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Quantifying competition benefits of transmission investment

Methodology selection

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Deloitte
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Contents

Executive summary

This report sets out a review of different approaches to quantifying the competition benefits of increased transmission investment in New Zealand. These approaches have been evaluated against a set of criteria, based on their relevance to modelling imperfect competition and strategic bidding in the New Zealand electricity market and practicality of each application. The specific criteria are:

- The extent to which there are examples of the approach being practically applied, with a particular focus on applications related to the consideration of competition impacts of transmission constraints.
- Whether the approach allows for explicit consideration of strategic bid offers by generators.
- Whether there are clear data requirements for the approach.
- Whether there is an existing model which could be adopted for the purpose of this application.
- Whether the approach allows for forward looking modelling with an appropriate level of granularity.

Approaches reviewed include:

- Full market game theory models, such as Nash-Cournot, Stackelberg, Bertrand equilibrium or supply function equilibrium models. These models look to apply game theory to study optimal bidding strategies and evaluate market outcomes under these. However, some of these approaches suffer limitations, such as becoming complex when applied to real world market conditions or having limited examples of real-world applications. However, a Nash-Cournot game theory model, where firms compete on production quantity, has been identified as a potentially suitable approach.
- Full market agent-based machine learning models, which are computer simulation models using algorithmic 'agents' and a market dispatch solver to model the strategic behaviours of firms in realistic electricity networks, where each agent seeks to maximise their own profit levels. Advantages of this approach include their ability to capture evolving strategies and existence of accessible pre-built models. However, potential disadvantages include perceived complexity and computational intensity.
- Other approaches, such as residual supply analysis and congestion surplus analysis. These approaches, while relatively simple and computationally light, are typically backwards looking and modelling strategic bidding is limited. For this reason, we have concluded that these approaches are unlikely to be best suited.

Based on our assessment of these approaches, this report recommends an Agent-based Machine Learning approach. Overall, Agent-based Machine Learning offers a robust and adaptable framework for simulating electricity market behaviour, providing a strong basis for assessing the competition benefits of transmission investment.

We have also assessed suitable options for specific Agent-based Machine Learning applications, and have identified ASSUME, an open-source agent-based model with deep reinforcement learning, as the starting point for developing a simplified two-node model before being expanded to a full proof-of-concept model of the New Zealand market.

Purpose, scope and structure

Purpose

Deloitte Access Economics (we or us) has been engaged by Transpower to identify a methodology and to measure the competition benefits of new transmission investment.

Transpower is seeking to develop a model that adopts an approach to quantitatively assess the potential competition benefits of new transmission investment and alleviation of transmission constraints. The ultimate model, once developed, can be used to evaluate competition benefits of Transpower's potential new investment in transmission.

Scope

This report outlines our approach to selecting and developing a theoretical framework to model competition benefits of transmission investment. This methodology is required to be forward-looking and not limited to historical market data, behaviour or trends. Additionally, it should take as an input demand and generation forecasts, short-run marginal costs and transmission constraints, and produce as an output the total price of delivered electricity, given any strategic behaviour which may occur in the market.

This report describes our review of different approaches that could be leveraged for quantifying the competition benefits of new transmission investment and a view on the recommended approach that Transpower should adopt, with a focus on methodologies that can capture competition benefits that may arise from new transmission investment.

Structure of this report

The structure of this report is provided below:

Chapter	Content
Competition benefits of transmission investment	• Discussion on how competition benefits are a key component of the overall benefits of transmission investment. • Description of the relevant investment test and the link to competition benefits • Context for the development of a model that considers competition benefits with respect to Transpower's existing modelling suite.
Definition of competition benefits	• Description of the factual and counterfactual for the purpose of this modelling • Definition of competition benefits in the context of transmission investment • An illustrative example demonstrating the concepts of dead-weight efficiency loss (or 'deadweight' loss) and the transfer of wealth from consumers to producers
Our process to identify the most suitable modelling approach	• Diagrammatic overview of our process to identify the most suitable modelling approach
Potential approaches for modelling competition	• Identified potential approaches for modelling the competition benefits of transmission investment • Detailed description and examples from the literature and commercial applications
Approach selection	• Description of the selection criteria to synthesise long list • Overview of how each modelling approach ranks against selection criteria
Recommended approach	• Our recommended approach based on the above selection criteria. • Discussion of the key benefits and considerations of this approach.
Selection of preferred application	• Overview of the practical application criteria used to rank applications based on their relevance. • Discussion of the two applications considered including a comparison of the benefits, limitations and risks.

Competition benefits of transmission investment

Measuring competition benefits of transmission investment matters. It helps quantify how such investment can improve market outcomes by increasing competition, leading to lower prices and greater efficiency for consumers. This is a key consideration for Transpower's future investment decisions and regulatory requirements.

Why does the measurement of competition benefits matter?

Competition benefits are a key component of the overall benefits of transmission investment

In wholesale electricity markets, the configuration of transmission networks can determine the extent of competition that a supplier faces. The more extensive the transmission network that a generator operates in, the more competition that generator is likely to face, increasing their incentive to submit offer prices closer to their short run marginal cost (**SRMC**) of production. Conversely, in a portion of a transmission network that has transmission constraints, there may be an incentive for a generator to act strategically to withhold output to raise the price it receives for the energy it can supply.[1]

Transmission investment to alleviate constraints has the potential to facilitate more competition between generators, resulting in offers that are closer to marginal cost of production. Generation that is closer to marginal cost of production potentially results in a number of benefits. This includes meeting existing demand at a lower price to consumers and inducing additional demand from consumers due to lower prices. We describe these effects in more detail below.

It is important to note that benefits occurring from transmission investment will comprise of the competition benefit as discussed above, as well as other benefits attributable to reduction in underlying costs, such as reliability and resilience benefits.[2]

The investment test Transpower is subject to

Competition benefits are also relevant to the investment test that Transpower is subject to. Transpower is regulated by two separate input methodologies (**IM**) under Part 4 of the Commerce Act 1986. These are the Transpower IM and the Capital Expenditure (**CAPEX**) IM:[3]

[1] See, for example, Frank A Wolak "Transmission planning and operation in the wholesale market regime" in Transmission Network Investment in Liberalized Power Markets (Springer International Publishing, 2020) at 101-133.
[2] See, for example, Transpower "Western By of Plenty Development Plan: Major Capex Proposal: Attachment 5 – Options analysis" (December 2024) <WBoP-Attachment-5-Options-analysis.pdf> at 8-9.
[3] Commerce Commission " " <Part-4-IM-Review-2023-Final-decision-Transpower-investment-topic-paper-13-December-2023.pdf> at [1.1] – [1.3].

- The Transpower IMs promote regulatory certainty for Transpower and consumers by setting out a number of the key 'inputs', to information disclosure regulation and individual price-quality regulation.
- The Capex IM has two major functions. These are to provide for the scrutiny of Transpower's proposed and actual capital investment, and to incentivise Transpower to deliver those investments efficiently.

The Capex IM investment test uses a cost benefit analysis which discounts relevant costs and benefits in the electricity market over a defined calculation period to identify a preferred investment option. The costs and benefits to be included in the investment test are those accruing to participants in the electricity market. Accordingly, the investment test is called a 'net electricity market benefit test' and the costs and benefits are those "accruing to participants in the electricity market".[4] The CAPEX investment test sets out a prescriptive framework around the inputs Transpower must use, the costs and benefits it must quantify and the sensitivity analysis it must perform.[5]

Of relevance to this report are the requirements for defining the competition effects that Transpower can quantify. Competition effects are the "value of the expected change in economic surplus due to a change in competition among participants in the electricity market as a result of a major capex project undertaken by Transpower". [6]

The Electricity Authority's trading conduct rules

Offers that generators place into wholesale electricity markets are subject to trading conduct rules under the Electricity Industry Participation Code. Clause 13.5A of the Electricity Industry Participation Code requires that generators make offers that are consistent with an offer they would have made in a market where no party could exercise significant market power.[7]

Clause 13.5A is therefore intended to prevent generators from submitting prices above the SRMC in situations where transmission constraints could limit competition and potentially enable the exercise of market power.

However, determining whether a price submitted by a generator is consistent with what would be offered in a market where no party could exercise significant market power is difficult. For example, in its Post Implementation Review of Clause 13.5A, the Electricity Authority found that while the provisions appear to be having an impact on generator behaviour, with prices tending to reflect underlying supply and demand conditions, definitive conclusions could not be drawn on whether offered prices were competitively determined.[8]

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[4] Commerce Commission " " <Part-4-IM-Review-2023-Final-decision-Transpower-investment-topic-paper-13-December-2023.pdf> at [3.4] & [3.5].

