Low-carbon energy policy analysis based on power energy system modeling

Xiao Han¹  |  Jing Qiu¹  |  Lingling Sun²  |  Wei Shen²  |  Yuan Ma¹  |  Dong Yuan¹

¹ School of Electrical and Information Engineering, The University of Sydney, Sydney, Australia
² School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney, Australia

Abstract
The effect of carbon policies and mechanisms on the behavior of market participants and market equilibrium has been increasingly recognized, of which tax incidence is one of these important issues. Tax incidence is the market output of both producers and consumers that respond to taxes with market equilibrium, whether the tax is levied on sellers or buyers. This paper aims to study the carbon tax incidence on the transmission level of a power system based on different carbon tax collection methods in electricity market environment. A statistical demand elasticity model, power flow and carbon emission flow models are applied to simulate the electricity market equilibrium to analyze the effects of the tax levied on demand-side or supply-side. Furthermore, the Australian 59-bus system is employed in the case study with four stages and four main cases. The results demonstrate that consumers share more burden of the carbon tax in all carbon tax collection methods. Moreover, the proportion of the tax burden and emission reduction effect are different in each method and degree of renewable energy capacity. The results of this paper contribute to the establishment of emission-related energy policies toward a low-carbon economy.

KEYWORDS
energy policy, energy system modelling, low-carbon economy

1 | INTRODUCTION
Global warming is increasingly being recognized as a serious, worldwide public concern, and limiting global warming to 1.5°C above preindustrial levels is a crucial component of reducing emissions. This requires a “rapid and far-reaching” revolution in all aspects of society, as proposed by the UN Intergovernmental Panel on Climate Change (IPCC) [1]. Carbon pricing (such as carbon taxes and emissions trading schemes) is the most commonly used tool internationally [2] for emission reduction. Meanwhile, several compensation mechanisms are applied as alternative methods of carbon cost to reduce greenhouse gas emissions, such as the large-scale generation certificates in the power industry [3]. All the above mechanisms applied in the power industry have an impact on electricity prices. Furthermore, emission cost, according to pre-existing economic theories, increases electricity prices and exacerbates distortions of price in the economy [4]. Therefore, questions have been raised about how the policies and mechanisms of carbon emission cost affect the market participants’ behavior and market equilibrium.

Several attempts have been made to analyze the performance of the policies and mechanisms of carbon emission costs. The effectiveness of primary political tools and the related influencing factors have been reviewed worldwide, revealing that income level plays a vital role in choosing carbon emission policies, whereby demand-side policies are more suitable for high-income countries, such as carbon tax and cap-and-trade instruments [5,6]. Furthermore, the supply-side policies considered in that study include renewable portfolio standards, targets, and regulations, which are more feasible for changing the generation fuel mix. Moreover, a comparison between carbon tax and an emission trading system was performed to qualitatively and quantitatively measure the economic and political feasibility in the Mexico power sector, which showed...
that the emission trading system is more suitable for Mexico when these two mechanisms are added to generators \[7\]. Furthermore, the carbon tax could be absorbed into the electricity price in calculations for generators, and the influence of carbon tax on distributed energy resources is low \[8,9\]. A power system, including traditional thermal plants and wind turbines, is applied to analyze the impacts of carbon tax. As a result, an embedded carbon tax mainly affects conventional power plants to reduce emissions, and political subsidies are necessary to model the carbon cost \[10\]. Combined with a carbon emission flow model and internalized carbon tax, a carbon tax levied on consumers is applied to analyze the emission and energy price in multiple energy systems, and a node emission intensity is proposed to analyze carbon tax \[9\]. However, most previous studies rarely consider consumer behaviors and the demand function of electricity to evaluate a power energy system’s carbon tax incidence.

Generally, the tax incidence is driven by the supply–demand equilibrium to analyze the tax effect \[11\]. Nevertheless, in a power system, the supply function is determined by the marginal cost \[12\], and the demand function is more difficult to obtain. The generalizability of widely published research on the carbon tax incidence of electricity with a carbon tax on the demand side is applied to analyze the relationship between income and household demand, including food, fuel, transport, and share of power \[13,14\]. Some of these works commonly embed the computable general equilibrium model into the input–output framework with the household demand system \[14–16\]. Furthermore, some evaluate the carbon-sensitive differences between the supplier and the manufacturer based on the supply chain \[17\].

The demand elasticity of electricity is used to determine the demand response with respect to varying electricity prices in the real-time wholesale market, and there are certain problems with information security and market stability \[18\]. To the best of our knowledge, we are among the first to study carbon tax incidence with the demand elasticity of electricity on the transmission level of a power system. To address this issue, a statistical demand elasticity model is applied to make behavioral decisions with loads divided into categories as individual tasks, which could solve security and market problems \[19\]. Furthermore, a carbon emission flow model is employed to calculate the node emission intensity when evaluating the impact of the emission tax levied on the consumer side.

