Impact of the NZ ETS, carbon taxation and energy efficiency on New Zealand's carbon emissions: A dynamic CGE analysis

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Abstract

Given the concern of New Zealand's transition to the low-carbon economy, this dissertation will study New Zealand's emission trading scheme (NZ ETS) with forestry sequestration and carbon tax and technology progress on largest agricultural emissions, energy efficiency improvement in energy sectors, and political background. Meanwhile, this research will clarify the gains and loss of New Zealand's economy, energy and environment systems due to emission-reduction policies by an integrated analysis through the dynamic Computable General Equilibrium (CGE) Analysis.

First, in this study, the dynamic CGE model is used to capture the dynamic impact of the forestry carbon sequestration on endogenous carbon price, given emission caps, free allocation, and emissions coverage. Meanwhile, the essential factors are involved in the NZ ETS, such as carbon cap and free allocation, to simulate the impact of an external reduction target on carbon prices, land-use change, and macroeconomic variables. The results show that, to achieve New Zealand's carbon emissions targets in 2050, the carbon price ranges from NZ$136.37 per ton to NZ$325.74 per ton.

Second, it is challenging to implement policies to reduce emissions without damaging the interests of the agricultural sector. In this study, I use the dynamic recursive land-based CGE model to analyse the impact of agricultural carbon tax and technology progress combined on agriculture emissions. This enables us to explore the differential impacts of technological progress, given an emissions tax, on the economy and agricultural GHG emissions reduction. A carbon tax, in the absence of technological progress, lowers GDP but does not cause substantial reduction in CO_2-e emissions. Land-augmenting progress outperforms labour and capital augmenting technological progress.

Third, in this dissertation, a recursive dynamic CGE model is used to estimate the impact of New Zealand's energy efficiency policy as an exogenous factor on energy use and carbon emissions because of rebound effect. The effectiveness of energy efficiency improvement is also evaluated in terms of its impact on CO_2-e emissions and macro economy variables. Results show the economy-wide rebound effects brought by

four energy types (coal, oil gas and electricity) are all much greater than 100%, which increase the final demand for energy consumption. However, 5% electricity efficiency improved has the most significant positive impact on reducing energy use and CO_2-e emissions on the production side and contributes to 0.3% growth in GDP.

To:

My dearest parents and brothers

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Chapter 1 Introduction

1.1 Motivation

Global warming caused by human activities is 1°C higher than pre-industrial levels and continues to impact the environment (Masson-Delmotte et al., 2018). Climate change has a large-scale, comprehensive, and multi-level impact, on nature, ecology and the environment, and even the survival and development of human society (Pecl et al., 2017). There is a growing international consensus on the need to reduce global carbon emissions (George et al., 2019). According to the Paris Agreement, the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are determined to control the increase of the global average temperature less than 2°C above that of the pre-industrial level (Schleussner et al., 2016). The New Zealand Parliament recently passed the Climate Change Response (Zero Carbon) Amendment Act, which formalizes its intention to have net zero emissions for all greenhouse gases except for biogenic methane by 2050 (MfE, 2019a).

Transitioning to a low-carbon economy is a challenge for New Zealand. First, the NZ ETS is the principal emission reduction mechanism, which commenced operation in January 2008 as a policy tool to combat climate change. The only allowed emissions unit is the New Zealand Unit (NZU), which equals one metric ton of CO_2, or CO_2-equivalent of any other greenhouse gas. New Zealand was the first country to include forestry sequestration into an ETS and encourage forestry owners to plant trees to get NZUs (Manley & Maclaren, 2012). Emission reductions linked with forestry carbon sequestration are eligible for producing carbon credits which are available for purchase on the ETS market, allowing carbon emitters to offset their emissions (van Kooten, 2017). The ETS price applies as a cost on pre-1990 deforestation and a credit for post-1989 afforestation. Any eligible emissions unit in the NZ ETS can meet deforestation and harvest liabilities. Carbon sequestered by post-1989 forests has consistently earned NZUs (Carver, Dawson, & Kerr, 2017). However, modifications to design of the carbon market mechanism have resulted in price volatility which, in turn, creates uncertainty over returns to investment in forestry carbon sequestration. An analytical model that includes forestry sequestration, with an endogenous ETS price, provides greater insights into the potential impacts on the economy. The thesis uses a dynamic CGE model that includes both forestry sequestration and an ETS.

Second, New Zealand is a unique developed country where agricultural GHG emissions play a crucial role in the national emissions profile (Clark, Kelliher, & Pinares-Patino, 2011). In 2019, New Zealand's agriculture emitted 39.6 Mt CO_2-e emissions, the largest emission source and 48% of New Zealand's total emissions (MfE, 2020a). Agricultural CO_2-e emissions reductions will make a massive contribution to climate change. Considering that carbon price will increase the cost of agricultural products, weaken New Zealand's agricultural international competitiveness, agriculture is the last sector to be included in the NZ ETS. It is estimated that bio-agricultural emissions will be priced from 2025 (Leining, Kerr, & Bruce-Brand, 2020). As to the other carbon pricing tool, the carbon tax is different from caron ETS in terms of operation mechanism (Goulder & Schein, 2013). Carbon tax or subsidies come in the form of an exemption: a lower tax rate or rebates. While, the ETS takes the form of free allowances or rebates (Haites, 2018). Carbon tax has the advantage of keeping a stable price and not impairing other effects of carbon control instruments (Pezzey & Jotzo, 2013). However, carbon tax is not a panacea that makes everything painless. The uncertainty of its environmental benefit, cost-effectiveness and possible distributional inequity reduces its popularity among the policymakers. Therefore, it is challenging to implement an appropriate scheme of the carbon tax and other supporting instrument, which can alleviate negative effects and strengthen positive effects on emissions reduction in agricultural sectors.

Technological progress is considered an alternative approach to alleviate the shortages or controversies surrounding the carbon tax. According to Solow's economic growth model, technological progress here refers to the theory of marginal productivity or factor-augmenting technology progress. One input factor is more conducive to improving the marginal output than the others (Hicks, 1963). Studies pointed out that labour-augmenting technical progress, and capital-augmenting technical progress, are manifested by changes in the efficiency of production factors (Acemoglu, 2002, 2003, 2007) and technological progress has different growth patterns (Geylani & Stefanou, 2011; Oh, Heshmati, & Lööf, 2012). Based on the aforementioned studies, few has estimated the combined effects of carbon tax and augmenting-technological progress on agricultural emissions reduction and macroeconomy. In chapter 3, it adopted the dynamic CGE model to simulate carbon tax and factor-augmenting technological progress. One thing needs to clarify here, technological progress simulated refers to factor-saving productivity not the specific technological practices used (such as methane inhibitors or methane vaccines) in the agricultural emissions reduction.