[5] See *Transpower Capital Expenditure Input Methodology (IM REVIEW 2023) Amendment Determination 2023* [2023] NZCC 39 <Transpower-Capital-Expenditure-Input-Methodology-IM-Review-2023-Amendment-Determination-13-December-2023.pdf> at Schedule D, Division 1

[6] *Transpower Capital Expenditure Input Methodology (IM REVIEW 2023) Amendment Determination 2023* [2023] NZCC 39 <Transpower-Capital-Expenditure-Input-Methodology-IM-Review-2023-Amendment-Determination-13-December-2023.pdf> at [D3(3)] & [D5].

[7] Electricity Industry Participation Code 2010, cl 13.5A.

[8] Electricity Authority "Post implementation review of the trading conduct provisions" (2022) at ii and 31

In addition, Clause 13.5A allows generators to increase prices to signal genuine scarcity. Distinguishing between the exercise of market power and the signalling of actual scarcity is likely to be challenging.

Investing in transmission to reduce constraints, which has the potential to encourage greater competition among generators, is likely to be beneficial even with Clause 13.5A in place. Addressing transmission constraints and supporting increased competition among generators would help ensure that offers are made in a competitive environment. This would also remove the need to determine, after offers have been submitted, whether prices were set competitively or reflect genuine scarcity.

Competition benefits related to strategic behaviour are currently not measured for future transmission investments

Transpower's *Te Kanapu* Future Grid Blueprint is an initiative to develop and publish a Grid Blueprint, to guide Transpower's investments in the national electricity grid and the way it manages New Zealand's electricity system. Consultations are currently underway, with a final Grid Blueprint to be published later in 2026.[9]

Transpower's *Te Kanapu* Future Grid Blueprint builds off *Whakamana i te Mauri Hiko*, which recognises that a step change of investment in renewable electricity generation and accompanying grid connections and interconnections will be needed to deliver the demand for electricity in the future. Transpower estimates that:[10]

- By 2035 approximately 40 new power stations (including five large-scale battery installations) will need to be connected to Transpower's grid.
- Approximately 70 new grid scale connections will be required by 2045: 40 to connect the new power stations and 30 connections to accommodate increased electricity demand on the grid due to electrification.
- 10 -15 large interconnection (grid upgrade) projects by 2035 to accommodate the increase in both demand and supply. Seven of these interconnections are large-scale 'grid backbone' connections, requiring Commission approval.
- On top of the Seven large-scale 'grid backbone' interconnections, between three and eight regional transmission upgrades.

Transpower's modelling suite forecasts many aspects of the electricity market. This includes market modelling of demand growth, build-out of new generation, dispatch of new generation and power flows on the transmission network.

However, competition benefits are currently assessed qualitatively and are not quantified explicitly.

By modelling improved competitive outcomes from transmission investment, Transpower seeks to explicitly quantify benefits arising from strategic behaviour based on the framework presented in the next section in this report.. If such benefits are material, they may form an important part of business cases and inputs into investment tests to support Transpower's strategic pipeline of investment as part of its *Te Kanapu: Future Grid Blueprint*.

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[9] Transpower "A future grid blueprint for Aotearoa – Consultation 1: Imagining Aotearoa in 2050" (July 2025) < Te Kanapu Future Grid Consultation 1.pdf>,
[10] Transpower "Whakamana i Te Mauri Hiko: Empowering our Energy Future" (March 2020) <TP Whakamana i Te Mauri Hiko.pdf> at 45-47.

Definition of competition benefits

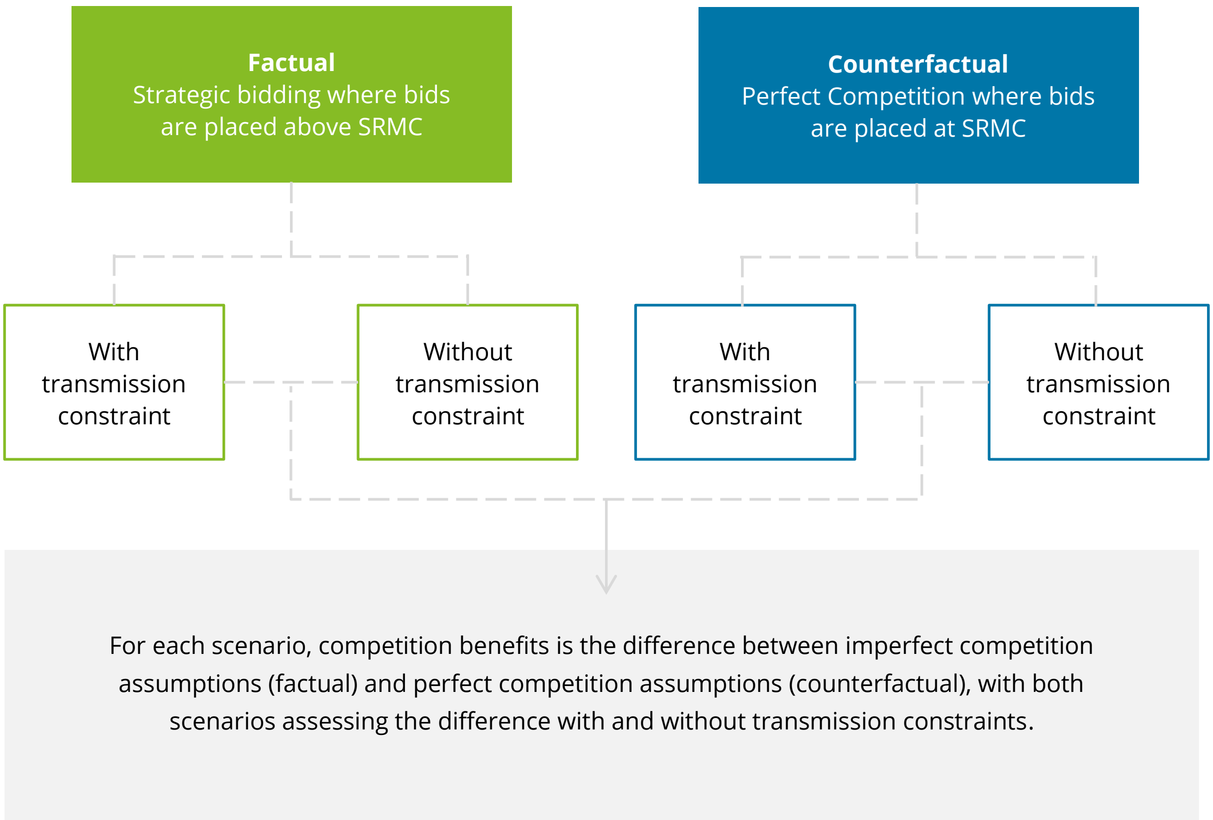
Competition benefits include efficiency and welfare impacts of comparing market outcomes under different bidding strategies with differing transmission constraints.

Factual and counterfactual for purpose of this modelling

Competition benefits of transmission investment is the difference between dead-weight loss and wealth transfer impacts under a scenario with strategic bidding behaviour compared to impacts under perfect competition.

Competition benefits are therefore considered under two scenarios when assessing proposed investment, the factual and the counterfactual, as shown in Figure 1.

Figure 1: Factual and counterfactual for the purpose of this modelling



Defining the competition benefits of transmission investment

Competition benefits can be considered to consist of three main economic efficiency elements. These include:

- Allocative efficiency gains (i.e., the more efficient meeting of consumer demand from more competitive prices)
- Productive efficiencies (i.e., the increased incentive for firms to be more efficient with more competition)
- Dynamic efficiencies (i.e., the potential for an increased incentive to innovate from increased competition).

In the context of electricity transmission investment there are many dynamics that should be considered in the calculation of competition benefits. As transmission upgrades typically increase the extent of competition suppliers face, suppliers then begin offering energy prices closer to SRMC. Lower offers then lead to lower wholesale energy prices, resulting in a wealth transfer from suppliers to consumers in the form of reduced total wholesale energy payments.

Given these dynamics, both wealth transfers and avoided deadweight loss should be considered in determining competition benefits.

We further note that pricing above competitive levels as a result of transmission constraints, and the resulting wealth transfer to producers, are arguably not the form of price signals needed to incentivise and reward investment in last-resort and flexible generation (i.e., generation capacity that can be ramped on and off when required), which is likely to often sit unused for most trading periods. Rather, by alleviating transmission constraints, lower priced generation could be dispatched to more efficiently meet demand for any trading period. We consider, therefore, that the avoided transfer of surplus from consumers to producers by alleviating transmission constraints is a relevant competition benefit.