Overall, this study makes three significant contributions to the research on emission tax incidence of the power system: First, a carbon tax and cap-and-trade mechanism are embedded into the power equilibrium and market equilibrium to determine which policy approach is more effective. Second, a transmission model with various generation technologies is proposed and applied to simulate and evaluate the emission carbon tax allocation, which could achieve the result of social welfare loss and emission reduction. Third, a statistical demand function and carbon emission flow model is employed to estimate the tax incidence precisely.

The remainder of this paper is organized as follows: in Section 2, the theories and mechanisms of power systems, carbon flow, and economics are discussed. Sections 3 and 4 present the case study and results. Finally, conclusions are drawn in the final section.

## 2 | THEORIES AND METHODS OF POWER SYSTEMS, CARBON FLOW, AND ECONOMICS

In the most recent studies, carbon tax has been added to the supply side, such as generators. In this study, a carbon tax is applied to both the demand side and supply side to measure how it affects the equilibrium price and the electricity market demand, and this section presents the detailed models and methods. Specifically, when a carbon tax is levied on the demand side, a statistical demand elasticity model is implied as the electricity market demand model to calculate the supply–demand equilibrium \[19\]. Moreover, the carbon emission flow (CEF) is synthesized by adapting the procedure used by Cheng et al. \[9\].

The structure of this section is as follows. The power system model and CEF model are respectively presented in Sections 2.1 and 2.2. Carbon tax collection methods are modeled in Sections 2.3 and 2.4. Then the tax incidence theory and model are discussed in Sections 2.5 and 2.6.

### 2.1 | Conventional power system model

Generally, it has been assumed that the electricity market price is determined by the marginal cost. The objective function of this model is to minimize the total generation cost of meeting demand at each node, which is expressed as

\[
\text{min } \sum_{g \in \Omega^G} C_{g}^{\text{total}}(P) \tag{1}
\]

Equation (1) denotes the total generation cost of the set of all generators \( \Omega^G \) for all generation types, including both traditional and renewable energy units; \( P \) presents the generation output, including thermal power units, wind turbines, and solar units. This generation cost is a function related to the generation output. Only direct current power is considered in this power system model. To achieve grid equilibrium and the minimum cost, the complete constraints of the power system model are given as follows:

\[
\sum_{g \in \Omega^G, \ell \in \Omega^T} P_{g,\ell,t} = \sum_{\ell \in \Omega^T} D_{\ell,t} \tag{2}
\]

\[
0 \leq P_{g,t} \leq P_{g,\text{max}}, \quad g \in \Omega^G \tag{3}
\]

\[
-l_{ij,t} \leq I_{ij,t} \leq l_{ij,t}, \quad (i,j) \in \Omega^L \tag{4}
\]

Equation (2) is the power balance constraint at time \( t \), where \( P_{g,\ell,t} \) indicates the generation output of generator \( g \) at time \( t \). This balance includes each node balance and the whole system balance of the power system; \( D_{\ell,t} \) indicates the node demand at time \( t \); (3) is the generation constraint, where \( P_{g,\text{max}} \) is the...
maximum power output of generator $g$. Equation (4) denotes the branch flow constraint that $l_{ij}$ and $p_{ij}^\text{max}$ represent the power flow and maximum rating of the transmission line between nodes $i$ and $j$, respectively. The power generation cost functions are functions of the power output (5), which is dependent on the generation technology.

$$C_{g}^{ele} = F\left( P_{g} \right), \quad g \in \Omega^{G} \tag{5}$$

### 2.2 Carbon emission flow model

This section presents detailed formulations of the carbon flow equation with the carbon tax. Whether the carbon tax is imposed on consumers or producers, the total carbon emissions of electricity generation and consumption could be measured and recorded on the supply side based on the electricity network. In this work, the CEF is adapted to measure and calculate the carbon emission intensities of nodes, lines, and the grid [9]. The emission intensities of a node and a transmission line are described as follows:

$$e_{\text{node}} = \frac{\sum_{g \in \Omega^{G}} P_{g} \cdot C_{\text{emi}}^{g}}{\sum_{g \in \Omega^{G}} P_{g} + \sum_{g \in \Omega^{V}} P_{g}} \quad i \in \Omega' \tag{6}$$

$$e_{\text{line}}^{\text{ij}} = \begin{cases} e_{\text{node}}, & \text{if } f_{ij} \geq 0 \\ e_{\text{node}}, & \text{if } f_{ij} < 0 \quad (i,j) \in \Omega' \tag{7} \end{cases}$$

$$e_{\text{grid}} = \frac{\sum_{g \in \Omega^{G}} e_{\text{node}} \cdot (\sum_{g \in \Omega^{G}} P_{g} - \sum_{j \in \Omega^{G}} f_{ij})}{\sum_{g \in \Omega^{G}} \sum_{g \in \Omega^{G}} P_{g}} \tag{8}$$

The emission intensity of node $i$ is the average carbon emission of the energy flows injected into this node in (6), and the carbon emission intensity of a transmission line is equal to the emission intensity of the node from which the energy flowing out, as in (7). As a result, the emission intensity of node $i$ is the weighted average of all the generators at node $i$ and all the transmission lines related to node $i$ in (6). To prevent double-counting in the entire network, the total node emissions are equal to the node emission intensity multiplied by the total node energy consumption. Consequently, the emission intensity of the entire system is the weighted average of all the nodes, as in (8). Moreover, this calculation method could cover the total carbon emissions of all electricity generation and transmission processes.