New Zealand is the only country with an “Energy Efficiency and Conservation Act” (Verma, Patel, Nair, & Brent, 2018) with energy policy linked to emissions reduction targets. New Zealand’s total energy consumption was 596 Petajoules, of which the consumption of fossil energy (including oil, gas and coal) accounted for 65%, and the consumption of electricity accounted for 24% in 2017 and energy intensity has improved at an average annual rate of 1.4% since 1990 (IEA, 2018). It is a challenge for New Zealand to transit to a low-caron economy. The Energy Efficiency and Energy Conservation Authority (EECA) is responsible for the implementation of a carbon reduction plan that is aimed at achieving improvements in efficiency and reductions in emissions at least cost (EECA, 2018). However, energy savings brought by increased energy efficiency can be offset by increased energy demand, which is the so-called “rebound effect” (Bentzen, 2004). The existence of the rebound effect may undermine the effects of energy efficiency improvements and be a major barrier to fully realizing the potential for energy conservation and emissions reduction. Furtherly, the rebound effect may adversely impact the government target of developing an affordable, resilient and sustainable economy system.

Many scholars in different countries estimated the rebound effect caused by energy-efficiency improvements from costless exogenous energy efficiency improvement in different industries. For example, Du et al. (2019) studied the rebound effect of different energy sources used in the construction industry in China based on a static computable general equilibrium (CGE) model. Their results show that natural gas efficiency improvement resulted in the largest rebound effect of 99.20%. The lowest rebound was associated with improvements in electricity efficiency, with an average of 83.47%. Du, Chen, Zhang, and Southworth (2020) focused on the transportation sector in China using a CGE model to examine the rebound effect from an improvement of 10% in energy efficiency. Lecca, McGregor, Swales, and Turner (2014) estimated changes in the energy efficiency of the household sector, adopting a CGE model for the UK. The CGE model has been broadly adopted to analyze the macro-level rebound effect and to better capture the multi-sectoral nature of the rebound effect (Koesler, Swales, & Turner, 2016; Lu, Liu, & Zhou, 2017). To date, few studies have estimated the rebound effect associated with improvements in New Zealand's energy efficiency as an exogenous factor influencing both energy use and carbon emissions using a recursive dynamic CGE model.

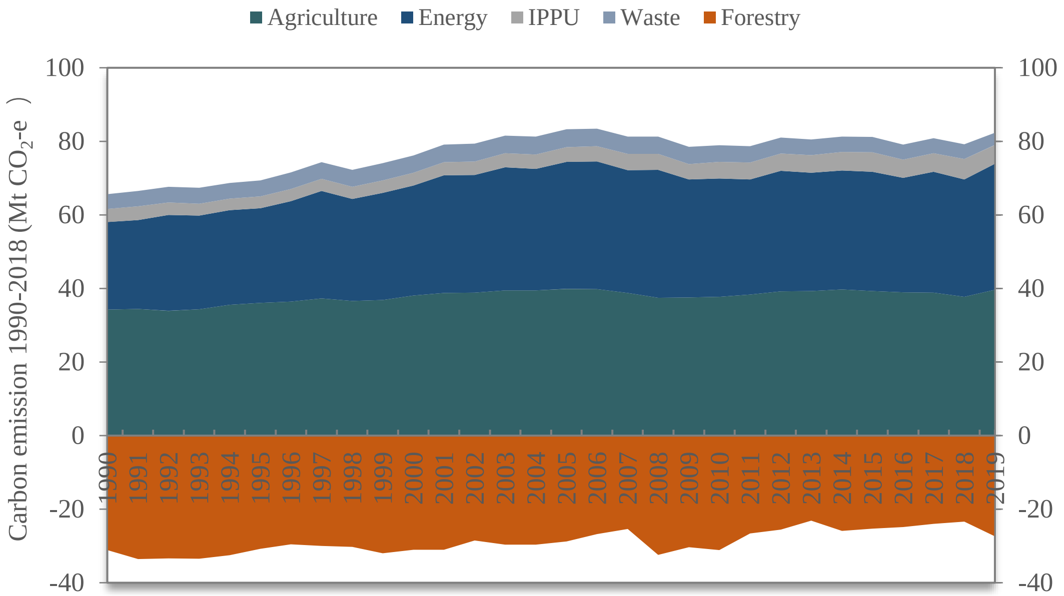


Figure 1 Emission profiles from 1990 to 2019 in New Zealand

Against this background, the focus of this dissertation is on the impacts of the NZ ETS, carbon taxation and augmenting technological progress, and energy efficiency on emissions reduction and transitioning to a low-carbon economy. Given the concern of carbon emission cost and benefits, this research will study their effects on emission reductions and the macroeconomy. It will also clarify the gains and losses associated with the transition to a low-carbon economy.

1.2 Research background

1.2.1 NZ ETS and forestry sequestration

Carbon emissions can be priced by either of two tools-an ETS or a carbon tax (Haites, 2018). ETS is a cost-effective instrument to counteract climate change and has been implemented across many countries. According to ICAP (2017), emissions trading scheme around the world raised nearly US$30 billion dollars of public revenue by auctioning a certain percentage of carbon permits. The 21st Paris Climate Conference agreed that economic tools must play a crucial role to ensure cost-effective climate policy. However, the setting and implementation of an ETS need to be consistent with their national climate goals and efforts (Fan, Jia, Wang, & Xu, 2017). According to the Paris Agreement, New Zealand has committed to reducing emissions to 30% below 2005 levels by 2030. In 2019, the Zero Carbon Bill was passed to formalize a target of net zero emissions for all greenhouse gases except for biogenic methane by 2050 (Ministry for the Environment, 2019).

As a main tool for combating climate change, the NZ ETS was been introduced by New Zealand government to meet emission reduction targets since January 2008, which incorporates forestry sequestration, in terms of coverage, it is more comprehensive than any other country's ETS (Adams & Turner, 2012). The only legal emissions unit in NZ ETS is the New Zealand Unit (NZU). The NZ ETS prices carbon emissions and encourages forest planting by allowing eligible foresters to earn NZUs as their trees grow and absorb CO_2-e emissions (MfE,2017). Post-1989 forest landowners receive NZUs for carbon sequestration. Carbon credits add to forest owners' profit up to the time the trees are harvested; at which point forest owners are liable for the carbon sequestered. Forest owners can use carbon credits to offset other emission activities, to reduce their emissions liability from other activities (NZ Forestry, 2020). Up to the point of harvest, forest owners benefit from selling NZUs derived from carbon sequestration which contributes to reducing production costs. Hence, after the implementation of New Zealand's carbon trading mechanism, the valuation of post-1989 forest has dramatically increased, and the rotation time as well.

How does forestry carbon storage affect carbon prices and economic development? Little research has focused on the influence of forestry carbon sequestration on the carbon prices, land use and land-use change, CO_2-e emissions, and the whole economy.

Most studies have been conducted from a certain micro perspective. For example, Tee, Scarpa, Marsh, and Guthrie (2014) used binomial tree models with random prices (one is carbon price and the other is wood price) to predict the impact of carbon price on New Zealand's forestry. They found that when the carbon price is NZ $10, the forest rotation time is increased from 25 to 27 years. When the carbon price is NZ $ 20, the tree rotation time is 33 years. Although forest growers care about the best time to plant trees, they also realize that it might be beneficial to harvest timber at a steady annual rate (Conrad, 1999).