Such benefits of transmission investment have also been recognised in Australia. In their Cost Benefit Analysis guidelines, the Australian Energy Regulator (AER) provide an explanation of the treatment of bidding behaviour and competition benefits in the Australian context.[11] They note that in order for changes in offer behaviour to be recognised as competition benefits it must result in changes to the generation that is dispatched (i.e., lower cost generation displacing higher cost generation).

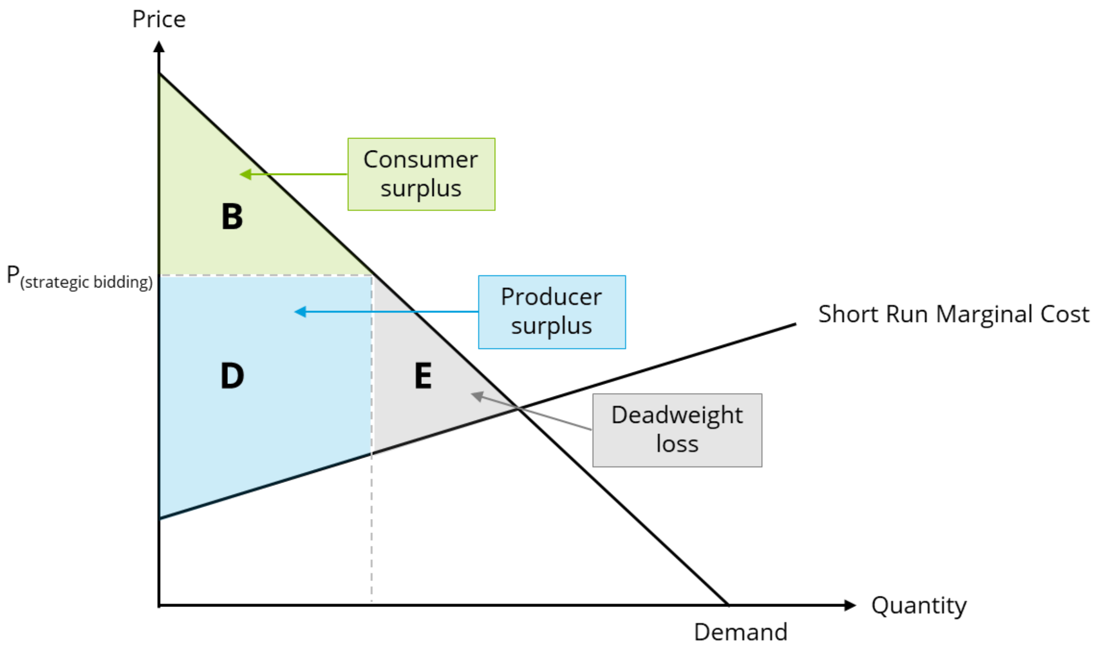
[11] AER "Cost benefit analysis guidelines" (November 2024) <Current CBA guidelines | Australian Energy Regulator (AER)> at 24.

Demonstrating the competition benefits of transmission investment

Below we provide an illustrative example two markets, one with strategic bidding the other with

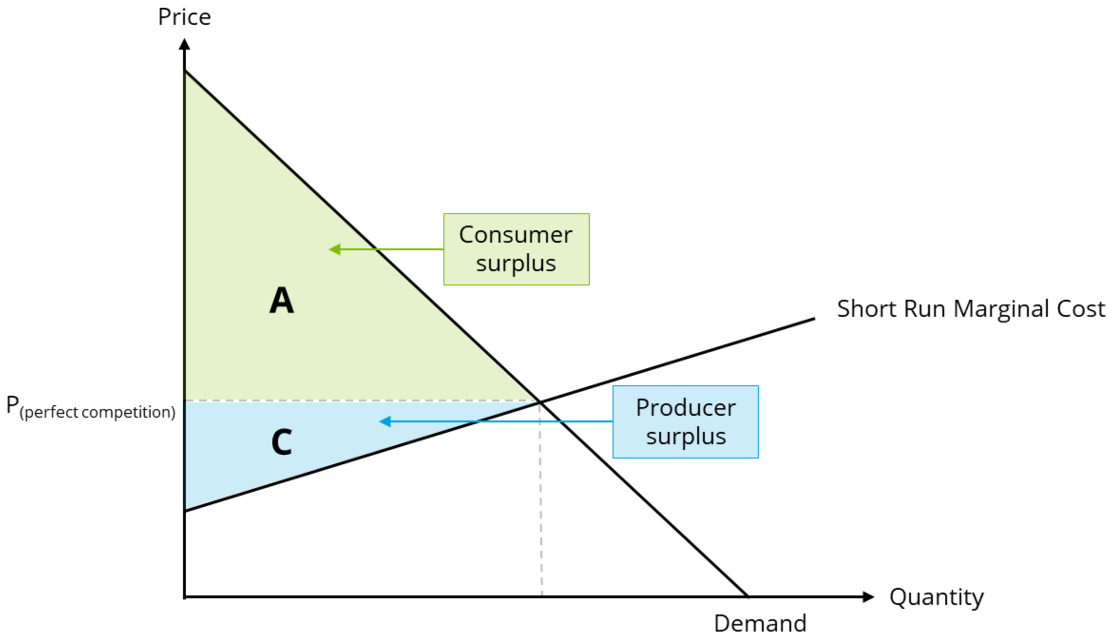
perfect competition, demonstrating the concepts of deadweight loss and the transfer of wealth from consumers to producers.

Figure 2: A market with strategic bidding



Source: Deloitte Access Economics

Figure 3: A perfectly competitive market

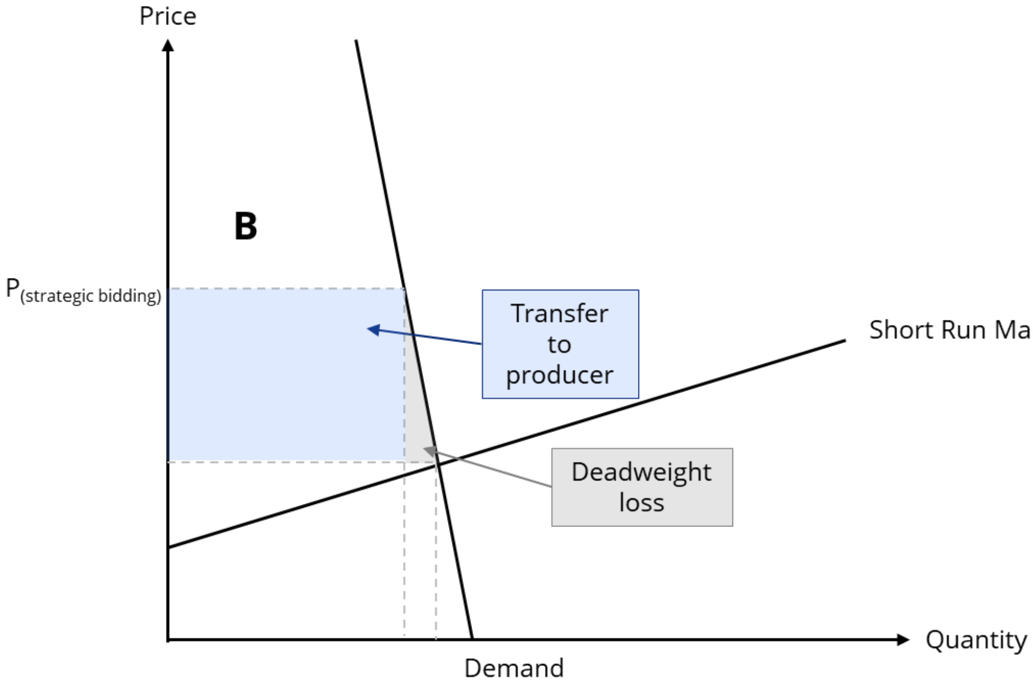


Source: Deloitte Access Economics

As Figure 2 and Figure 3 demonstrate, in a market where prices are set above the competitive equilibrium, welfare (often referred to as surplus) is not efficiently distributed between producers (shaded in blue) and consumers (shaded in green). As a result, there is a loss of efficiency in the market which is referred to as the deadweight loss. In contrast, a perfectly competitive market does not have any deadweight loss, as surplus is allocated efficiently between both producers and consumers.

We note that in practice, demand for electricity is often inelastic for a large proportion of electricity demanded. As demonstrated in Figure 4, shifting from perfect competition to strategic bidding under the assumption of inelastic demand, leads to a market outcome with only a small deadweight loss (approaching zero as demand becomes perfectly inelastic) but creates a relatively larger transfer of welfare from consumers to producers.