### 2.3 Carbon emission pricing

Based on the CEF, the carbon price could easily be raised on both the demand and supply sides, which facilitates taxation and trading. For governments limiting emissions, there are two mechanisms to raise the price of emissions: cap-and-trade systems and carbon tax [20,21]. In this work, one of the most important cap-and-trade mechanisms, an emissions trading system (ETS), is used to analyze the impact of the carbon price on electricity generation and consumption. Although auctions are commonly used in the power industry, the free allocation of allowances is more suitable for the early stages of an ETS [21]. Therefore, the free allocation method of allowances is adopted in this study.

There are two refinement methods of free allocation of allowances to calculate the carbon price based on an ETS: the grandfathering method and benchmarking (a specific example of which is the output-based allocation method) [21]. In the proposed model, allowances can be traded on the carbon trading system, and all carbon emissions that exceed allowances must be purchased in the carbon emission market.

Because the horizons of electricity and carbon trading are different, the calculation and trading of both could be dispatched into the same trading interval, such as hourly and daily [2]. For the benchmarking method, the output-based allocation is one of the main approaches to prevent carbon leakage [22]. In this method, the emission quotas are determined by the industry emission intensity, and the carbon emission cost of generators at time interval $t$ is expressed in (9).

$$C_{g,t}^{emi} = (\bar{e} - \tilde{e}) \cdot \mu_{g}^{emi} \cdot P_{g,t} \quad g \in \Omega^{G} \tag{9}$$

where $\bar{e}$ is the industry emission standard of different generation technologies, including thermal, wind, and solar. $\tilde{e}$ is the actual emission intensity of generator $g$. Moreover, carbon prices in many countries might be less volatile or fixed in one-day trading; therefore, it is assumed that the price of carbon emission, $\mu_{g}^{emi}$, is equal to the daily carbon price.

For the grandfathering method, the value of free allocation of allowances $C_{g,t}^{free}$ is a fixed cap at each calculated cycle. Therefore, it must be dispatched to each trading interval of electricity trading, hourly, for convenient evaluation (10). Furthermore, the emission intensities of each generation unit are different from each other.

$$C_{g,t}^{emi} = \sum_{t=1}^{12} P_{g,t} (\bar{e} - C_{g,t}^{free}) \quad g \in \Omega^{G} \tag{10}$$

### 2.4 Supply and demand model

#### 2.4.1 Total supply model

For electricity, as with most commodities, the supply curve is upward-sloping, and the inverse supply function could be obtained by the cost function for each generator unit [12]. It is assumed that the power trading market is perfectly competitive, and that the supply function of each generator is the marginal cost curve above the average variable cost. According to the cost function model of different categories (5), the inverse supply functions of generators are presented in (11). Different technologies have different marginal cost functions, such as linear functions for thermal plants and wind farms, and constant...
functions for solar units. It is worth mentioning that the inverse supply function of solar units is equal to zero. Therefore, regardless of the price, solar power is generated at full capacity. However, this pricing method makes it difficult for renewable energy to recover investment costs. Therefore, a method with a capital recovery factor (CRF) is more suitable in the real-time market. In (12), \( r \) is the interest rate and \( t \) is the number of annuities received. Therefore, the marginal cost of a solar farm is related to a function of the CRF and total investment (13).

\[
\mu_{s,t}^{dem} = dF(P_s) / dP_s \quad g \in \Omega^G
\]

\[
CRF = r(1 + r)^t / ((1 + r)^t - 1) \quad g \in \Omega^G
\]

\[
\mu_{s,t}^{inc} = F(CRF_s, C_{inv,s}) \quad g \in \Omega^G
\]

### 2.4.2 Total demand model

There are various methods to derive demand functions. For electricity, the demand curve could be constructed according to the procedure used by Xu et al. [19], which could be estimated by a marginal welfare function and a utility function. Detailed formulations of the demand model and curve are as follows:

\[
\omega - \delta (t - \alpha), \quad \alpha < t < \alpha + \gamma
\]

\[
0, \quad \text{otherwise}
\]

\[
F_{dem,m}(P, t) = \begin{cases} D_{dem,m}^{m}, u_m^{w} > 0 \rightarrow u_m^{w} = \max u_m^{w}(t) \\ 0, \quad \text{otherwise} \end{cases}
\]

\[
D(P, t) = \sum_{m=1}^{M} D_{m}^{w}(P, t)
\]

\[
\hat{D}(P, t) = E \left[ \sum_{m=1}^{M} F_{m}^{w}(P, t) \right]
\]

\[
= \sum_{m=1}^{M} D_{m}^{w} \mathbb{P} \left\{ u_m^{w} > 0, u_m^{w} = \max u_m^{w}(t) \right\}
\]

Equation (14) describes the marginal welfare function, which represents the difference between the utility that consumers get from task \( m \) and the cost that they must pay to obtain electricity to complete task \( m \). Equation (15) is the marginal utility function of power consumption based on a statistical method. It is assumed that this marginal utility function is a linearly decreasing function of the time slot \( t \). The initial marginal utilities \( \omega \) and utility decay rates \( \delta \) are different for the different tasks of each consumer at different times. Therefore, the initial marginal utilities and utility decay rates are randomly assigned within a certain range of values. Equation (16) presents the demand function of a user of task \( m \) such that the demand could be shed and deferred based on the fluctuating price. Statistically, demand occurs at the interval of the maximum welfare, and demand might be shed totally if utility values are smaller than the electricity price at all time intervals. Equation (17) shows the total demand function of a user as a sum of the energy consumption from all the tasks of the consumer.