Including timber growth in the NZ ETS has been controversial. Up to now, there has been disagreement on the impacts of carbon price on forestation sequestration, agriculture, and trade-exposed sectors. Adams and Turner (2012) simulated the profitability of forestry and agricultural land use under different scenarios with a carbon price of $20, $50 and $0 per ton. Their profit maximisation model showed that an ETS contributes to afforestation and increasing rotation age, boosting carbon sequestration, especially with a $20 carbon price or higher. However, there is an opposite conclusion that the NZ ETS is not the correct policy to increase carbon sequestration by planted forests (Evison, 2017). Lennox and van Nieuwkoop (2009) took international carbon emissions prices as exogenous variables through CGE model, simulating different ETS coverage of sectors and greenhouse gases. They found that effective abatement of greenhouse gas emissions is accompanied by GDP loss, but it does not weaken overall consumption, assuming permit auctioning revenues are used rationally. Although, a handful of issues have been addressed by previous studies, such as the economic impact of the NZ ETS in terms of reduced GDP and the carbon cost. These studies do not take the dynamics of timber growth into account. Nor do they systematically analyze the carbon prices to meet the net-zero emissions target with minimal economic cost.

Effectiveness of the NZ ETS has been challenged since the carbon price collapsed in 2011 and bottomed out till mid-2013 (Diaz-Rainey & Tulloch, 2018). In 2020, a floor price of NZ$20 was set (MfE, 2020b). According to the Productivity Commission, only by raising carbon price from NZ$21 per ton to between NZ$75 and NZ$152 will New Zealand be able to transition to a low-carbon economy by 2050. Furthermore, to achieve net-zero emissions, the price of carbon needs to increase from NZ$200 to NZ$250 per ton. In an equilibrium state, the price of CO_2-e emissions should equal to the cost of emission reduction (Li & Jia, 2016). In NZ ETS, NZUs gained from tree planting can directly affect the relationship between the supply and demand in the carbon trading market. The trading price of NZUs and the incentives it creates to reduce emissions is a crucial factor to examine whether the NZ ETS is working as intended.

Figure 2 New Zealand Unit Prices 2010-2021

Source: https://en.wikipedia.org/wiki/New_Zealand_Emissions_Trading_Scheme

Therefore, Chapter 2 uses a dynamic CGE model to capture the possible impact of external emission reduction caps on economic activity when forestry carbon sequestration is included. Endogenous carbon prices are figured out in equilibrium taking into account carbon sequestration, emission caps, as well as free allocation.

1.2.2 Carbon tax and agricultural technological progress

The idea of imposing a tax on externalities was proposed by Pigou (1924). He proposed setting the tax equal to the marginal damages associated with externality. By making polluters pay for the price, the externality is effectively internalized. Unlike ETS, the carbon tax has the advantage of creating a stable price, while not undermining other carbon control efforts even when carbon pricing is impossible or ineffective (Pezzey & Jotzo, 2013). What is more, when there is large uncertainty about the costs of damages, then carbon taxes could be significantly less costly than cap-and-trade systems (Aldy, Ley, & Parry, 2008).

Some studies have evaluated the implications of the carbon tax on the New Zealand's economy. Hasan, Frame, Chapman, and Archie (2020) found that imposing a higher carbon price of NZ$235/ton CO_2 on New Zealand's transportation sector could reduce transportation emissions by 44% in 2030 from 2016 levels and increase the annual domestic transportation expenditure of low-income households by 42%. Some policy analysts prefer a carbon tax over an ETS because carbon tax revenues can be used to offset household tax burdens and provide funds for emission-reduction technologies and infrastructure. However, emission permit auctions can also generate revenue for government as can royalties applied to the prevailing market price. Gangadharan and Saadeh (2018) collected quantitative data from 15 New Zealand companies by a closed questionnaire. They found that most companies are willing to bear the additional cost of carbon taxes based on their emissions. Lennox and van Nieuwkoop (2009) pointed out that carbon price should be adjusted to avoid high economic or social costs of the export-oriented company, especially in the agricultural sector. Leining et al. (2020) estimated that agricultural bio-emissions would be priced from 2025. As one of the carbon pricing instruments, carbon tax is quicker and cheaper to administer than emission trading scheme (OECD, 2013).

However, determining the emission reduction tasks in the land sector and designing a pricing system for agricultural emissions will face substantial technical and political challenges in New Zealand (Leining et al., 2020). New Zealand's unique emissions profile-the importance of agricultural emissions-is a challenge for climate policy (Boston, 2008). In 2018, New Zealand agriculture emitted 37.7 Mt CO_2-e emissions, which is the largest emission source and accounts for 48% of New Zealand's total emissions (MfE, 2019). According to the Climate Change Commission's requirements, the agricultural sector needs to reduce biomethane emissions by 10% by 2030 compared to emission levels in 2017, and 24%-47% by 2050.

Successive New Zealand governments have grappled with the challenge of pricing emissions from agriculture. According to the 2008 Act, free quotas were allowed to allocate to eligible agricultural sectors based on 90% of the 2005 emissions and gradually reduced by 2029 (Parliament, 2008). This gradually process can be divided into three stages. First, the agricultural sector was not required to report on their emissions, purchase and surrender emissions units to the government and the time for the agricultural sector to join ETS has been postponed from 2009 to 2013. Second, during the transition period from 2015 to 2018, agriculture can enjoy a free emission allowance of 33.7 Mt CO_2-e, which is 90% of the emissions level in 2005. Third, from 2019, the free emission allowance will be not phased out until 2030 (Moyes, 2008). The aim of government is to protect the competitiveness of emissions-intensive, trade-exposed industries. The evolution of New Zealand's climate change policy highlights the difficulties of a unique emissions profile and vital political interests, particularly the influence of a robust agriculture sector (Bullock, 2012).

Uncertainty over the impacts of agricultural carbon pricing (in terms of carbon tax) on the environment, economy and its possible distributional inequity reduce its popularity among the policymakers. Ntombela, Bohlmann, and Kalaba (2019) used a dynamic CGE model to assess the potential impact of carbon tax policies on agriculture, food and other sectors in South Africa. Their results show that although a carbon tax is a useful policy tool to reduce emissions, it also resulted in a welfare loss of US$5.9 billion. Meng (2015) simulated the impact of different carbon tax policy scenarios by using a CGE model and found that all agricultural sectors were negatively affected. He also pointed that incorporating the agricultural industry into the carbon-tax plan resulted in emission reductions but also led to a decline in the output, employment and profitability of the agricultural sector, and a substantial decline in real GDP. This instrument could be even more cost-effective if its implementation is improved or combined with other instruments, such as encouraging technological progress. There is a need to more thoroughly examine carbon taxation by considering broader issues such as the dynamics of technological change.