Figure 4: Impact of strategic bidding with inelastic demand



Source: Deloitte Access Economics

In practice, when we consider the factual and counterfactual scenarios described above, a wealth transfer occurs between the strategic bidding factual scenario (Figure 2) and the perfect competition counterfactual (Figure 3). The difference between the consumer surplus, producer surplus and dead weight loss can be estimated using the equations below:

- Change in consumer surplus = area A – area B
- Change in producer surplus = area C – area D
- Deadweight loss = area E

Calculating the competition benefits of transmission investment
To calculate the specific competition benefits of transmission investment, we calculate the change in consumer surplus, producer surplus and deadweight loss under:

- Strategic bidding, with and without transmission investment (factual).
- Perfect competition, with and without transmission investment (counterfactual).

This process is visualised in Figure 1.

This calculation provides the reduction in deadweight loss from transmission investment. The reduction in transfers from consumers to producers can be identified in an extra step. The change in consumer surplus when moving from strategic bidding (Figure 2) and closer to perfect competition (Figure 3) is made up of gains from deadweight loss converted to consumer surplus, as well as producer surplus converted to consumer surplus (that is, area A – area B which is attributable to change in area D).

The role of transmission investment in encouraging competitive market outcomes

Transmission investment is a key mechanism for mitigating market power and strategic generation offers. By alleviating physical network constraints, transmission investment enhances competition between generators, especially if it occurs in regions where limited capacity would otherwise allow a local generator to become 'net pivotal' (i.e. the generator's capacity is required to meet regional demand).

Expanding transmission capacity increases the pool of generators able to serve a constrained region. This increased competition makes it significantly harder for any single generator to influence wholesale electricity prices, pushing market outcomes closer to efficient SRMC levels. This has two primary benefits:

- First, it avoids instances of allocative and/or productive efficiencies loss (or 'deadweight' loss) in any region, node and/or trading period from the result of pricing above competitive levels. Dead-weight loss occurs when a proportion of consumers reduce their demand for electricity in any trading period as a result of prices being higher than competitive levels.

- Second, it avoids a transfer of surplus from consumers to producers. Pricing above competitive levels means that consumers are purchasing electricity at prices above levels that would be observed in competitive markets. This leads to a transfer or wealth from consumers to producers.

Our process to identify the most suitable modelling approach

To select a suitable modelling approach, we undertook a literature review to identify a list of potential approaches, developed selection criteria to identify a short list and applied practical considerations to select a preferred approach.

Figure 5: Overview of process

Literature review
Identify potential approaches to quantifying competition benefits.

List of options
Develop a list of options and selection criteria

Apply selection criteria
Based on applied selection criteria, select the preferred modelling approach

Select preferred application within the preferred approach
By applying practicality criteria to preferred approach, identify a preferred application as a next step

Potential approaches for modelling competition

We have reviewed a number of approaches to quantifying competition benefits, from full-market game theory models, to agent-based models and statistical methods.

Approaches reviewed

This section discusses the potential approaches for modelling the competition benefits of transmission investment that we have identified and reviewed. For further detail on each approach including all literature and commercial options considered please see Appendix A.

We have grouped the potential approaches into three high level categories below:

Full Market Game Theory

- Nash-Cournot
- Stackelberg
- Bertrand equilibrium
- Supply Function Equilibrium

Full Market Agent-Based Machine Leaning

- Algorithmic Agent-Based Machine Learning

Other Identified Approaches

- Residual Supply Analysis
- Congestion Surplus Analysis

Full market game theory

Nash-Cournot

In a Nash-Cournot model firms employ quantity strategies, i.e., each firm chooses its production quantity, taking as given the output being produced by all other firms.

This model has been widely applied and is an accepted technique when calculating competition benefits in electricity markets. This is largely due to the fact it requires relatively low computational and similar data requirements when compared to agent based or statistical models. However, as these models are theoretical, applications require careful consideration of assumptions. These assumptions include, but are not limited, to fixed price elasticity, linear demand and supply curves, constant marginal costs, fixed capacity and role of the fringe firms.

We have identified many examples of this approach with varying degrees of relevance to informing the selection of the preferred approach. In 2008, Transpower commissioned McLennan Magasanik Associates (MMA) to complete an independent assessment of competition benefits and consumer benefits associated with Transpower's short-listed HVDC options. This approach used a forward looking PLEXOS Nash-Cournot game theoretic model to assess the future bidding behaviour of market participants with market power taking into consideration transmission constraints. The outcomes of the model were then compared to the outputs of the model where perfect competition is assumed and the difference between the two was the level of competition benefits (excluding wealth transfers) from each option considered.

While this study's application in the New Zealand context and its ability to model outcomes across the transmission network on an annual basis are advantages, two factors require careful consideration. Firstly, the MMA assessment excluded wealth transfers from its definition of competition benefits, a notable difference from the above definition of competition benefits. Secondly, while the PLEXOS software is commercially available for use, its nature as an off-the-shelf package restricts the ability to customise the underlying code. This lack of flexibility presents a significant risk, as it could limit the capacity to model the specific nuances of New Zealand's evolving market, especially concerning the future integration of renewable generation.

Stackelberg

The Stackelberg model is similar to the Nash-Cournot model where firms compete on quantity. However, in this approach, firms bid in a sequential nature where the leader firm makes a strategic decision first and other firms (the followers) then make decisions taking into account the leaders decision.

This model is relatively new in the literature and is growing in popularity as applications of this model consider the competitive fringe as a Stackelberg follower which more accurately represents the decision-making process in wholesale electricity markets. However, as this model grows in complexity when there are multiple leaders, or levels of optimisation, the computational requirements tend to be higher than that of the Nash-Cournot models.

The most relevant example identified in the literature was an approach presented by Garcia, Street and Pereira. Their 2024 paper "*Long-term hydrothermal bid-based market simulator*" explored an approach to simulate long-term hydrothermal bid-based markets with multiple strategic agents.

This approach is based on solving multistage stochastic strategic bidding problems for each agent using Stochastic Dual Dynamic Programming (SDDP) which estimates the stochastic cost structure and Optbid which allows each agent to optimise its own bidding strategy to maximise expected profit, given the bids of other agents. In other words, the algorithm considers each agent's bidding strategy under uncertainty and inter-temporal constraints, then iteratively updates bids until the market converges, reflecting realistic competition and strategic behaviour.

The model was applied to the Brazilian power system considering multiple reservoirs, stages, scenarios and price-maker agents to comment of the state of market power abuse within the system. Despite being designed for the Brazilian market the paper notes the method is suitable for parallel computing and can be extended to consider other physical and regulatory details.

Another approach which we considered was presented by Bjørndal, Gribkovskaia and Jörnsten in their 2014 paper "*Market Power in a Power Market with Transmission Constraints*." This paper used a Stackelberg leader-follow game which modelled strategic bidding as an iterative process. In this case the supply functions of competitive fringe were fixed while the strategic player's bids were changed in successive order until the bid maximising profit was found.

This paper compared the outcomes of the Stackelberg game against a competitive equilibrium where all participants act as price-takers. This comparison, which focused on price and welfare impacts, was conducted under scenarios both with and without transmission constraints to assess the short-run implications of a generator's strategic behaviour on the electricity network under different conditions.

Despite the model being applied in a simple example of the electric power network with three interconnected nodes, the paper does not undertake modelling for specific trading periods or into the future. Rather, it is a single period (one hour) static model. The theoretical basis of this application means that it is not readily available to be applied in the context of this modelling task.

Bertrand Equilibrium

In the Bertrand equilibrium model, firms compete on price with a winner-takes-all assumption.

Despite this approach being referenced in multiple studies, within the literature, price bidding game models are found not to be an efficient tool in energy market modelling.[12] This is because the assumption that any firm can capture the entire market by pricing below others and can expand output to meet such demand is not viable in an electricity market where generation capacities are fixed in the short term. This approach is therefore not appropriate for the New Zealand context and as such has not been explored further.

[12] In papers such as: Mountain & Swier "An analysis of competition benefits – A report to the ACCC" (July 2003), Borenstein et al "Market Power in Electricity Markets: Beyond Concentration Measures" (February 1999), Borenstein et al "Market Power in Electricity Markets: Beyond Concentration Measures" (February 1999), and Bompard et al. "Comparative analysis of game theory models for assessing the performances of network constrained electricity markets" (December 2008)

Supply Function Equilibrium

In this model firms specify price-quantity 'supply' bid functions rather than an inflexible quantity or price as given in the Cournot and Bertrand models respectively.