Based on (14)–(17), this total demand function is established through statistical methods, and the main stochastic process is to solve the probability distribution of the utility function \( u_m^{w} \). Consequently, the aggregated demand function could be calculated by the expectation of the distribution of \( u_m^{w} \), as in (18).

#### 2.5 Incidence of carbon emission cost

Generally, if a tax is only levied on sellers or buyers, the market output is affected by both producers and consumers responding to taxes, which is defined as tax incidence [11]. In the same vein, a carbon price, including a direct carbon tax and carbon-trade systems, changes the supply and demand quantities through changing the market equilibrium if it is only added on the supply side or the demand side. The new equilibrium quantity is less than the original equilibrium, because of changes in the price. Regardless of the side on which the carbon price is levied, there are two significant prices, the amount that suppliers received and the price that consumers paid. When the new market equilibrium is achieved, these two prices are different, which are the same as the equilibrium prices in the case of no tax. The difference between the two equilibrium prices is mainly related to the carbon price. Meanwhile, the relationship between the elasticities of demand and supply mainly affects the differences among the new equilibrium price, the price that suppliers received, and the price that consumers paid. Furthermore, the relationship among these three prices succinctly illustrates the incidence of the carbon price, which is expressed by the formula below, where the total supply and demand functions are assumed as linear functions.

\[
\mu^{isp} = \frac{\hat{D}}{\hat{D} + \theta} \quad \mu^{dem} = -\rho \cdot \theta + \kappa
\]

\[
\mu^{isp} = \frac{\hat{D} + \theta}{\hat{D} + \theta + \mu^{emi}} \quad \mu^{dem} = -\rho \cdot \theta + \kappa - \mu^{emi}
\]

Equations (19) and (20) are the initial inverse supply function and initial inverse demand function. Furthermore, (21) and (22) are the new inverse supply function and new inverse demand function with the carbon price \( \mu^{emi} \). The market equilibrium is evaluated by (19) and (20) if there is no carbon emission cost, and the equilibrium quantity and price are as follows:

\[
D^q = (\kappa - \theta) / (\theta + \rho)
\]

\[
\mu^q = -\rho \cdot (\kappa - \theta) / (\theta + \rho) + \kappa
\]

When the carbon emission cost is added on the supply side, the inverse supply function is changed from (19) to (21).
Therefore, the new market equilibrium is determined by (20) and (21). The market equilibrium quantity and price with carbon cost on the supply side are given by (25) and (26). As the demand function is not changed when the emission cost is added on the supply side, the equilibrium price is the price paid by the consumer \( \mu_{d}^{\text{sup}} \). The price received by the supplier \( \mu_{s}^{\text{sup}} \), shown as (27), is calculated by the new equilibrium quantity \( D^{\text{sup}} \) and the original supply function (19).

\[
D^{\text{sup}} = (\chi - \theta - \epsilon_{\text{emi}}) / (\theta + \rho) \tag{25}
\]

\[
\mu_{d}^{\text{sup}} = \mu_{s}^{\text{sup}} = (\chi \theta + \theta \rho + \rho \epsilon_{\text{emi}}) / (\theta + \rho) \tag{26}
\]

\[
\mu_{d}^{\text{dem}} = (\chi \theta + \theta \rho - \theta \epsilon_{\text{emi}}) / (\theta + \rho) \tag{27}
\]

When the carbon emission cost is added on the demand side, the inverse demand function is changed from (20) to (22). The market equilibrium quantity and price with the carbon price on the demand side are given by (28) and (29), respectively. As opposed to the supply side, the supply function is not changed when the emission cost is added on the demand side. Therefore, the equilibrium price is the price received by the supplier \( \mu_{d}^{\text{dem}} \). The price paid by the consumer \( \mu_{s}^{\text{dem}} \), as shown in (30), is calculated by the new equilibrium quantity \( D^{\text{dem}} \) and the original demand function (20).

\[
D^{\text{dem}} = (\chi - \theta - \epsilon_{\text{emi}}) / (\theta + \rho) \tag{28}
\]

\[
\mu_{d}^{\text{dem}} = \mu_{s}^{\text{dem}} = (\chi \theta + \theta \rho - \theta \epsilon_{\text{emi}}) / (\theta + \rho) \tag{29}
\]

\[
\mu_{d}^{\text{sup}} = (\chi \theta + \theta \rho + \rho \epsilon_{\text{emi}}) / (\theta + \rho) \tag{30}
\]