When analyzing the effects of a carbon tax on agriculture emissions, technological progress should be investigated. According to Acemoglu (2007), technological progress is divided into neutral technological progress, labour-augmenting technical progress, and capital-augmenting technical progress from the perspective of output contribution, and augmenting technological progress is manifested by changes in the efficiency of production factors. Wollenberg et al. (2016) pointed out that agricultural GHG emissions reduction requires more transformative technologies and policy options to reduce non-CO_2 emissions. However, Shahbaz, et al. (2016) found that technological development leads to economic growth and eventually boosts carbon emissions. Amri, Zaied, and Lahouel (2019) claimed that whether technological progress effectively helps carbon reduction is still controversial.

At present, research on agricultural GHG emission reduction in New Zealand focuses on how to reduce emissions through animal, feed, soil and management interventions (Beauchemin, Kreuzer, O'mara, & McAllister, 2008; De Klein & Eckard, 2008; Kirschbaum et al., 2015; McNally et al., 2017). Few studies focus on the land-augmenting technical progress and the impact of the agricultural carbon tax on the entire economic system. Chapter 3 analyses the combined impacts of agricultural carbon tax policy and agricultural technological on the economy and land use. A land-based New Zealand dynamic CGE model is used to comprehensively consider the impact of agricultural carbon tax on the competitiveness of agriculture, GDP growth, agricultural output, domestic prices, and trade. Besides, in this chapter, it also analyses the effect of technological advancement in agriculture sector.

1.2.3 Energy efficiency and rebound effect

In 2018, New Zealand's total energy consumption was 589 Petajoules, of which the consumption of fossil energy (including oil, gas and coal) accounted for 65%.

According to the IEA (2018), New Zealand's energy intensity has improved at an average annual rate of 1.4% since 1990, which means that the energy consumption needed to produce one unit of GDP is growing at an average of 1.4% annually. New Zealand's energy intensity remains high. It is the 6th highest in the OECD and 18 per cent above the average.

New Zealand energy-related emissions have increased over the last few decades from 23.8 Mt CO_2-e in 1990 to 32.1 Mt CO_2-e in 2018, representing 41 per cent of New Zealand's gross emissions. Generally, pricing carbon will eventually increase the cost of using fossil fuels. In consequence, there would be a shift in demand from carbon-intensive fuels to "clean energy" or technology progress.

Improving energy efficiency is seen as an affordable and sustainable energy policy and an important step towards a low-carbon economy. This is consistent with the government's prospective target to develop an affordable, resilient, and sustainable energy system. New Zealand is the only country with an "Energy Efficiency and Conservation Act" (Verma et al., 2018), and its energy policy is linked to emissions reduction targets. EECA is responsible for the implementation of a carbon reduction plan, aimed at achieving improvements in efficiency and reductions in emissions at least cost (EECA, 2018).

However, energy savings brought by increased energy efficiency can be offset by increased energy demand. This is the so-called "rebound effect" (Bentzen, 2004) that comprises direct, indirect, and economy-wide effects. The direct rebound effect is the result of the substitution of energy for other factors of production leading to increased demand for specific energy services. The indirect rebound effect is associated with the income effect when lower energy costs, due to increased efficiency, increase household consumption of other goods and services. The economy-wide rebound effect arises from the economy-wide increased use of resources. In particular, if energy efficiency is improved, production in the economy can expand and economic growth increase (Bentzen, 2004; Greening, Greene, & Difiglio, 2000; Steve Sorrell, 2007). Estimates of price elasticity and cross-price elasticity of demand provide insights into the first two effects. However, estimating the economy-wide rebound effect requires a macroeconomic approach that includes resource prices changes and how these changes affect energy demand (Matos & Silva, 2011).

There are few studies of the rebound effect associated with improvements in New Zealand's energy efficiency and energy-related emissions. Most of New Zealand's research studies a specific energy sector, lacking a systematic analysis of carbon emissions reductions related to overall energy use, nor does it study the rebound effect from the national macroeconomic level. Jones (2015) studied New Zealand's light transport fleets (private passenger cars) and claimed that improving their energy efficiency can reduce carbon dioxide emissions. However, it mainly investigated whether New Zealand had formulated a framework for introducing energy efficiency laws and regulations from a legal perspective. Atkins, Morrison, and Walmsley (2010) introduced the expansion of Carbon Emissions Pinch Analysis (CEPA), which took into account the close relationship between the increase in demand in New Zealand's electricity industry and carbon emissions. It also illustrated some of the issues in achieving meaningful emission reductions, but there was no mention of energy efficiency improvement in electricity. Although Scrimgeour, Oxley, and Fatai (2005) utilized a New Zealand CGE model, their model only emphasized the relationship between environmental taxes and other related taxes. It was specially designed for the energy sector and imposed energy and carbon taxes on all fossil fuels. This article did not mention the energy structure changes by different taxes, which has a significant impact on emission reduction, let alone energy efficiency improvement and rebound effect.

1.3 Research questions

This dissertation proposes three research questions and aims to examine whether three different emission-reduction tools can achieve New Zealand government's target to transition to the low-carbon economy.

Research question one: what is NZ ETS endogenous carbon price in the context of different emission-reduction targets and dynamic forestry sequestration? New Zealand's two largest greenhouse gas emissions sources are agriculture and energy, which account for almost 90% of New Zealand's total emissions. Agricultural greenhouse gas emissions occupy a critical position in New Zealand's CO_2-e emissions, which account for 48% of total carbon emissions in 2018 (MfE, 2019a). However, including the agriculture sector in the ETS has been postponed (Leining, Allan, & Kerr, 2017). The agricultural sector is exempt from participating in the NZ ETS and do not need to report their emissions, purchase and surrender emissions units to the Government to cover their emissions. However, it does not mean that the Government will always exclude the agricultural sector from NZ ETS. Once the agricultural sector is included in ETS, the carbon price will impact land use and the development of agricultural industries. The NZ ETS encourages forest planting by allowing eligible landowners to gain NZUs as the trees grow and absorb CO_2-e emissions. Under these circumstances, timber growth and forestry carbon sequestration are included into the model. Therefore, Chapter 2 examines the impact of dynamic changes in forest net carbon stock on carbon prices in the carbon trading market, which includes agriculture sectors. The CGE model is considered a valuable tool to capture the potential impact of pricing carbon on complex economic activities (Liu, Tan, Yu, & Qi, 2017). In Chapter 2, the challenge is to incorporate and estimate the forest carbon sequestration into the mechanism so as to meet emission reduction targets in different phases.

Research question two: what is the impact of agricultural carbon tax and agricultural factor-augmenting technology progress on the transition to the low-carbon economy? Emission credits from the NZ ETS encourage forest owners to increase the area of forest plantation. An endogenous carbon price comes about through the interaction between demand and supply (Sorrell & Sijm, 2003). However, pricing agricultural emissions will increase the cost of agricultural production and weaken New Zealand's agricultural international competitiveness. For example, Frank et al. (2017) found that including agriculture in the NZ ETS will increase the price of agricultural products in deprived areas. Since the carbon tax may harm economic growth, technological progress provides an opportunity to offset the harmful effects. After all, reducing biogenic methane emissions from livestock has proved to be a major scientific challenge to which there are currently no solutions other than reducing livestock numbers (Carroll & Daigneault, 2019).