The idea behind this model is that even if a firm knows its competitors' outputs, the presence of demand uncertainty implies that the firm faces many possible demand profiles. Accordingly, internal firm decisions implicitly determine a supply function that identifies the outputs that the firm will sell at prices that the market will accept. This model allows for a strategy space in which competing firms choose entire supply functions which are flexible and can adapt to changing business conditions.

One of the key features of the Supply Function Equilibrium approach is that it assumes production costs are common knowledge, and that demand is uncertain, which is reasonable in electricity markets, where technology characteristics and some fuel prices are transparent, and producers make offers before demand has been realised.

Despite this approach being generally referenced in the literature[13], there were limited studies with Supply Function Equilibrium models being applied either in a real world or example wholesale electricity markets. This is due to the computational difficulty in applying these models to electricity networks. Generally, when applied to large transmission networks with many generators subject to capacity constraints, a generator's optimisation problem is often non-convex and may yield multiple, local optima. Therefore, it is necessary to impose unrealistic assumptions (e.g. firms possess identical marginal cost functions) to ensure the modelling results are sensible.

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[13] In papers such as: Mountain & Swier "An analysis of competition benefits – A report to the ACCC" (July 2003), Borenstein et al "Market Power in Electricity Markets: Beyond Concentration Measures" (February 1999), MMA "Competition benefits of short-listed HVDC options" (March 2008) and Holmberg & Newbery "The Supply Function Equilibrium and Its Policy Implications for Wholesale Electricity Auctions" (November 2009)

Full Market Agent-Based Machine Learning

Full market agent-based machine learning models involve computer simulation modelling using algorithmic 'agents' and a market dispatch solver to model the strategic behaviour of firms in realistic electricity networks. Instead of bidding at cost, an agent places bids for each plant, using an algorithm that aims to choose bids to increase profit.

This modelling framework is able to consider the different strategies of various market participants, each optimising their own objectives, leading to more accurate and realistic simulations of market outcomes under various scenarios.

There are many examples of agent-based machine learning models applied to energy markets. One key example is the model proposed by Young, Poletti & Browne in their 2012 paper "Can agent-based models forecast spot prices in electricity markets? Evidence from the New Zealand electricity market." This model is based on a modified Roth and Erev algorithm which uses publicly available network and plant data to calibrate key parameters, with consideration of transmission constraints. The simulated prices are then validated against historical pricing data across a wide range of market conditions to test the accuracy of the model. The paper finds that the model can accurately predict the price on average at any South Island node under a range of demand and water values. However, it is less consistent in predicting North Island nodal prices.

A key advantage of this model is that it has been applied in the New Zealand market in a similar context to the modelling question at hand and access to the model and underlying code is possible. However, the modelling software and underlying model is relatively outdated, and some effort would be required to operationalise the model for the purposes of the modelling task at hand.

Another key example of a full market agent-based machine learning model designed for simulations of electricity markets is ASSUME. This model is a modular, open-source agent-based model for simulating electricity markets incorporating multi-agent deep reinforcement learning (applying machine learning to allow agents in the model to learn) for the study of different market dynamics under various scenarios. It's agent-based modelling framework means that the model is able to consider the different strategies of various market participants seeking to maximise profits.

As this model is a modern but established open-source model built in Python, it offers a significant advantage in terms of both technical accessibility and future adaptability. A key limitation of this approach is that it has not been applied in the context of the problem at hand nor the New Zealand market

Other identified approaches

Residual Supply Analysis

Residual supply analysis uses statistical relationships to relate the margin of spare capacity to the exercise of market power. For example, as supply becomes scarcer, the opportunity of the remaining producers to mark up their sales would seem to increase.

There are a few real-world applications of residual supply analysis in energy markets such as California, Alberta and Italy.[14] The approach in Wolak uses the relationship between the supplier's offer curve (i.e. the generators supply curve) and the residual demand curve to consider the extent of which a proposed transmission expansion changes completive dynamics in each respective energy market.

Wolak notes that the residual demand curve distribution determines the extent of competition that a supplier faces, and therefore how close the supplier's offer curve is to its marginal cost curve. Transmission expansion increases this competition by allowing more generators to compete, which flattens the residual demand curve. In response profit-maximising suppliers to submit offers closer to their true marginal costs, ultimately driving market prices toward more competitive levels.

The Wolak paper employs an econometric model using the hourly offer curves submitted by all market participants over a 5-year period. The model estimates the relationship between the hourly offer price and hourly inverse semi-elasticity for each market participant to simulate a counterfactual scenario that considers how these suppliers would adjust their offer curves in response to the increased competition from transmission expansion.

There are two key drawbacks to residual supply analysis. Firstly, as the studies are applied in a research setting, there is no immediate access to an underlying model if one was to exist. Secondly, as this approach is based on statistical techniques, it relies on historical data to establish the statistical relationships used to inform the model. Therefore, the model implicitly assumes historical relationships inform future relationships and does not consider the strategic development in the market as a result to of the investment over the long term.

[14] California ISO "Residual supply metrics: Preliminary methodology and results" (October 2009), Wolak "Measuring the Competitiveness Benefits of a Transmission Investment Policy: The Case of the Alberta Electricity Market" (November 2014), and Bresesti et al. "The benefits of transmission expansions in the competitive electricity markets" (July 2008)

Congestion Surplus Analysis

Congestion Surplus Analysis examines the difference between the price paid by consumers in a congested area (which is higher due to the constraint) and the marginal cost of generation in that area.

There are a limited number of applications of this approach in the literature and to our knowledge no commercial applications of this model. We note that in particular these approaches tend to be aimed at designing electricity markets with respect to transmission congestion to support competitive electricity markets and transmission investments. We do not consider this case is relevant to this application.

Approach selection

We have considered a number of approaches to quantifying competition benefits, and ranked each against selected criteria to identify our recommended approach.

Approach selection criteria

In order to evaluate each approach and select a preferred approach, we have applied a set of criteria to each of the approaches identified earlier in this report. Based on our analysis of each approach, including underlying literature and practical applications, we have assigned a 'Harvey ball' rating based on each of the following criteria:

- The extent to which there are examples of the approach being practically applied, with a particular focus on applications related to the consideration of competition impacts of transmission constraints.
- Whether the approach allows for explicit consideration of strategic pricing.
- Whether there are clear data requirements for the approach.
- Whether there is an existing model which could be adopted for our purposes.
- Whether the approach allows for forward looking modelling with an appropriate level of granularity.

Ratings were assigned to each criterion on the following basis:

Table 1: Harvey ball rating criterion

Rating	Practical applications	Strategic pricing	Forward looking and granular	Clear data requirements	Accessible existing model
●	Clear precedence of the approach being applied to competition impacts of transmission constraints.	Approach allows for explicit modelling of strategic pricing behaviour.	Approach is forward looking in nature, able to capture dynamic nature of the market, and consideration of granular time periods.	Data requirements are clearly laid out.	There are existing models which we would be able to access and leverage.
◐	Some relevant applications to electricity markets, but of potentially limited applicability.	There is some consideration for strategic pricing behaviour, but not necessarily explicit.	Approach might be forward looking but limited to some relevant time periods and may be more static.	Data requirements are generally able to be deduced, but with some limitations.	There are existing models which we may be able to access, but this is not clear.
○	Few to no relevant applications.	There is limited to no ability to capture strategic pricing behaviour.	Approach is not forward looking and typically used for historical analysis.	It is not clear what sort of data would be required.	There are likely no existing models which we could access.

Source: Deloitte Access Economics

Results of criteria assessment

The table below sets out a summary of our review of modelling approaches and an overview of how each rank against our selected criteria based on the Harvey ball rating system. Appendix A contains a detailed overview of the individual papers and models reviewed, and evaluation of each individual paper and approach.

Table 2: Summary of review and evaluation of modelling approaches

Cournot-Nash

Firms compete based on quantity strategies

Criteria	Rating	Description
Practical applications	◑	Many applications tend towards theoretical, with real-world applications tending to be stylised.
Strategic pricing	●	Applications all considered strategic conduct and deviations from perfect competition.
Forward looking and granularity	◑	While some models went into more granular detail, most applications were higher-level of targeted specific time periods. Some papers used a 'single shot' game, which is not especially forward looking.
Clear data requirements	●	Typically yes, papers tended to set out key data requirements (such as generators at each node, capacities, marginal cost, demand elasticity estimated).
Accessible existing model	●	Given theoretical tendencies of applications, there are few examples of publicly available models. However, commercial applications have been developed (such as in PLEXOS).