Based on (24), (26)–(27), and (29)–(30), the difference between the price paid by the consumer and the price received by the supplier is the carbon price \( \epsilon_{\text{emi}} \). In addition, the incidence of the carbon price is the difference between the original equilibrium price \( \mu_{d}^{\text{op}} \) and the price received by suppliers \( \mu_{s} \), or the price paid by the consumer \( \mu_{d} \). According to (26)–(27) and (29)–(30), the price received by the supplier \( \mu_{d}^{\text{sup}} \) and \( \mu_{d}^{\text{dem}} \) are the same, regardless of the side to which the carbon price is added. In the same vein, the prices paid by the consumer \( \mu_{d}^{\text{sup}} \) and \( \mu_{d}^{\text{dem}} \) are the same on both sides. Therefore, the burdens shared by suppliers or consumers are equal for both methods, which is expressed as (31) and (32). Meanwhile, the value of the burdens is related to the elasticity of demand function \( \rho \) and the supply function \( \theta \).

\[
\Delta \mu_{s}^{\text{dem}} = \Delta \mu_{d}^{\text{sup}} = \left| -\theta \epsilon_{\text{emi}} / (\theta + \rho) \right| \tag{31}
\]

\[
\Delta \mu_{d}^{\text{dem}} = \Delta \mu_{d}^{\text{sup}} = \left| \rho \epsilon_{\text{emi}} / (\theta + \rho) \right| \tag{32}
\]

As a result, both suppliers and consumers share the burden of the carbon price if there is an additional emission cost, unless the demand or supply is entirely inelastic. Furthermore, regardless of which side the emission cost is added to, the burden values shared by suppliers or consumers, are the same when the carbon price is the same.

2.6 Detailed formulations of tax incidence models on demand side and supply side

The aim of this study is to analyze how different carbon pricing with varying methods of calculation affects the electricity market outcomes. Figure 1 presents the logical relationship among previous submodels. The top half of Figure 1 represents the model with a carbon tax, and the lower half shows the model without a carbon tax. Furthermore, the model with a carbon tax has three detailed methods to levy and calculate the tax.

First, the carbon price is increased on the demand side, where the carbon cost is calculated at the node for consumers according to the node emission intensity, which is driven by the CEF model based on the electricity balance. As a result, the unit cost of electricity including the carbon price at the demand side is \( \mu_{d}^{\text{dem}} \), as in (33), and the total electricity cost of a node is given by (34), where \( \mu_{d}^{\text{ele}} \) is the node price without carbon emission cost when the grid reaches equilibrium.

\[
\mu_{d}^{\text{ele}} \mu_{d}^{\text{dem}} = \mu_{d}^{\text{ele}} + \mu_{d}^{\text{emi}} \cdot \epsilon_{\text{emi}} \tag{33}
\]

\[
\epsilon_{\text{emi}} = \left( \mu_{d}^{\text{ele}} + \mu_{d}^{\text{emi}} \cdot \epsilon_{\text{emi}} \right) \cdot D^{\text{dem}} \tag{34}
\]

As the unit cost of electricity paid by consumers is increased, the new demand at node \( i \), \( D_{i}^{\text{new}} \), generally decreases, depending on the total demand function and the market equilibrium. Consequently, the new demand drives the new supply quantity and the new node price \( \mu_{d}^{\text{new}} \) by the optimal power flow (OPF) model to keep the grid balanced. As mentioned in the previous section, the new node price \( \mu_{d}^{\text{new}} \) is the price that suppliers received, and the unit cost of electricity \( \mu_{d}^{\text{new}} \) is the price that consumers paid.

Second, the carbon price could be levied at the supply side, where the total generation cost function of generators is increased with the emission cost, as in (35). As mentioned in the previous section, there are two different methods to calculate the emission cost at the supply side; one is the grandfathering method, and the other is the benchmarking method. Consequently, there are two different total generation cost functions.
to achieve the marginal cost function to determine the new node price. Detailed information about the two emission cost functions could be found in (9) and (10). Equation (36) shows the marginal cost function from the total generation cost function of the two methods.

\[
C_{ij}^{\text{em}} = C_{ij}^{\text{dil}} + C_{ij}^{\text{emi}}
\]

(35)

\[
\mu_{ij}^{\text{em}} = \frac{dC_{ij}^{\text{em}}}{dP_{ij}}
\]

(36)

With the applied OPF model with carbon cost and the statistical demand function, the new total generation cost function drives the node price and new equilibrium quantity. The new node price with carbon emission cost determines the new equilibrium quantity; therefore, the new node price is the price consumers paid \(\mu_{ij}^{\text{em}}\). After reaching the market equilibrium, the price suppliers received, \(\mu_{ij}^{\text{em}}\), is solved by the OPF model to maintain the electricity balance.

3 | CASE STUDY

The proposed model is verified on an Australian 59-bus system to quantify the impacts of rising carbon emission costs on the supply side and demand side. Five cases and four scenarios are applied to simulate the evaluations of the model.

