modified by any relevant CSP or CSC payments).

171. The inter-regional settlement residues that arise under the CSP/CSC mechanism are equal to the status quo inter-regional settlement residues plus the payments to and from the interconnector as noted above. In other words:

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[16] Do CRA actually make the claim that the CSP/CSC mechanism can achieve fully firm inter-regional hedging? Most of the CRA documents do not seem to make this claim explicitly. However, CRA (2005) does seem to claim that the CSP/CSC mechanism can be designed so as to achieve fully firm hedging. That document claims that "both intra-regional and inter-regional settlement surpluses can be made as firm as the RHS. Thus, if all generator and ancillary service terms are included in the regime, the settlement surplus will be as firm as the underlying transmission system, after adjustment for the impact of local load variations". CRA (2005), page 20. CRA (2004a) seems to make a slightly lesser claim: "Hedging on each interconnector can be totally firm, up to the minimum of (a) the actual physical interconnector capacity; and (b) its share, as defined by its CSC, of the 'unsupported' trans-regional transfer capacity augmented by any participant CSCs which may have been entered into". CRA (2004a), page 34.

[17] CRA (2005), page 12.

$$IRSR_l^{CSP} = IRSR_l - \sum_{n \in CSPC} \lambda^n \beta_l^n F_l + \sum_{n \in CSPC} \lambda^n RHS^n b_l^n$$
$$= IRLR_l + \sum_{n \notin CSPC} \lambda^n \beta_l^n F_l + \sum_{n \in CSPC} \lambda^n RHS^n b_l^n$$

172. As we have seen in the previous two sections, where a constraint is binding which is not included in the CSP/CSC mechanism, it is only possible to obtain a perfect hedge using inter-regional settlement residues when that constraint is of the "pure radial" form. To focus on the impact of the CSP/CSC mechanism, let's assume that all the binding constraints are included in the CSP/CSC mechanism, so that $IRSR_l^{CSP} = IRLR_l + \sum_{n \in CSPC} \lambda^n RHS^n b_l^n$.

173. Let's focus first on the case of pure inter-regional constraints. The case of "mixed" constraints is considered next.

174. Let's suppose that a market participant attempts to purchase a fixed share $\frac{1}{\overline{F}_l}$ of the relevant inter-regional settlement residues. In order for this to yield a perfect hedge it must be that $\frac{1}{\overline{F}_l}(IRSR_l^{CSP} - IRLR_l) = \frac{1}{\overline{F}_l} \sum_{n \in CSPC} \lambda^n RHS^n b_l^n = \sum_{n \in GC} \lambda^n \beta_l^n$ for all realisations of λ^n.

175. This expression can only hold for all realisations of λ^n if we choose $b_l^n = \frac{\beta_l^n \overline{F}_l}{RHS^n}$. In other words, the inter-regional settlement residues are a firm hedging instrument if and only if the CSP/CSC mechanism is chosen in such a way that the allocations to each interconnector are independent of the constraints that are binding: $\overline{F}_l^n = \overline{F}_l$. Revenue neutrality then implies that we must choose $\overline{F}_l$ so that $\sum_{l \in L} \beta_l^n \overline{F}_l = RHS^n$, $\forall n \in CSPC$. In other words, it must be that the numbers $\overline{F}_l$ must be chosen so as to be a solution (with equality) to every pure inter-regional constraint which may simultaneously bind in the set of constraints included in the CSP/CSC mechanism.

176. But, it may well be the case that it is not possible to find a set of numbers $\overline{F}_l$ which satisfy all the pure inter-regional constraints in the CSP/CSC mechanism with equality. For example, it might be that there are just two interconnectors in the network, but there are three distinct pure-inter-regional constraints affecting these interconnectors. In this case, there is no guarantee that it will be possible to find a set of numbers $\overline{F}_l$ which satisfy all the pure inter-regional constraints in the CSP/CSC mechanism with equality.

177. For example, suppose that we have three constraints which may bind. The first constraint has the form $F_{SN \to NSW} \le 2000$. The second constraint has the form: $0.79 F_{SN \to NSW} - 0.164 F_{VIC \to SN} \le 1350$ (this is the form of the Murray-Tumut constraint in the northerly direction, ignoring terms involving Upper and Lower Tumut). The third constraint is of the form: $F_{VIC \to SN} \le 1500$. These constraints cannot all be satisfied with equality, so there is no way to obtain a perfect hedge using a revenue neutral, narrowly focused CSP/CSC mechanism.