Stackelberg

Firms compete based on quantity strategies with leader-follower behaviour

Criteria	Rating	Description
Practical applications	◑	Many papers were more theoretical, but some examples had been validated on standardised test systems (IEEE 30-bus and IEEE 118-bus).
Strategic pricing	●	Most considered strategic conduct and deviations from perfect competition.
Forward looking and granularity	◑	Models were generally forward looking at an hourly time interval.
Clear data requirements	●	For the papers that were validated, clear data inputs were generally noted.
Accessible existing model	◑	It was not clear in any of the papers reviewed whether the underlying models would be accessible.

Bertrand Equilibrium

Firms compete based on price under 'winner-takes-all' assumption

Criteria	Rating	Description
Practical applications	○	Typically not found to be a decent practical approach, due to the assumption that any firm could capture the entire market through pricing below competitors and expanding output.
Strategic pricing	◑	Able to consider strategic pricing, but subject to the assumption firms could price below competitors and expand output to capture the whole market.
Forward looking and granularity	◑	Most applications tend to be high-level looking at specific time periods.
Clear data requirements	●	Generally clear data requirements.
Accessible existing model	◑	It was not clear in any of the papers reviewed whether the underlying models would be accessible. However, commercial applications have been developed (such as PLEXOS).

Supply Function Equilibrium

Firms compete on price-quantity supply bid functions

Criteria	Rating	Description
Practical applications	◑	While the assumptions made by this approach are generally appropriate, there are limited studies applying this approach to real world markets.
Strategic pricing	●	Able to consider strategic pricing and quantity bidding without making assumptions as restrictive as Bertrand equilibrium.
Forward looking and granularity	◑	Forward looking, but level of granularity is uncertain given few practical applications to real world markets.
Clear data requirements	●	Generally clear data requirements.
Accessible existing model	○	It was not clear in any of the papers reviewed whether the underlying models would be accessible, and given most were theoretically applied they may be of limited use.

Agent-based Machine Learning

Computer simulation of optimal strategies for heterogenous agents

Criteria	Rating	Description
Practical applications	●	Many papers tended to focus on particular models being applied to specific energy markets, including in the transmission context. However, as these tended towards research questions, computational burdens were not often clear.
Strategic pricing	●	These approaches tended to consider heterogenous agents acting to maximise profits.
Forward looking and granularity	●	Yes
Clear data requirements	●	Papers tended to set out the data used, and additionally as many are open-source the data inputs could be interrogated in the model code directly.
Accessible existing model	●	Many papers related to open-source models (e.g., ASSUME, Battula et al, EMLab and MASCEM) or models we may be able to gain access to.

Residual Supply Analysis

Statistical relationships between margin of spare capacity and ability to exercise market power

Criteria	Rating	Description
Practical applications	●	There are multiple papers applying this approach to considering transmission constraints in real world electricity markets.
Strategic pricing	●	Typically included strategic pricing, based on historical observations.
Forward looking and granularity	○	While this approach can be used for forward analysis, the model itself is based on historical bidding patterns and projecting these forward.
Clear data requirements	◑	To a degree papers tended to set out data requirements.
Accessible existing model	◑	Papers do not indicate whether the models could be available. However, commercial applications such as PLEXOS offer options.

Congestion Surplus Analysis

Examines the difference between prices and marginal costs in the presence of transmission constraints

Criteria	Rating	Description
Practical applications	◑	There are multiple papers applying this approach to considering transmission constraints in real world electricity markets.
Strategic pricing	◑	Typically included strategic pricing, based on historical observations.
Forward looking and granularity	○	While this approach can be used for forward analysis, the model itself is based on historical bidding patterns and projecting these forward.
Clear data requirements	◑	To a degree papers tended to set out data requirements.
Accessible existing model	◑	Papers do not indicate whether the models could be available. However, commercial applications such as PLEXOS offer options.

Source: Deloitte Access Economics

In order to construct the short list of options, we first discounted any approach which received an empty Harvey bull rating. This discounted Bertrand Equilibrium (due to unrealistic assumptions), Supply Function Equilibrium (due to there likely being no accessible existing models), Residual Supply Analysis (due to being based on historical patterns) and Congestion Surplus Analysis (also due to being based on historical patterns).

Each of Cournot-Nash, Stackelberg and Agent-based Machine Learning at least partially met the criteria. However, Cournot-Nash applications tended towards theoretical with limited examples of deployed models. Additionally, due to the theoretical foundations of the model, care is needed in setting up the model to ensure results are coherent. Likewise, real-world applications of Stackelberg models are limited. For these reasons, it was decided not to progress these approaches further, despite partially meeting the criteria.

However, Agent-based modelling fully met all aspects of the criteria and therefore has been selected as our recommend approach.

This approach is analysed in further detail in the next section of this report.

Recommended approach

We have recommended Agent-based Machine Learning as the most appropriate approach as it enables realistic, flexible modelling of electricity market dynamics, supporting the assessment of competition benefits from transmission investment.

Our recommended approach

Based on the above approach selection criteria we have selected Agent-based Machine Learning as our recommended approach. As described earlier in the report Agent-based modelling is based on algorithmic agents aiming to bid to increase profit. In other words, this approach allows firms to act strategically over realistic electricity markets. Below we identify the key strengths and considerations of this approach.

Key strengths of Agent-based Machine Learning include:

- This approach can be applied to many different market structures allowing for exploration of full network constraints and their ability to allow profit maximising behaviour.
- More closely models the function of the market than other options as participants profit maximise within a Security Constrained Economic Dispatch (SCED) market.
- Algorithm bids based on realistic participants strategy through learnt behaviour.
- It is specifically designed for analysis of competitive and non-competitive outcomes as it allows for bidding at and above SRMC.
- Relatively easy to program compared to other approaches that solve for participant level profit over facility level profit and can be leveraged for other market analysis tasks.

Despite this being a strong approach there are a few considerations worth noting:

- As Agent-based models are based on learnt strategic offer behaviour and do not predict competitive, nor Nash equilibrium prices, there is no theoretical basis against which to validate the results.
- As a result, these models require careful network aggregation and parameter calibration to avoid biasing outputs.
- Complex Agent-based models can be computationally intensive and needs long solve time.
- Often seen as a "Black box" as it can be difficult to understand offer strategies without significant analysis in some situations.

Overall, Agent-based Machine Learning offers a robust and adaptable framework for simulating electricity market behaviour, providing a strong basis to assess the competition benefits of transmission investment. While this approach has challenges around validation, calibration, and computational demands, its ability to replicate market dynamics and adapt to varying market structures outweighs these limitations.

Through our literature and commercial options scan, we have identified several practical applications of this approach which will be assessed in the next phase of this work.

Selection of preferred application

Given our preferred approach of Agent-based Machine Learning, the next step of this analysis is selecting a practical application to build the model within.

Selecting a practical application that is fit for purpose

In order to select a practical agent-based application, we have evaluated the approaches against a set of practical criteria to rank applications based on their relevance to the modelling task at hand and the ease by which they could be adapted for this. The table below sets out the criteria considered.

Table 3: Practical criterion for evaluation of applications

Practical criteria	Reasoning
Demonstrated ability for model to be applied to successfully modelling non-competitive behaviour, in particular with relevance to markets with large penetration of renewable energy	Some models may produce unreasonable results when considering markets which, like New Zealand, have a large amount of low marginal cost renewable energy. For this reason, an idea modelling approach would have been successfully applied to a market with a large amount of renewable energy.
Integration with SDDP watervalue	New Zealand is highly dependent on hydropower, which has a low SRMC but also a significant opportunity cost of using scarce stored water. The medium-term opportunity cost of water is therefore a crucial price-setter in the market. Models with easy integration of SDDP (which has a strong ability to reflect this opportunity cost) are likely to provide more robust results.
Ability to convert base model for New Zealand	From a practical perspective, a key consideration is the complexity involved in converting the base model to be relevant for New Zealand.
Solve time	Algorithms which require many iterations may have large solve times, reducing the usefulness of the model.
Storage optimisation	If storage is not optimised over the medium term, dispatch of storage resources does not take into account forward-looking security of supply, causing under and over-utilisation compared to actual market outcomes.
Customisation	Access to wide ranging model parameters allows for greater tuning of the model. Access to the source code is preferred, but significant pre-built options may provide adequate control.
Integration with Transpower's modelling stack	Greater integration in Transpower's modelling stack reduces the time required to run models.

Source: Deloitte Access Economics

Practical options considered

Deloitte has identified two suitable options for the analysis of competition benefits. Both models have strong fundamentals and are suitable for the task. However, the choice between the two options comes with differing levels of benefits and risks.

The following section compares the benefits, limitations and risks of using either application, noting that similarities between the two models is omitted from this section.