Therefore, this part of the thesis focuses on factor-augmenting technical progress and the impact of agricultural carbon tax on the entire economic system. A land-based New Zealand dynamic CGE model is used to comprehensively consider the combined impact of agricultural carbon tax and technological progress on the competitiveness of agriculture, GDP growth, agricultural output, and international trade. This chapter also analyses the effect of technological advancement of agriculture sector on emissions and economy.

Research question three: what is the rebound effect derived from the energy efficiency improvement? Transitioning to a low-carbon economy is a challenge for New Zealand. In 2017, New Zealand's total energy consumption was 596 Petajoules, of which the consumption of fossil energy (including oil, gas and coal) accounted for 65%, and the consumption of electricity accounted for 24%. According to the IEA (2018), New Zealand's energy intensity has improved at an average annual rate of 1.4% since 1990. The Energy Efficiency and Energy Conservation Authority is responsible for the implementation of a carbon reduction plan, aimed at achieving improvements in efficiency and reductions in emissions at least cost (EECA, 2018). Improving energy efficiency is seen as an affordable and sustainable energy policy and an essential step towards a low-carbon economy, consistent with the government's planned target to develop an affordable, resilient and sustainable energy system. However, energy savings brought by improved energy efficiency can be counteracted by increased energy demand. This is the so-called "rebound effect" (Bentzen, 2004). That means, producers tend to use more energy instead of other inputs, and consumers tend to consume more energy products and services, resulting in part of the energy savings generated by energy efficiency improvements counterbalanced by additional energy consumption (Ang, Mu, & Zhou, 2010; Belaïd, Bakaloglou, & Roubaud, 2018; Brännlund, Ghalwash, & Nordström, 2007). In Chapter 4, the recursive dynamic CGE model is used to estimate the impact of New Zealand's energy efficiency policy as an exogenous factor on energy use and carbon emissions because of rebound effect. The dynamic mechanism is based on dynamic changes of labor growth and capital accumulation.

Estimates of changes in energy consumption and the rebound effect derive from the rate of improvement in energy efficiency. The effectiveness of energy efficiency improvement is also evaluated in terms of its impact on CO_2-e emissions and macroeconomic variables.

All in all, these three research questions rely on the use of a dynamic CGE model, which will be introduced in section below.

1.4 Methodology

The computable general equilibrium (CGE) model is a policy simulation tool used in the macroeconomic field. According to Johansen (1960), a CGE model can be used to examine the impact of changes in prices, quantities, and market supply and demand of all commodities and factors in the entire economic system caused by changes in exogenous variables. This enables the analyst to investigate the transition from one equilibrium state to another equilibrium state caused by exogenous policy shocks. Thus, the complex interaction process of various activities, commodities and factors in the real economic environment is expressed in the model. Every economy represented in these models typically has the same basic structure: a set of households, firms and the governments whose activities are defined and linked by markets for commodities and factors as well as taxes, subsidies and perhaps other distortions (Sue Wing & Balistreri, 2018).

Generally, there are two parts of the CGE model. First, the database, it consists of an input-output table or a social accounting matrix (SAM). It is a general equilibrium data system (usually representing one-year) that links production activities, factor and commodity markets, institutions (firms, households and the government), and other accounts. It can capture the circular interdependence of nation-wide economy (Defourny & Thorbecke, 1984); elasticities are the dimensionless parameters that capture behavioural response. Second, the numerical equations in line with the SAM table, which is used to solve variables in the model. CGE models can quantitatively analyse shocks associated with policy scenarios.

Since the late 1980s, environmental factors have been included in the CGE analysis framework. The initial environmental-CGE model internalizes pollution effects into the production function or utility function, which are used to assess the impact of various environmental policies on energy, environment and economy (Bergman, 1988; Hazilla & Kopp, 1990; Jorgenson & Wilcoxen, 1990). In recent years, the CGE model research has been applied to study the impact of market-based instruments on energy and environment (Ciaschini, Pretaroli, Severini, & Socci, 2012; Orlov & Grethe, 2012; Sancho, 2010; Solaymani & Kari, 2014), and impact of gains in energy efficiency on the rebound effect (Freire-González, 2020). In this dissertation, the dynamic CGE model is applied to simulate the ETS market, assuming that carbon emission credits are traded in a perfectly competitive market. Thus, the trading price and the auction price of carbon emission rights are the same in the market clearing state. The equilibrium price of NZUs can be gained in the NZ ETS under the conditions of market equilibrium. The CGE model is considered a useful tool to capture the possible impact of pricing carbon on complex economic activities (Liu et al., 2017). It typically includes a production block, trading block, income and expenditure block. In this dissertation, it also includes a dynamic block and environmental block with land use and timber growth as well as energy use for calculating carbon emissions. The framework of the CGE model as illustrated in Figure 3 is based on Li and Jia (2016).