178. More generally, if the potentially binding constraints include pure radial constraints of the form $F_l \le RHS^n$, it follows that we must choose $\overline{F}_l = RHS^n$ and these values must satisfy

all the constraints (whether pure radial or not) with equality. This is clearly a very strong condition which is highly unlikely to be satisfied.[18]

179. As a result, it is not the case that under a revenue neutral, narrowly focused CSP/CSC mechanism a market participant can always obtain a perfect hedge for inter-regional trading using a simple fixed portfolio. At best, the portfolio necessary to obtain perfect hedging will vary with the combination of constraints which are binding.

180. CRA do not appear to claim that the CSP/CSC mechanism will be revenue neutral. Specifically, CRA note that the mechanism will not be revenue neutral

> "if CSCs have been entered into for higher or lower generation levels than can actually be sustained, given the constraint RHS value in a particular period. Thus, exactly the same 'revenue adequacy' problem arises with respect to CSCs as in standard FTR theory".[19]

181. CRA go on to discuss how this surplus or deficit of revenue could be funded:

- "The CSC payments could be simply scaled down, or conceivably up, if a deficit or surplus accumulates over time, as in many FTR markets; and/or
- The CSC payments could be supported by CSC contracts under which payments are made to and from the TNSP, as discussed with respect to interconnector support; and/or
- The CSC payments pool could be supported by some form of uplift, thus spreading the cost of congestion across loads".[20]

182. In Appendix B of CRA (2004b), CRA provide an example of an implementation of a CSP/CSC mechanism which is not revenue neutral.[21] In contrast, the constraint-based residues approach is automatically revenue neutral and requires no additional mechanisms to ensure that the system operator incurs neither a surplus nor a deficit.

183. Now let's allow for the possibility of mixed constraints. Allowing for the possibility of terms in the constraint equations affecting individual connecting points increases the degree of freedom of the designer of the mechanism. Now, let's define $a_i^n = \frac{\alpha_i^n \bar{z}_i^n}{RHS^n}$ for some set of values $\bar{z}_i^n$. Now, the problem of finding a revenue neutral, narrowly focused CSP/CSC

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[18] We can define a mechanism to be "revenue adequate" if the revenue received by the system operator exceeds its obligations. In the context of this model, the CSP/CSC mechanism is revenue adequate if $\forall n \in CSPC$, $\sum_{i \in CP} a_i^n + \sum_{l \in L} b_l^n < 1$. From the analysis above we can see that it is possible to construct a CSP/CSC mechanism which is revenue adequate for pure inter-regional constraints by choosing a set of values $\overline{F_l}$ which satisfy all the pure inter-regional constraints in the CSP/CSC mechanism simultaneously (not necessarily with equality).

[19] CRA (2004a), page 37.

[20] CRA (2004a), page 37-38.

[21] See CRA (2004b), page 60

mechanism comes down to the problem of finding a set of allocations $\overline{z}_i^n$ and $\overline{F_l}$ satisfying all the binding constraints with equality. That is, which satisfies:

$$\forall n \in CSPC \,,\ \sum_{i \in CP} \alpha_i^n \overline{z}_i^n + \sum_{l \in L} \beta_l^n \overline{F_l} = RHS^n$$

184. We saw earlier that it is not possible to find a solution to this problem when all the constraints are pure inter-regional constraints. However, in general, it will be possible to find a solution when enough constraints have intra-regional terms.

185. For example, let's vary the three constraints above slightly. The three constraints will now take the following form:

1) $F_{SN \to NSW} \leq 2500$

2) $0.79 F_{SN \to NSW} - 0.164 F_{VIC \to SN} + 0.9 Q_T \leq 1350$

3) $F_{VIC \to SN} \leq 1900$

186. Let's choose $\overline{F}_{SN \to NSW} = 2500$, $\overline{F}_{VIC \to SN} = 1900$. This implies that we must chose $\overline{z}_T$ to satisfy the equation: $0.9 \overline{z}_T + 0.79 F_{SN \to NSW} - 0.164 F_{VIC \to SN} = 1350$ which implies we must choose $\overline{z}_T = -348.22$.

187. This implies that the CSC payment to Tumut generation, given these parameters, is equal to $0.9 \lambda^2 \overline{z}_T = -313.4 \times \lambda^2$. As long as the Murray-Tumut constraint is binding in this example, Tumut generation receives a total CSP + CSC payment equal to $0.9 \lambda^2 (\overline{z}_T - z_T) = -0.9 \times \lambda^2 (348.22 + z_T)$. Tumut is unambiguously worse off than under the status quo.