Each limitation/risk has been given a rating on a scale of one to five based on the perceived level of risk this factor adds to increasing project costs and delivery timeframes and the achievable quality of model outputs. In this case a rating of one reflects minimal or low risk, while five reflect significant or high risk.

ASSUME: Agent-Based Electricity Markets Simulation Toolbox

Harder et al. (2025) presents ASSUME, an open-source agent-based model with deep reinforcement learning of market participants to allow for the study of different market dynamics under various scenarios. ASSUME is likely the superior option, coming with more features and benefits than SWEM. However, ASSUME has not been designed for or tested in the New Zealand market and carries greater risks in its development.

Assume has a number of practical benefits over the SWEM model. These include:

- Python based: Model development is relatively simple compared to SWEM due to an easier, more commonly understood programming language.
- Active development: ASSUME is actively being developed. New features are likely to arrive over the next decade with the potential to increase the quality of competition modelling in the future.
- Good documentation: The ASSUME wiki is well-written, explains many different parts of the model, and is easy to understand.
- Incorporation of multiple algorithms: ASSUME allows multiple algorithms to be applied to the same model allowing flexibility in approach.
- Simple data input/output methods: ASSUME uses a combination of csv files and SQLite databases for input and output of data.
- Optimisation of short-term storage: ASSUME allows generators with storage to look ahead over multiple periods to predict their potential future profit and weigh the opportunity cost of generating now vs later when setting their offer prices.

Outlined below are the key limitations of ASSUME and the risk rating based on the perceived level of risk this factor adds to increasing project costs and delivery timeframes and the achievable quality of model outputs.

Hydropower

Hydropower in ASSUME is purely focused on pumped hydro storage, not large reservoirs with natural inflows like in New Zealand. Therefore, there is a potential need to write new functions in the code to track hydro storage and inflows over time. This was determined to be a relatively manageable exercise to achieve the outcomes required for model competition benefits.

Risk rating	
3	Incorporation of hydro inflows may require considerable effort to develop and could significantly increase solve times.

Learning Algorithm

ASSUME was designed to identify bidding strategies over time in markets without majorly varying spot prices. The agents in the model develop an offer strategy over multiple periods (each agent remembers the profit function from previous periods). This differs to other agent-based models like SWEM where the agent learns a completely new strategy from scratch in each period (the profit function from past periods doesn't influence the current period). As the market environment in New Zealand changes seasonally due to hydropower constraints, we consider that the base algorithms will fail to adequately capture the seasonal effects of the New Zealand market (for example, the model may use summer bidding strategies in a dry winter). There are ways we can get around these issues such as:

- Increasing the learning rate of the algorithm, increasing the speed at which the agent explores new bidding methodologies. This must be balanced with retaining some stability in bidding strategy as overly high learning rates may yield non-sensical bids.
- Breaking up learning periods into seasonal portions so that generators change their strategies seasonally
- Allowing the learning algorithm to access other model data such as season, or an overall water value. The current base reinforcement learning algorithm only has access to its past profits, demand, and forecast price of the current period. Access to more parameters could allow strategies to incorporate seasonal variation.

Until a New Zealand model can be built and tested, there is no way of assessing the suitability of the base algorithms in the model.

Risk rating	
3	Adaptation to learning algorithm may require trialling of various approaches.

Solve time

The full-German market example model has more generators than New Zealand but does not model any transmission system. As a market model with the level of transmission complexity required for the analysis of competition benefits has not been observed, we are unable to assess model solve times.

Risk rating	
3	High solve times may reduce the number of periods we are able to model, requiring extra time to setup simplified scenarios. Analysis could be limited to specific periods if solve times are very slow.

SWEM: Simulation of Wind in Energy Markets

In 2012, Young, Poletti and Brown developed an agent-based model using a modified Roth and Erev algorithm that simulates the New Zealand electricity market. This model uses network and plant data to calibrate key parameters of the model with careful consideration of transmission constraints. The results are then validated against historical pricing data across a wide range of market conditions to test the accuracy of the model.

SWEM is not as refined compared to ASSUME but has a track record of success in the New Zealand market and is suitable to the required objective of modelling competition benefits of transmission investment with less risk of unexpectedly high development times and costs.

SWEM has a few of practical benefits over the ASSUME model. These include:

- Tested in the New Zealand market: Previous modelling has shown the success of SWEM in modelling New Zealand spot prices.
- Hydro storage: SWEM was built with New Zealand's hydro system in mind. It already models hydro storage as a function of inflows and generation.
- Known solve times: Fast run speed: 8760 trading periods (one-year hourly granularity) in ~4 hours with a network simplification of ~20 nodes

Below we outline the key limitations of SWEM, and the risk rating based on the perceived level of risk this factor adds to increasing project costs and delivery timeframes and the achievable quality of model outputs.

Slow to develop

Written in C, the model is difficult to develop. Transpower's current modelling stack does not include models in C, which could result in additional maintenance effort and compatibility, risks around integration and resourcing challenges, compared to Python.

Risk rating	
2	low risk, however, development times may be drawn out.

Requires general updates before use

Uses an old Visual Studio 2010 Windows C compiler – requires a re-write to run with something more modern and will require update to use a new solver as it has been set up for an old academic CPLEX license.

Risk rating	
1	low risk, however, requires initial set up effort.

Simplified of hydropower

All hydro reservoirs are modelled as a single storage, significant work is required to segment storages.

Risk rating	
2	Medium risk as significant model overhaul is required if separate reservoirs are desired

Simplified treatment of batteries

SWEM does not have a generator type for battery and cannot currently track battery storage or optimise battery dispatch over time.

Risk rating	
3	Methods to approximate battery storage through input manipulation exist. There is the potential of incorporation of battery storage could be added at the same time as additional hydro reservoirs, however, it is unclear the difficulty at this stage.

Difficulty in debugging

All hydro reservoirs are modelled as a single storage, significant work is required to segment storages.

Risk rating	
1	Low risk, however, can slow down use of the model significantly.

Error-prone data inputs

Model requires separate texts file for generator and network and intermittent output for each period. These can be generated easily with a python script and could be addressed by incorporating simplified csv or database inputs.

Risk rating	
1	Low risk if addressed sufficiently with csv files and python scripts.

Selection of preferred application

Based on our evaluation of the ASSUME and SWEM applications, we will progress with a simplified two-node model based on the ASSUME application. This will test the capability of ASSUME to model competition benefits, before being expanded to a full Proof-of-concept model of the New Zealand market.

This conclusion was reached based on a trade-off of the various strengths and risks of each application. On the whole, given ASSUME has been developed in Python and has an active development community, we viewed that the risks associated with ASSUME would be easier mitigated than those associated with SWEM.

List of tables and figures

List of Tables

List of Figures

Glossary

Acronym or term	Full name
AER	Australian Energy Regulator
CAPEX	Capital Expenditure
IM	Input Methodologies
MMA	McLennan Magasanik Associates
SCED	Security Constrained Economic Dispatch
SRMC	Short Run Marginal Cost

Use, limitations and disclaimer

Restrictions and limitations

This report is commissioned by and in accordance with the scope agreed with our addressee client Transpower. This report is based on the specific facts and circumstances relevant to our addressee client. Our report is intended to inform Transpower's approach to quantitatively assessing the potential competition benefits of new transmission investment and alleviation of transmission constraints.

This report includes a compilation of evidence from desktop research and data sources. Some of the evidence presented, particularly from the desktop research, are perspectives provided from third parties, which may not necessarily represent the view of Deloitte.

Deloitte, its partners, principals, employees, and agents make no statements or representations whatsoever concerning this report, and the reader acknowledges that it may not rely on any such statements or representations made or information contained within this report.