3.1 | Australian 59-bus system and data

In order to study the impact of emission cost in the market, a 59-bus system is established to simulate the Austrian electricity market, as shown in Figure 2. This 59-bus system is divided into five areas with five different trading prices, and these areas simulate five states of Australia: Queensland (QLD), New South Wales (NSW), Australian Capital Territory (ACT), Victoria (VIC), and South Australia (SA).

The numbers in Figure 2 are node/bus numbers, and there are 59 nodes/buses. Meanwhile, some of the nodes only have loads or generators, and the others have both loads and generators. There are six categories of generation technology: black coal, brown coal, wind, solar, open cycle gas turbine (OGCT), combined cycle gas turbine (CCGT), and hydro power station. Furthermore, all consumers are assumed to be retailers, aggregators, or other large consumers/companies, who could purchase electricity directly in this 59-bus system.

Data of the OPF model and CEF model for this study are collected from the primary source, AEMO, including the AEMO map [23], planning and forecasting consultation, and electricity statement of opportunities.

3.2 | Cases and scenarios

There are four different stages to develop system planning, with each stage representing a 5-year interval during the period of 2020–2035. Some coal and gas power plants are retired in the first, second, and third stages, which are shown in Figure 2 as light blue, purple, and yellow rectangles, respectively. Additionally, some renewable power plants are planned to increase capacity, as shown by the triangle with different colors in different stages.

Moreover, the proposed model is verified in five cases to quantify the impacts and evaluation of raising the carbon emission cost based on this 59-bus system. The five cases are as follows:

Case 1: Reference case. This reference case is that of traditional power optimization without the demand function and carbon cost.

Case 2: Demand case. In this case, the traditional power optimization is implemented with the demand function. The carbon emission cost is not considered. Consequently, this case introduces the effect of demand function as a reference case to analyze the performance of carbon cost with the demand function.

Case 3: Demand carbon case. The carbon emission cost is directly added on the demand side, and the traditional power optimization for the electricity balance is applied after the market equilibrium.

Case 4: Supply carbon case with the benchmarking policy. In this case, the carbon cost is calculated following the benchmarking method, and this carbon price is added to the traditional power optimization. Afterward, the demand function model and another traditional OPF function are applied to maintain the market equilibrium and electricity balance.

Case 5: Supply carbon case with grandfathering. Most of the details of this case is the same as that of the supply carbon case, except for the method for calculating the carbon price.

4 | RESULT

Case 1 is the reference case, which is the traditional power optimization with four stages.

4.1 | Reference case

Data, establishing and testing the proposed model, are drawn from the AEMO database [23]. The bars in Figure 3 represent the installed capacity of various generator sets from 2020 to 2035, including black and brown coal-fired plants, gas-fired plants, hydro plants, centralized and rooftop solar plants, and wind plants. This planning of AEMO suggests that renewable energy will be significantly developed, and traditional thermal power will be gradually retired from 2020 to 2035, as shown Figure 2. Therefore, without any carbon cost as administrative penalties in the reference case, the system emission intensity decreases gradually as the percentage of renewable energy output increases. Moreover, the range of node price of this 59-node system is [29.78, 92.7]. Meanwhile, the orange line in Figure 3 shows the trend of the total demand for four stages.
4.2 Statistical demand function

Case 2 is used to analyze the performance of the demand function, which only considers the traditional power optimization and total demand function under the supply–demand equilibrium. The main parameters of the statistical demand function are randomly generated within a specific range. Meanwhile, different nodes have different demand preferences, and the same node has different demand preferences at different times. Therefore, the demand could not be cut or deferred when the electricity price is high. Similarly, the demand might be cut or suspended when the electricity price is relatively low. However, the relationship between demand and electricity price is in line with the law of demand in economics, which states demand is inversely proportional to the electricity price. Furthermore, the electrical demand is generally less elastic, which is one of the critical assumptions of the statistical demand elasticity model.

The results shown in Figure 4-1 indicate there is a difference between the two conditions, such that the total demand of the whole grid with the statistical demand function application is smoother than the reference case without the aggregate demand function. Moreover, after the demand function is applied in Case 2, the daily reduction of the whole grid is 1722.40 MWh,
4.3 Emission reduction

Figure 5 introduces the total emissions and emission reduction in five cases from Stage 1 to Stage 4. Detailed information of Cases 1–5 is mentioned in the last section. Meanwhile, Cases 1, 3_1, 4_1, and 5_1 are those without the demand function, and Cases 2, 3_2, 4_2, and 5_2 are those with the demand function applied.

First, the efficiency of political cases with the demand function is mostly higher than those without the demand function. The maximum difference in effect appears in Case 4; however, the difference is slight.

The control variant method is applied to ensure the validity of the data comparison. To compare the political reduction effect, government tax revenue is equal in all political cases (Cases 3–5) at each stage. As a result, political cases of the emission cost levied on suppliers achieve the maximum reduction of carbon emission in all stages, particularly for Case 4 with the benchmarking method. Moreover, the emission reduction illustrates that different policies and instruments have different effects at different stages of renewable development. Less emission reduction occurs at Stage 1 with lower development of renewable energy. On the contrary, with the rapid growth of solar and wind energy, the reduction efficiency of the policy increases from Stage 2 to 5, which is the light green line in Figure 5.