188. In other words, although it is possible to ensure that the IRSRs are a firm hedging instrument in this case, it requires a market participant to accept an allocation of CSCs which leaves them significantly worse off. It is unclear how this could be achieved in practice.

Intra-regional hedging

189. Let's now look at intra-regional hedging under the CSP/CSC mechanism. CRA do not appear to discuss the issue of intra-regional hedging. I can find no mention in the CRA documents of how a market participant obtains a firm hedge between its local connection point and the regional reference node.

190. We saw earlier that a participant can obtain a perfect intra-regional hedge if it can obtain access to a hedging instrument with a payoff equal to $H_{ir} = P_r LF_i - p_i^{eff}$, where p_i^{eff} is the effective local spot price. We saw above that the effective local spot price under the CSP/CSC regime is $p_i^{eff} = P_r LF_i - \sum_{n \in CSPC} \lambda^n \alpha_i^n = p_i + \sum_{n \notin CSPC} \lambda^n \alpha_i^n$, so we need a hedging instrument with a payoff equal to $H_{ir} = \sum_{n \in CSPC} \lambda^n \alpha_i^n$ for all realisations of λ^n.

191. Where do the residues necessary to form this hedging instrument come from? These residues must come from the "CSC" payments in some way. It must be that the market participants are able to trade these CSC payments between themselves in some way so as to obtain the hedge portfolio that they desire. But what form would that trading take? How would the CSC payments be "bundled" in that market?

192. Let's suppose, first, that each connection point makes available to trade a proportion of the total CSC payments it receives. In other words, each connection point makes available for trade a residue fund equal to: $\sum_{n \in CSPC} \lambda^n a_i^n RHS^n$. We need that the purchase of a fixed proportion $\frac{1}{\bar{z}_i}$ of this residue fund yields the payoff $\sum_{n \in CSPC} \lambda^n \alpha_i^n$ for all realisations of λ^n.

193. But this is only possible if we choose the a_i^n are chosen so that $a_i^n = \frac{\alpha_i^n \bar{z}_i}{RHS^n}$ for some set of values $\bar{z}_i$.

194. Now, as before, if we focus on pure intra-regional constraints, revenue neutrality implies that $\forall n \in CPSC \ \sum_{i \in CP} a_i^n = 1$, which implies that $\forall n \in CPSC$, $\sum_{i \in CP} \alpha_i^n \bar{z}_i = RHS^n$. This implies, in turn, that the values $\bar{z}_i$ satisfy all the intra-regional constraints with equality.

195. We saw above that it is likely to be the case that it is not possible to find a set of values $\bar{z}_i$ which satisfy all the intra-regional constraints with equality. We can conclude that if the market participants can only trade in shares of the total CSC payments at each connection point, it will not always be possible to design a revenue neutral, narrowly focused CSP/CSC mechanism which allows for perfect intra-regional hedging.

196. Therefore, if we are to obtain perfect intra-regional hedging we must assume a greater degree of "disaggregation" of the CSC payments. For example, let's suppose that it is possible for market participants to purchase not just the total CSC payments at each connection point, but the CSC payments at each connection point broken down by the corresponding constraint. The number of such "markets" in CSC payments could easily exceed the number of constraints (and therefore the number of constraint-based residues) by a large margin.[22]

197. In other words, each market participant can choose how much it purchases of a fund with the payoff $\lambda^n a_i^n RHS^n$. We need that the purchase of a fixed proportion $\frac{1}{\bar{z}_i^n}$ of this residue fund (and summed over $n \in CSPC$) yields the payoff $\sum_{n \in CSPC} \lambda^n \alpha_i^n$ for all realisations of λ^n. As before, this is only possible if we choose the a_i^n are chosen so that $a_i^n = \frac{\alpha_i^n \bar{z}_i^n}{RHS^n}$ for some set of values $\bar{z}_i^n$. In this case, it will be possible to obtain revenue neutrality by choosing the values $\bar{z}_i^n$ in such a way that all of the binding intra-regional constraints are satisfied with equality $\forall n \in CPSC$, $\sum_{i \in CP} \alpha_i^n \bar{z}_i^n = RHS^n$.

198. These conclusions are stated more formally in the following Proposition:

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[22] CRA (2004a) do raise the possibility that CSC payments could be traded between market participants. They note that: "Given their purpose and specificity, generalised trading of CSCs would not be appropriate, but note that bilateral trading is actually quite legitimate. Although different coefficients apply to different participants, the CSCs can all be translated back into the RHS units of the underlying constraint, and traded between those participants involved without any need for a wider 'revenue adequacy' calculation". CRA (2004a), page 59.