Appendix A

Table 4: Long list of potential modelling approaches

Approach	Model	Model features and requirements	Benefits	Limitations	Applications in energy modelling
Full market game theory	Cournot-Nash	Firms employ quantity strategies, i.e., each firm chooses its production quantity, taking as given the output being produced by all other firms. This model has relatively low computational requirements when compared to agent based or statistical models. To estimate the Cournot game the model requires data on the marginal cost and capacities of the firms, demand data represented by a demand function including current observed prices in the market and transmission capacity data if network congestion is considered. As these models are theoretical, applications require careful consideration of assumptions. These assumptions include, but are not limited, to fixed price elasticity, linear demand and supply curves, constant marginal costs, fixed capacity and role of the fringe firms.	• Mathematically defendable approach to estimating competition benefits. • Generally easy to calculate when compared to other theoretical games • Widely used and accepted technique when calculating competition benefits in electricity markets.	• Model assumes that firms have perfect information when decision making while in reality there is limited transparency on competitors' output in the energy market. • Few controls over the solution, other than varying the price elasticity of demand, therefore the solutions may not reflect observed prices. • May produce unreasonable results in markets with large amounts of low marginal cost renewables • There is the possibility of multiple equilibria if there are flat regions in the demand and supply curves. • Generally, more short term focussed and may run into errors over the longer term.	MMA "Competition benefits of short listed HVDC options" (March 2008) Mountain & Swier "An analysis of competition benefits – A report to the ACCC" (July 2003) Borenstein et al. "Market Power in Electricity Markets: Beyond Concentration Measures" (February 1999) Borenstein et al. "The competitive effects of transmission capacity in a deregulated electricity industry" (2000) Devine & Lynch "Cournot competition in an integer-constrained electricity market model" (November 2023) Willems "Cournot competition in the electricity market with transmission constraints" (November 2000) Barquin et al. "Network-constrained Models of Liberalized Electricity Markets: the Devil is in the Details" (February 2004) PLEXOS Energy Modelling Software

Approach	Model	Model features and requirements	Benefits	Limitations	Applications in energy modelling
	Stackelberg	Firms compete on quantity but in a sequential nature where the leader firm makes a strategic decision first and other firms (the followers) then make decisions taking into account the leaders decision. Applications of this model consider the competitive fringe as a Stackelberg follower which more accurately represents the decision making process in the real market. Similar to the Cournot model this model requires an understanding of cost data, prices and transmission capacity. Alongside this the model assumes full information and linear supply and demand functions.	• Mathematically defendable approach to estimating competition benefits. • Allows for more nuanced understanding of how other players react to each other's decisions • Widely used and accepted technique when calculating competition benefits in electricity markets.	• Similar to the Cournot model there is limited transparency on competitors' output in the energy market and it is assumed that all players act rationally. • May produce unreasonable results in markets with large amounts of low marginal cost renewables • More difficult to solve than Bertrand and Cournot and can become complex if there are multiple leaders or multi-level optimisation • Generally, more short term focussed and may run into errors over the longer term.	Bompard et al. "Comparative analysis of game theory models for assessing the performances of network constrained electricity markets" (December 2008) Tian et al. "Strategic Investment in Transmission and Energy Storage in Electricity Markets" (January 2022) Wang et al. "Stackelberg equilibrium-based energy management strategy for regional integrated electricity–hydrogen market" (July 2023) Bjørndal et al. "Market Power in a Power Market with Transmission Constraints." (June 2014) Yang et al. "How to operate electricity market using a trilevel optimisation framework" (January 2025)

Approach	Model	Model features and requirements	Benefits	Limitations	Applications in energy modelling
	Bertrand equilibrium	Firms compete on price, and it is assumed that the winner-takes-all i.e. any firm can capture the entire market by pricing below others and can expand output to meet such demand. Despite this approach being referenced in multiple studies, within the literature price bidding game models are found not to be an efficient tool in energy market modelling due to the limitations of this approach.	• Mathematically defendable approach to estimating competition benefits.	• Assumes that any firm can capture the entire market by pricing below others and can expand output to meet such demand is not viable in the electricity market where generation capacities are fixed in the short term. • Generally, more short term focussed and may run into errors over the longer term.	Mountain & Swier "An analysis of competition benefits – A report to the ACCC" (July 2003) Borenstein et al "Market Power in Electricity Markets: Beyond Concentration Measures" (February 1999) Bompard et al. "Comparative analysis of game theory models for assessing the performances of network constrained electricity markets" (December 2008) Borenstein et al. "The competitive effects of transmission capacity in a deregulated electricity industry" (2000) PLEXOS Energy Modelling Software

Approach	Model	Model features and requirements	Benefits	Limitations	Applications in energy modelling
	Supply Function equilibrium	firms specify price-quantity 'supply' bid functions rather than an inflexible quantity as given in the above models. This model assumes that production costs are common knowledge, and that demand is uncertain which is reasonable in electricity markets, where technology characteristics and fuel prices are transparent, and producers make offers before demand has been realised. This model may serve as a more realistic approach to modelling imperfect competition as firms choose entire supply functions, however, applying this model to electricity markets is computationally difficult. Therefore, requires unrealistic assumptions, (e.g. firms possess identical marginal cost functions) to produce mathematically sensible results (this does not mean the results are economically sensible).	• Mathematically defendable approach to estimating competition benefits. • Corresponds to the actual bidding strategies of firms in electricity markets. • Price equilibria are generally between the Bertrand and Cournot extremes.	• Trades occur primarily through a supply-function bid process and elasticity of demand is constant across time and demand levels. • Produces multiple equilibria which is complicated when there is a competitive fringe whose capacity may be limited due to either generation or transmission constraints. • Difficult to develop and needs careful consideration of assumptions • Generally, more short term focussed and may run into errors over the longer term.	Mountain & Swier "An analysis of competition benefits – A report to the ACCC" (July 2003) Borenstein et al "Market Power in Electricity Markets: Beyond Concentration Measures" (February 1999) Holmberg & Newbery "The Supply Function Equilibrium and Its Policy Implications for Wholesale Electricity Auctions" (November 2009) PLEXOS Energy Modelling Software

Full market Agent-based machine learning		Full market agent-based machine learning models involve computer simulation modelling using algorithmic 'agents' and a market dispatch solver to model the strategic behaviour of firms in realistic electricity networks. Instead of bidding at cost, an agent places bids for each plant, using an algorithm that aims to choose bids to increase profit. These models are well suited to capturing dynamic strategic bidding behaviours and undertaking detailed modelling of electricity markets. However, their complexity can raise computational concerns.	• Allow exploration of full network constraints and their ability to allow profit maximising behaviour. • Relatively easy to program compared to other approaches that solve for participant level profit over facility level profit and can be leveraged for other market analysis tasks • More closely models the function of the market than other options as participants profit maximise within a SCED market. • Ability to accurately model short-run prices	• Since agent-based models typically predict neither competitive prices, nor Nash equilibrium prices, there is no theoretical basis against which to validate the results. • Are computationally intensive and needs long solve time • Ability of existing model to be manipulated by wrapper code can be limited or clunky in some situations. • Requires careful network aggregation and parameter calibration to avoid biasing outputs. • Could be seen as a "Black box", difficult to understand offer strategies without significant analysis in some situations.	Young, Poletti & Browne "Can agent-based models forecast spot prices in electricity markets? Evidence from the New Zealand electricity market" (January 2012) Veit, Weidlich & Krafft "An agent-based analysis of the German electricity market with transmission capacity constraints" (October 2009) Rastegar, Guerci & Cincotti "Agent-based model of the Italian wholesale electricity market" (June 2009) Tao et al. "Review and analysis of investment decision making algorithms in long-term agent-based electric power system simulation models" (October 2020) Praça et al. "Mascem: A Multiagent System That Simulates Competitive Electricity Markets." (December 2003) Trimarchi et al "A Review of Agent-Based Models for Energy Commodity Markets and Their Natural Integration with RL Models" (June 2025) Harder et al. "ASSUME: An agent-based simulation framework for exploring electricity market dynamics with reinforcement learning" (May 2025)

Approach	Model	Model features and requirements	Benefits	Limitations	Applications in energy modelling
Simplified congestion/ transmission rent analysis	Residual supply analysis	Uses statistical relationships to relate the margin of spare capacity to the exercise of market power i.e., as supply becomes more scarce the opportunity of the remaining producers to mark up their sales would seem to increase. Based on econometric techniques, this approach is relatively simple to implement. However, tends to be best suited to historical analysis and is based on previous behaviour.	• Have light computational requirements • Is fast and simple to develop • There are examples of this approach being applied to transmission investment.	• Based on statistical techniques, and is therefore backwards looking rather than forwards. • Unlikely to withstand logical, empirical scrutiny	California ISO "Residual supply metrics: Preliminary methodology and results" (October 2009) Wolak "Measuring the Competitiveness Benefits of a Transmission Investment Policy: The Case of the Alberta Electricity Market" (November 2014) Bresesti et al. "The benefits of transmission expansions in the competitive electricity markets" (July 2008) PLEXOS Energy Modelling Software
	Congestion Surplus analysis	Examines the difference between the price paid by consumers in a congested area (which is higher due to the constraint) and the marginal cost of generation in that area. Based on econometric techniques, this approach is relatively simple to implement. However, tends to be best suited to historical analysis and is based on previous behaviour.	• Have light computational requirements • Is fast and simple to develop • There are examples of this approach being applied to transmission investment.	• Based on statistical techniques, and is therefore backwards looking rather than forwards. • Unlikely to withstand logical, empirical scrutiny	Hogan "Market-based transmission investments and competitive electricity markets" (August 1999)

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