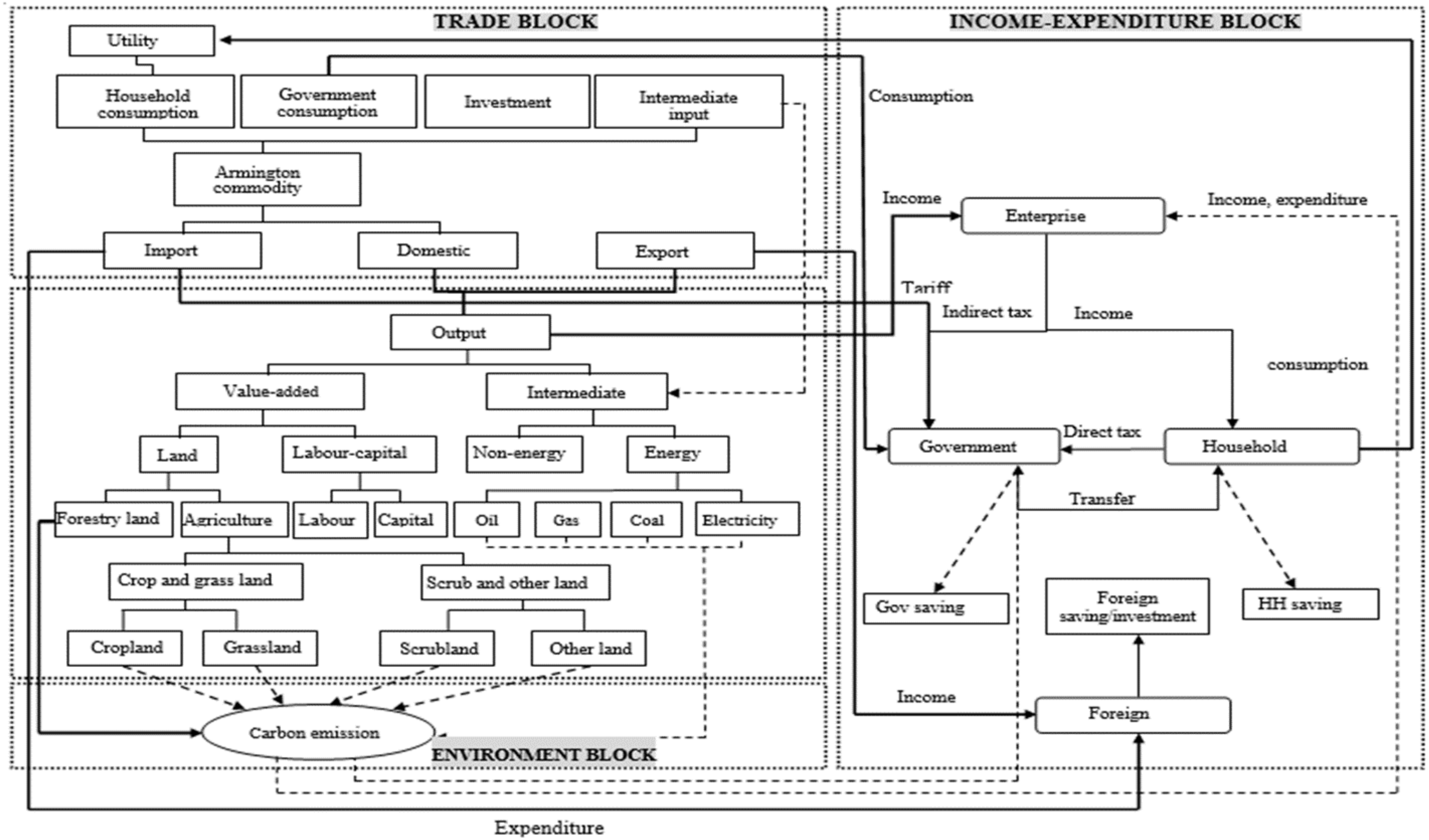


Figure 3 The framework of CGE model

Because CGE model has sound micro-economic foundations and a complete description of the economy with both direct and indirect effects of policy changes, it provides a consistent framework to analyse the economic impacts of energy and environmental policy. The most recent SAM table is based on 2013 data. The structural details and equations of the model are given in each chapter.

1.5 Innovations

Chapter 2 analyses the economic and environmental impact of endogenous carbon prices with forest sequestration included in NZ ETS, based on a dynamic recursive CGE model in different scenarios. The innovation of this study includes three parts: First, timber growth and the forestry carbon sequestration, where the forest carbon sinks react dynamically to capture the effects of forest growth on carbon removal and carbon prices. Second, a carbon ETS module is introduced to simulate some determinants of endogenous carbon prices, such as different emission caps, free allocation, coverage as well as forestry carbon sequestration. Different emission caps closely match New Zealand's emission reduction target to analyse the possible effects of NZ ETS with the coverage of multi-sectors, including agriculture sector. Third, the treatment of CO_2-e from the agricultural sector differs from previous research that dealt with agriculture separately. For example, CO_2-e modelled in LURNZ are treated as two parts: those from livestock as well as from synthetic fertilizer use (Lennox & van Nieuwkoop, 2010). Adjusted on the measurement of Timar and Kerr (2014), however, we model GHGs from agriculture as a whole, including biogenic emissions, nitrous oxide, and nitrogen in animal manure, which can be converted into emissions related to land use. CO_2-e emissions are obtained by land use area multiplied its corresponding emission factors. Other CO_2-e emissions modelled in this paper include emissions related to energy use, which is treated as usual in many previous literatures. Electricity, coal, oil and natural gas are used as energy intermediate inputs by the Leontief function. CO_2-e emissions can be obtained through energy demand and corresponding emission factors. Regardless of where carbon emissions come from, the implementation of ETS affects the production costs of sectors involved.

The major contribution of Chapter 3 is threefold. First, it divides factor-augmenting agricultural technological progress into three types: labour-augmenting, and capital-augmenting technical progress, and land-augmenting technological progress. This provides an estimate of the differential impact of the different types of technological progress on mitigating agricultural GHG emissions. Second, it combines the agricultural carbon tax policy with the impact of agricultural technology progress for the first time, to analyse their impact on agricultural carbon emission reduction and macroeconomic system from a macro perspective. Third, it introduces the agricultural technology progress to connect various sectors in the national economy, and at the same time quantifies the dynamic effects of the agricultural sector when facing external shocks, which comprehensively consider the impact of agricultural emission reduction on the competitiveness of the agricultural sector.

In Chapter 4 the dynamic CGE model is used to analyse the rebound effect of New Zealand's energy efficiency on the macro-economy, energy consumption and energy-related emission reduction. Three knowledge gaps are filled. (1) An estimate of the rebound effect of energy efficiency on the production side and the economy-wide level in the medium and long term. (2) Four energy sources (coal, oil, gas and electricity) are distinguished, and it can track each sector's energy-specific rebound effect. (3) The energy module and the dynamic module are embedded to establish a multi-sector dynamic CGE model with the SAM table based on the most recent 2013 input-output table (Statistics NZ). It incorporates CO_2-e emissions into the analysis framework of energy efficiency. This paper provides evidence on the rebound effect and provides insights for the government in aligning energy strategies aimed at transition to a low-carbon economy.

Chapter 2 Analysis of carbon-price impacts of NZ ETS

Overview

Global warming is a huge challenge facing all humankind. An increment in the concentration of greenhouse gases in the atmosphere will contribute to global warming. The contribution of New Zealand's biogenic methane emissions to global warming is higher than the cumulative emissions of fossil carbon dioxide and nitrous oxide. In this study, greenhouse gases emissions from agriculture, energy and forestry sectors in New Zealand are included and treated as CO_2-e emission in New Zealand's emission trading scheme (NZ ETS). In addition, this study introduces forest sequestration and different land types in a dynamic CGE model. Essential features of the NZ ETS are including in the model in order to simulate the impact of an external reduction target on carbon prices, land-use change, and macroeconomic variables. The results show that, to achieve New Zealand's carbon emissions targets in 2050, the carbon price ranges from NZ$136.37 per ton to NZ$325.74 per ton. In the long run, carbon prices have a negative impact on GDP.

2.1 Introduction

Climate change is expected to severely impact the environment, human health, social and economic wellbeing. For most countries, excessive energy consumption is the leading cause of greenhouse gas (GHGs) emissions (Zhang, Li, & Jia, 2018). However, as a developed agricultural country, New Zealand has a unique emission profile. Its gross GHGs emissions in 2018 were 78.9 Mt CO_2-e, comprising emissions from agriculture, energy, industrial processes and product use (IPPU), and waste sectors. Among them, the agriculture and energy sectors were the most significant two contributors to New Zealand's gross emissions, at 48 per cent and 41 per cent, respectively, in 2018 (MfE, 2019a).