Based on Case 2, with the emission cost added to consumers, the contribution of the demand function to carbon emission is insignificant. The main reason for this is the low demand elasticity; in particular, demand could be compensated according to the fluctuations in electricity price. The influence of low demand elasticity on carbon costs will be discussed later.

Furthermore, the emission gradually declines without any political instruments from Stage 1 to Stage 4, such as in Case 1 in Figure 6, which is caused by an improvement of renewable energy. The emission intensity of the power system is presented in Figure 6, which shows that Case 4 achieves the lowest emission intensity at Stage 1, and Case 5 retains the minimum system emission elasticity from Stage 2 to Stage 4.

4.4 “Tax incidence”

When the carbon emission cost is levied on suppliers or consumers, the carbon cost incidence is determined by the elasticities of demand and supply. The less elastic, the more carbon cost is shared [11]. However, the elasticity of electricity demand and supply are difficult to calculate accurately. Therefore, the carbon cost incidence could be estimated in this case study and Figure 7 presents an overview of the burden of carbon cost between supply and demand.

The burden of carbon taxes on consumers and producers is relatively stable when the carbon cost is levied on the demand side, and there is little difference in the apportionment ratio. Data on Case 3_D indicates that the burden on consumers declines from 70% to 60% in four stages in Case 3, which means that consumers bear more carbon tax, while generators bear less. Therefore, the elasticity coefficient of the supply function is higher than the demand elasticity in Case 3. For Cases 4 and 5, the carbon cost is added on the supply side. In Cases 4 and 5 with demand function application (Cases 4_D and 5_D), consumers share more tax, which is consistent with the result of Case 3 that the supply function is more flexible. Specifically, the incidence of consumers is greatest with the benchmarking method on the supply side, at more than 90%.

According to welfare economics, consumer surplus and producer surplus measures social welfare. Furthermore, social welfare could also be considered in terms of the externalities when analyzing the impact of the carbon tax [11]. Case 5 has the best effect of reducing emissions, followed by Cases 4 and 3, as shown in Figure 6. However, the social welfare loss in Case 5 (AU$834,251) is the highest, and it is the lowest in Case 4 (AU$519,404). Therefore, the benchmarking method is more effective in reducing carbon emissions with a minimal loss of social welfare.
Network stability

Figure 8 shows the fluctuation in the highest and lowest electricity prices. The electricity prices in Case 4 are less volatile than those in Cases 3 and 5 when compared with Case 1. Meanwhile, most of the highest node prices in Cases 3 and 5 are relatively high, followed by Case 4. The reason for this is that the node price includes the emission cost in Cases 3–5.

Table 1 shows a comprehensive comparison of the results of the case study, which indicates that the benchmarking method is more suitable for the Australian market, as it leads to high emission reduction, medium emission intensity, low welfare loss, and low price fluctuation.
CONCLUSION

A model combining the power flow, carbon emission flow, and a statistical demand function model was proposed to analyze the carbon tax incidence in a transmission network. Three political instruments were evaluated for AEMO, including carbon tax levied on consumers, as well as a benchmarking method and grandfathering method on suppliers. Based on the data from AEMO, we can conclude that the demand function has a weak effect on carbon reduction because of the low demand elasticity. Furthermore, consumers bear slightly more carbon tax than suppliers when the carbon cost is directly levied on consumers. In contrast, when the carbon tax is added on the supply side, suppliers bear more carbon tax than generators. Overall, applying the benchmarking method is more suitable for the Australian market, with its high emission reduction, medium emission intensity, low welfare loss, and low price fluctuation. This study can be a valuable guide for governments to establish emission-related energy policies toward a low-carbon economy.

In this work, to compare different cases, government tax revenue is considered as equal for the three political cases. In the future, the fluctuation of the carbon price and a new demand function driven by a machine learning method will be modeled and evaluated.

NOMENCLATURE

Parameters and variables

- $C$: cost functions
- $C^{inv}$: investment costs of power plants
- $CRF$: capital recovery factor
- $D$: electricity demand function
- $\bar{D}$: aggregated demand function of the system
- $\bar{e}$: average emission intensity of generators, nodes, and lines
- $\bar{\bar{e}}$: average emission intensity of the system
- $\bar{\bar{\bar{e}}}$: average emission intensity of each generation technology, such as thermal, wind, and solar
- $f$: power flow
- $F()$: functions
- $\bar{P}$: generation output of generator technology, such as thermal, wind, and solar
- $Q$: quota of a generator for each time interval
- $r$: interest rate of investment cost
- $u$: marginal utility function
- $w$: marginal welfare function
- $\alpha$: initial request time of task $m$
- $\gamma$: tolerable delay
- $\delta$: utility decay rate
- $\theta, \bar{\theta}$: parameters of supply function
- $\mu$: price
- $\rho, k$: parameters of a demand function
- $\omega$: initial marginal utility