Proposition 5: Under the CSP/CSC approach:

(a) Mis-pricing will arise at some connection points unless all constraints which bind with positive probability, and which are not included in the CSP/CSC mechanism, are pure inter-regional constraints.

Formally: mis-pricing at a connection point $i \in CP$ will occur unless $\sum_{n \notin CSPC} \lambda^n \alpha_i^n = 0$ for all possible realisations of . λ^n

(b) Even if the CSP/CSC mechanism includes all constraints which bind with positive probability, if all constraints are pure inter-regional, it is not the case that a revenue neutral, narrowly focused CSP/CSC mechanisms can always be designed so as to achieve firm inter-regional settlement residues.

Formally: It is only possible to construct a revenue neutral, narrowly focussed CSP/CSC mechanism if it is possible to find a set of numbers $\overline{F_l}$ which satisfy $\sum_{l \in L} \beta_l^n \overline{F_l} = RHS^n$, for all binding pure inter-regional constraints.

(c) It is not the case that a revenue neutral, narrowly focused CSP/CSC mechanism which is designed so as to achieve firm inter-regional settlement residues, will always involve granting market participants CSC rights with a positive value.

(d) Under the CSP/CSC mechanism, achieving a perfect intra-regional hedge is only possible if market participants have access to trade in the CSC payments to or from each connection point.

If the market participants only have access to trade in the *total* CSC payment to or from a connection point, achieving a perfect intra-regional hedge will only be possible if it is possible to find a set of numbers $\overline{z}_i$ which satisfy $\sum_{i \in CP} \alpha_i^n \overline{z}_i = RHS^n$, for each binding pure intra-regional constraint.

Is the Snowy CSP/CSC Trial a complete implementation of the CSP/CSC concept?

The CSP/CSC mechanism is, of course, already in place in one part of the NEM. For the past several months a "trial" of the CSP/CSC concept has been underway in the Snowy region of the NEM. This trial is intended to resolve some of the problems that arise when certain constraints between Murray and Tumut in the Snowy region are binding. But is the CSP/CSC trial as implemented in the Snowy region really a test of the CSP/CSC concept as set out here?

In fact, the Snowy trial of the CSP/CSC concept is incomplete in key respects. In particular, the Snowy CSP/CSC trial does not include payments to or from the VIC-Snowy interconnector. As a result, the trial does not achieve the objective of firming up the residues on either the VIC-Snowy or Snowy-NSW interconnectors.

The CSP/CSC trial defines the set CSPC to be a set of constraints reflecting the Murray-Tumut network limitation. Until recently, these constraints had a form similar to the following:

$$0.79F_{SN \to NSW} - 0.164F_{VIC \to SN} - 0.8Q_T \leq 1350$$

In the case of **northwards** flows, the Snowy CSP/CSC trial involves a payment from Upper and Lower Tumut equal to $\sum_{n \in CSPC} \lambda^n \alpha_i^n z_i$ and an equal and offsetting payment from the Snowy-NSW interconnector equal to $-\sum_{n \in CSPC} \lambda^n \alpha_i^n z_i$. (There is no payment to or from the VIC-Snowy interconnector under the original Snowy CSP/CSC proposal). Can we express these payments as a form of the CSP/CSC mechanism set out above?

As we have seen, the CSP/CSC mechanism involves the choice of a set of numbers $\bar{z}_i^n$ and $\bar{F}_l$ such that $\forall n \in CSPC$, $\sum_i \alpha_i^n \bar{z}_i^n + \sum_i \beta_l^n \bar{F}_l = RHS^n$ and the net payment from an individual connection point is $\sum_{n \in CSPC} \lambda^n \alpha_i^n (z_i - \bar{z}_i^n)$ and the net payment from an interconnector is $\sum_{n \in CSPC} \lambda^n \beta_l^n (F_l - \bar{F}_l)$.

Therefore, the allocation to Tumut generation $\bar{z}_T$, must satisfy: $\lambda\ \alpha_T (z_T - \bar{z}_i) = \lambda\ \alpha_T z_T$, which implies $\bar{z}_T = 0$. Similarly, the allocation to VIC-Snowy flows $\bar{F}_{VIC \to SN}$ must satisfy $\lambda\ \beta_{VIC \to SN} (F_{VIC \to SN} - \bar{F}_{VIC \to SN}) = 0$, which implies $\bar{F}_{VIC \to SN} = F_{VIC \to SN}$. Finally, the allocation to Snowy-NSW flows must satisfy $\lambda\ \beta_{SN \to NSW} (F_{SN \to NSW} - \bar{F}_{SN \to NSW}) = -\lambda\ \alpha_T z_T$, which implies that $\bar{F}_{SN \to NSW} = (RHS^n - \beta^n_{VIC \to SN} F_{VIC \to SN}) / \beta^n_{SN \to NSW}$.