To counteract CO_2-e emissions that contribute to climate change, emissions trading schemes have been implemented in many countries. It is a policy tool based on the market mechanism to achieve CO_2-e emissions reduction by pricing carbon (Diaz-

Rainey & Tulloch, 2018). ETS are designed to reach a specific CO_2-e emissions target at least cost (Steven Sorrell & Sijm, 2003). NZ ETS commenced operation in January 2008, Europe having implemented its scheme in 2005 (Richter & Mundaca, 2013). In the NZ ETS, the only allowed emission unit is the New Zealand Unit (NZU), which equals to one metric ton of CO_2, or CO_2-e of any other GHGs (MfE, 2017). Unlike the EU ETS, New Zealand NZU can be obtained from forestry sequestration, since trees absorb CO_2 from the atmosphere and store it until harvest or natural decay. Forest plantations, particularly Pinus Radiata, grow rapidly in New Zealand can sequester 25 Mt CO_2 from the atmosphere every year (Forest Owners Association, 2014). From a micro point of view, forest biomass sequesters about 50 per cent carbon, and most of the change in forest carbon stocks is determined by changes in the biomass of the four "pools" over time, which includes the above-ground live biomass, the below-ground live biomass, the coarse woody debris and the fine litter. The amount of carbon stored in forest land also changes over time, but these are small and not required to be measured under the ETS. In NZ ETS, carbon sequestration compensates for CO_2 emissions from other sectors, meets the demand for carbon credits, and ultimately affects carbon prices. Hence, capturing the dynamic change in of NZU arising from forest carbon sequestration is a focal point of this study, because it affects the price of carbon and the effectiveness of the ETS.

In addition to forest carbon sinks, the emission "cap" that limits the absolute amount of emissions also affect carbon prices (Schusser & Jaraite, 2016). Since the implementation of NZ ETS, the government has set different emission reduction targets for different stages. Initially, the Climate Change Response (Emission Trading) Amendment Act 2008 came into force with only the forestry sector included. Later the Amendment Act 2009 set a conditional cap of 10-20% abatement on GHGs emissions compared to 1900 levels by 2020. The government, yet again, revised Amendment Act 2009 and limited the cap to 5% reduction of GHGs emissions unconditionally below 1990 levels. According to the latest "New Zealand climate change work program– mitigation" announced by Ministry for the Environment, the most recent goal is to reduce GHGs by 30 per cent below the 2005 levels by 2030, which is equal to 11 per cent below 1990 levels. By 2050, the government aims to reduce emissions, excluding biogenic methane emissions to net-zero (MfE, 2019b).

According to Kuik and Mulder (2004), it is the best to design ETS to cover all sectors in the economy. The more industries ETS covers, the more effectively it operates. However, the introduction of agricultural emissions has been postponed into NZ ETS and yet to be priced (Leining et al., 2017). Leining et al. (2020) reported NZ ETS's policy insights that agricultural emissions will be priced from 2025. Policy has approached the agricultural sector with caution in order to protect its competitiveness. Nevertheless, the efficacy of NZ ETS has been challenged since the carbon price collapsed in 2011 and bottomed out till mid-2013 (Diaz-Rainey & Tulloch, 2018). In 2020, new price control has been set in case of high or low auction carbon prices in the trading market (MfE, 2020b). According to the Productivity Commission, only by raising carbon price from NZ$21 per ton to between NZ$ 75 and NZ$ 152 will New Zealand be able to transition to a low-carbon economy by 2050. Furthermore, to achieve net-zero emissions, the carbon price needs to rise from NZ$ 200 to NZ$ 250 per ton. Other studies also concluded that the cost of forest-based carbon sequestration ranges widely from US$3 to US$550 per ton (Stavins & Richards, 2005; van Kooten & Sohngen, 2007). In all, the potential contribution of pricing agricultural emissions and forestry sequestration credits are still in question.

Consequently, it is needed to conduct an integrated assessment on a policy-impact analysis since few studies answer how forestry carbon storage and agricultural emissions affect carbon prices of NZ ETS. Besides, severe socio-economic issues will emerge if the carbon emissions reduction target in New Zealand is set inappropriately. The CGE model is a useful tool to capture the possible impacts of external policy shocks on complex economic activities (Liu et al., 2017). The model contains an endogenous demand and price scheme, optimization of agent behavior, factor scarcity, income-expenditure of institutions and the macroeconomic environment (Banerjee & Alavalapati, 2009). Given the concern of achieving a low carbon economy transition in Zealand, this chapter adopted a dynamic CGE model to evaluate the effects of CO_2-e emissions reduction targets (as an external shocks) in New Zealand through the recursive dynamic mechanism. Forestry sequestration is modelled according to biomass growth over the whole simulation period. Endogenous carbon prices are estimated, given emission caps, free allocation, and carbon sequestration.

The chapter is organized as follows. Section 2.2 reviews a body of existing literature.

In section 2.3, this study outlines the CGE model with some main modules and scenario settings. For example, the NZ ETS and forestry sequestration are integrated into the dynamic CGE model. Section 2.4 shows the simulation results and discussion. The conclusions and suggestions are dawned in section 2.5.

2.2 Literature review

Many scholars have studied carbon ETS focusing on its economic and environmental effects. However, the results vary depending on the participating industries and regions. Nong, Nguyen, Wang, and Van Khuc (2020) analyzed negative impact of carbon ETS on GDP growth in Vietnam. They showed that GDP losses were 1.78% and 4.57%, respectively, caused by different sectorial coverage. Nong, Meng, and Siriwardana (2017) assessed the impact of Australia's ETS on the economy and the environment there; they found that when the carbon price was AU$13.1 per ton, GDP fell by 0.85% in 2020, while carbon prices rose to AU$ 41.3 per ton, it can be achieved 28% emissions reduction in 2030 compared to 2005 with 1.6% GDP loss. Hübler, Voigt, and Löschel (2014) used the CGE model to evaluate the 45% lower of emissions intensity per GDP in the context of carbon ETS in China and found that in 2020, it resulted in a GDP loss of about 1% and they assert that by 2030, it could result in a welfare loss of about 2%. While, the other study estimated the CO_2-e emissions of Nepal's agriculture, forestry and other land-use (AFOLU) sectors under the exogenous carbon price scenarios and found that a carbon price higher than US$75/t$CO_2$-e was not very effective in achieving a notable additional reduction in AFOLU's greenhouse gas emissions (Pradhan, Shrestha, Hoa, & Matsuoka, 2017).

There is vast of literature focusing on the determinants of ETS prices. Policies and economic activities are the two kinds of important external factors. For example, Ye, Dai, Nguyen, and Huynh (2021) conducted the multifractal detrended cross-correlation analysis and found that EU carbon price and the economic policy uncertainty do exist cross correlations. Koch, Fuss, Grosjean, and Edenhofer (2014) used the marginal abatement cost theory to analyze the reasons for the carbon price in EU-ETS. They found that carbon ETS price would be significantly affected by the changes in economic activity. Aatola, Ollikainen, and Toppinen (2013) investigated the European Union emission allowance on the ETS prices empirically based on the data between 2005 to 2010 in the EU ETS market. They found that the fundamentals, especially the price of electricity and the gas–coal difference decides the EUA forward price. Other studies about different policy adjustments and ETS prices can refer to EU ETS researched by Fan et al. (2017) and Blyth et al. (2007); the Shanghai Emission Trading Scheme pilot by Song, Liang, Liu, and Song (2018); Australia's ETS by (Jotzo, 2012). These studies mentioned are of particular importance since they provided insights about consequences and causalities of external factors in terms of carbon ETS prices.