Superscripts

- $\text{dem}$: demand
- $ee, \text{total}$: electricity generation and carbon emission
- $ele$: electricity generation
- $emi$: carbon emission
- $eq$: market equilibrium
- $\text{free}$: free carbon allocation of allowances
- $\text{line}$: lines
- $m$: user’s tasks
- $\text{max, min}$: maximum and minimum boundaries
- $\text{node}$: nodes
- $\text{sup}$: supply
- $\text{sys}$: system

Subscripts

- $d$: consumers
- $g$: generators
- $i, j$: nodes
- $l$: transmission lines
- $s$: suppliers
- $t$: time

Sets

- $\Omega^G$: all generators
- $\Omega^I$: all nodes
- $\Omega^L$: all transmission lines
- $\Omega^M$: all individual tasks
- $\Omega^T$: all time intervals
REFERENCES

1. Climate Change. https://www.un.org/en/sections/issues-depth/climate-change/ (2020). Accessed 1 Feb 2020.
2. Xenophon AK, Hill DJ. Emissions reduction and wholesale electricity price targeting using an output-based mechanism. Appl Energy. 2019;242:1050-63.
3. Large-scale generation certificates. http://www.cleanenergyregulator.gov.au/RET/Scheme-participants-and-industry/Powertations/Large-scale-generation-certificates (2020). Accessed 1 Feb 2020.
4. Fischer C, Fox AK. Combining rebates with carbon taxes: optimal strategies for coping with emissions leakage and tax interactions. Discussion Papers. 2009.
5. Zhang X, Wang Y. How to reduce household carbon emissions: a review of experience and policy design considerations. Energy Policy. 2017;102:116-24.
6. Green F, Denniss R. Cutting with both arms of the scissors: the economic and political case for restrictive supply-side climate policies. Clim Change. 2018;150(1–2):73-87.
7. Barragán-Beaud C, Pizarro-Alonso A, Xylia M, et al. Carbon tax or emissions trading? An analysis of economic and political feasibility of policy mechanisms for greenhouse gas emissions reduction in the Mexican power sector. Energy Policy. 2018;122:287-99.
8. Ben H, Zhou W, Nakagami K, et al. Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects. Appl Energy. 2010;87(12):3642-51.
9. Cheng Y, Zhang N, Zhang B, et al. Low-carbon operation of multiple energy systems based on energy-carbon integrated prices. IEEE Trans Smart Grid. 2020;11(2):1307-18.
10. Yao F, Dong ZY, Meng K, et al. Quantum-inspired particle swarm optimization for power system operations considering wind power uncertainty and carbon tax in Australia. IEEE Trans Ind Inf. 2012;8(4):880-88.
11. Mankiw NG. Principles of microeconomics. 5th ed. Boston, MA: South-Western Cengage Learning; 2009.
12. Kirschen D, Srbac G. Fundamentals of power system economics: Kirschen/power system economics. New York: John Wiley & Sons, Inc.; 2004.
13. Saelim S. Carbon tax incidence on household demand: effects on welfare, income inequality and poverty incidence in Thailand. J Cleaner Prod. 2019;234:521-33.
14. Buttraw D, Wiserman M, Paul A. Retail electricity price savings from compliance flexibility in GHG standards for stationary sources. Energy Policy. 2012;42:67-77.
15. Duarte R, Sánchez-Cholín J, Sarasa C. Consumer-side actions in a low-carbon economy: a dynamic CGE analysis for Spain. Energy Policy. 2018;118:199.
16. Cullenward D, Willkerson JT, Wara M, et al. Dynamically estimating the distributional impacts of U.S. climate policy with NEMS: a case study of the Climate Protection Act of 2013. Energy Economics. 2016;55:303-18.
17. Bai L, Shi X, Gao H, et al. Supply chain emission reduction optimization under consumer carbon sensitivity and carbon tax policy. Environ Eng Manag J. 2018;17(7):1645-56.
18. Kirschen D, Srbac G, Cumperayot P, et al. Factoring the elasticity of demand in electricity prices. IEEE Trans Power Syst. 2006;15(2):612-17.
19. Yu R, Yang W, Rahardja S. A statistical demand-price model with its application in optimal real-time price. IEEE Trans Smart Grid. 2012;3(4):1734-42.
20. Nordhaus WD. The climate casino: risk, uncertainty, and economics for a warming world. New Haven, CT: Yale University Press; 2013.
21. International Carbon Action Partnership (ICAP). https://icapcarbonaction.com (2019). Accessed Dec 1 2019.
22. Branger F, Sato M. Solving the clinker dilemma with hybrid output-based allocation. Clim Change. 2017;140:1435-45.
23. AEMO Map. https://www.aemo.com.au/aemo/apps/visualisations/map.html (2020). Accessed Jan 1 2020.

How to cite this article: Han X, Qiu J, Sun L, Shen W, Ma Y, Yuan D. Low-carbon energy policy analysis based on power energy system modeling. Energy Convers. Econ. 2020;1:34–44. https://doi.org/10.1049/enc2.12005