We can see that the current CSP/CSC "trial" in the northerly direction can be seen as an implementation of the CSP/CSC mechanism with a zero "entitlement" to Tumut generation $\bar{z}_T^n = 0$ and a non-firm "entitlement" to each interconnector. Specifically, the entitlement on the VIC-Snowy interconnector is $\bar{F}_{VIC \to SN} = F_{VIC \to SN}$ and the entitlement on the Snowy-NSW interconnector is $\bar{F}_{SN \to NSW} = (RHS^n - \beta^n_{VIC \to SN} F_{VIC \to SN}) / \beta^n_{SN \to NSW}$.

Since these "entitlements" depend on the flow on the VIC-Snowy interconnector they are not firm. The current "trial" of the CSP/CSC concept therefore doesn't achieve the objective of "firming up" the inter-regional settlement residues. CRA note that "including the VIC-Snowy interconnector in the CSP/CSC arrangement would provide a superior result, particularly in terms of dispatch optimality and inter-regional hedging".[23]

We might ask the question: What entitlements would be consistent with firm inter-regional hedging? As we saw above, if there are other constraints on the VIC-Snowy and Snowy-NSW interconnectors of the form $F_{VIC \to SN} \leq 1900$ and $F_{SN \to NSW} \leq 3000$, then we must choose $\overline{F}_{VIC \to SN} = 1900$ and $\overline{F}_{SN \to NSW} = 3000$. Since we must have $0.79\overline{F}_{SN \to NSW} - 0.164\overline{F}_{VIC \to SN} - 0.8\overline{z}_T = 1350$, this implies $\overline{z}_T = -885.5$. In other words, Tumut generation must accept a very sizeable negative "entitlement" in order to ensure the inter-regional settlement residues remain firm.

Another question we can ask is the following: Is it possible to express the Southern Generators' Proposal in the form of a CSP/CSC mechanism? The answer is yes, with the entitlements chosen as follows: $\overline{z}_T^n = 0$, $\overline{F}_{VIC \to SN} = 0$ and $\overline{F}_{SN \to NSW} = RHS^n / \beta_{SN \to NSW}^n = 1708.9$. Now the Snowy-NSW interconnector is "firm" for as long as the Murray-Tumut constraint is the only constraint binding. This result was noted in my earlier paper on the implications of the Southern Generators' Proposal.

[23] CRA (2005), page 2.

5. Conclusion

199. The current problems in the NEM – the mis-pricing and the hedging problems – should be addressed. A move to full nodal pricing and Financial Transmission Rights is possible but is unlikely. That leaves two approaches for resolving these problems: the CSP/CSC mechanism proposed by CRA and the constraint-based residues approach set out in this paper.

200. The CSP/CSC mechanism solves the mis-pricing problem as long as all the potentially binding constraints are included within this mechanism. However, it is not always possible to design a CSP/CSC mechanism which achieves firm inter-regional hedging without leaving some surplus or deficit on the system operator. CRA do not address the problem of achieving intra-regional hedging under the CSP/CSC mechanism. I show that this is possible, but only if participants can actively trade disaggregated CSC payments between themselves. This seems unlikely.

201. In contrast the constraint-based residues approach solves both the mis-pricing problem (again, as long as all the potentially binding constraints are included within this mechanism) and allows for fully firm inter-regional and intra-regional hedging. The mechanism is revenue neutral by design – that is, there is no surplus or deficit left with the system operator. The constraint-based residues approach is also a natural evolution of the existing market arrangements.

202. The benefits of the constraint-based residues approach depend on whether or not it is feasible to define separate residue funds for all relevant binding constraints. It is not yet clear precisely how many separate residue funds will be required. In addition, there remains a question as to the formulation of the "right-hand side" of constraint equations. How stable or predictable is this value? Can the constraint equations be formulated in a way which makes the right-hand side fixed?

203. In my view, the constraint-based residue approach offers the greatest promise as a medium or long-term solution to the mis-pricing and hedging problems in the NEM.

References

CRA (2004a), "NEM Regional Boundary Issues: Theoretical Framework", September 2004.

CRA (2004b), "NEM Transmission Region Boundary Structure", September 2004.

CRA (2005), "Constraint Support Pricing: Implementation of Snowy Proposal", March 2005.