Existing studies have concentrated on the internal determinants (such as emission caps, initial allowance allocation, free allowance rate, and sector coverage) on ETS prices and its impacts. A range of economic models have been used: including for example the Cournot model (Li, Yang, Chen, & Hu, 2017), Input-output Analysis (Zhu, Zhang, Li, Wang, & Guo, 2017), and Improved Stark-Berg model (Balietti, 2016; Jiang, Yang, Chen, & Nie, 2016). Turning to empirical models, for example, Benz and Trück (2009) used AR-GARCH models to compare the in-sample and out-of-sample forecasting analysis of the returns of carbon emission allowances. However, these empirical approaches are data-driven and do not endogenize the economy-wide responses from other economic sectors, market participants (such as households and governments) and factor markets, such as changes in land-use. In practice, they cannot simulate the dynamic environment and explain the internal drivers of carbon prices in the carbon trading market.

A growing body of literature has applied dynamic CGE models to study the effects of internal determinants of ETS mechanism. Wu and Li (2020) investigated the effects of allowance allocation and emission reduction on carbon prices and found the specific carbon price increased from 12.44–90.57 CNY per ton in 2017 to 65.20–523.44 CNY per ton in 2030. Li and Jia (2016) claimed that the free quota rate directly impacts carbon trading prices, gradually decreasing to below 50%, guaranteeing stable carbon prices in China. Later, they constructed a recursive dynamic CGE model to simulate the industries coverage of China's national carbon ETS in 2017, and found that more coverage would be better if transaction costs were ignored (Lin & Jia, 2017). In 2019, they analysed the impact of a different carbon price in China. The results show that as the carbon price level increases, GDP will decrease more. They recommended keeping the ETS price at US$10 and gradually increasing the carbon price to US$20 (Lin & Jia, 2019). Choi, Liu, and Lee (2017) analysed the South Korean ETS policies and found that the optimum carbon price to facilitate emissions trading is US$9.14 per ton. The rest of other studies are used CGE model about allowance allocation (Yu et al., 2018; Zhang et al., 2018); free quota rate (Li & Jia, 2016; Wang & Teng, 2015); sectoral coverage (Mu, Evans, Wang, & Cai, 2018).

In contrast with the above studies, the effect of carbon sequestration on carbon price has few disaggregated into a dynamic recursive CGE model. Forestry growth involves a long time, from planting to harvesting. Some CGE models distinguish between plantation and native forests with land heterogeneity to estimate the carbon emissions from the deforestation of native vegetation (Golub, Hertel, & Sohngen, 2007; Golub & Hertel, 2008). Lawson, Burns, Low, Heyhoe, and Ahammad (2008) used exogenous rotation time to establish partial equilibrium models. Pant (2010) supplemented the forestry harvesting activities when incorporated forestry into the model, which is applied to study the effects of deforestation and forest degradation on emissions. Michetti and Rosa (2012) assumed 20 years as a reasonable time that new plantations will not be harvested. They introduced forestry mitigation into the static CGE model based on carbon sink curves and found that forest sequestration contributed to 30% emissions reduction target with only 0.2% of GDP loss. Monge, Bryant, Gan, and Richardson (2016) employed a static CGE to analyse land-use change (LUC) and indicated that the high diversion of agricultural land in the US might increase the price of beef by 14%.

However, applications of the CGE model to analyse forestry-carbon sequestration remain rare in New Zealand. Tee et al. (2014) used binomial tree models with random prices (one is carbon price and the other is wood price) to predict the impact of carbon price on New Zealand's forestry. They found that when the carbon price is NZ $10, the forest rotation time is extended from 25 to 27 years. When the carbon price is NZ $20, the tree rotation time is 33 years. Kerr et al. (2012) used the New Zealand Rural Integrated Land Model to simulate different ETS scenarios and analyze the impact of NZ ETS on land use, emissions and output. The results showed that when including agriculture in the ETS, its effect is small compared to the effect of including forestry. At a carbon price of NZ$25 per ton, the forestry carbon sequestration from the new planting removals 17.6%–20% of agricultural emissions in 2008. Reisinger and Ledgard (2013) believe that policies aimed at agricultural GHG reductions are fundamental to realizing the ambitious climate change goals and have the potential to reduce global mitigation costs.

Application of CGE models to of the NZ ETS are mainly static. For example, Lennox and van Nieuwkoop (2009) took international carbon emissions prices as exogenous variables and simulated different NZ ETS coverage of sectors and GHGs through a static CGE model. They found that effective abatement of GHGs is accompanied by GDP loss. In 2010, they also used a static CGE model to analyze the impact of NZ ETS because of output-based allocation, and ETS auction revenue on industries and taxes distortion (Lennox & van Nieuwkoop, 2010). The other static CGE analysis of NZ ETS about free quota allocation in the medium and long term till 2025 (NZIER, 2008), output-based quota allocation in the short term (Stroombergen, 2007) and auction allocation considering the international carbon market (NZIER, 2009). The CGE model linked a partial equilibrium forest growth model (Wang, Sharp, Poletti, & Nam, 2021). However, the literature has used static CGE analysis, which has limitations because it does not consider the importance of dynamic forest carbon sequestration and land use and changes in NZ ETS.

The objective of this study is to evaluate the formation of endogenous carbon prices and analyze ETS's economic and environmental impact using a dynamic recursive CGE model. The innovation and contribution of this study can be drawn from three aspects: First, timber growth and the forestry carbon sequestration are included into the dynamic mechanism, where the forest carbon sinks react dynamically to capture the effects of forest growth on carbon removal and carbon prices. Second, a carbon ETS module is introduced to simulate some determinants of endogenous carbon prices, such as different emission caps, free allocation, coverage as well as forestry carbon sequestration. Different emission caps closely match New Zealand's emission reduction target to analyze the possible effects of NZ ETS with the coverage of multi-sectors, including agriculture sector. Third, the treatment of CO_2-e from the agricultural sector is different from the previous research. The previous research dealt with agricultural GHG separately. For example, CO_2-e modelled in LURNZ are treated as two parts: those from livestock as well as from synthetic fertilizer use (Lennox & van Nieuwkoop, 2010). Adjusted on the measurement of Timar and Kerr (2014), however, this study models GHGs from agriculture as a whole, including biogenic emissions, nitrous oxide, and nitrogen in animal manure, which can be converted into emissions related to land use. CO_2-e emissions are obtained by land use area multiplied its corresponding emission factors. Other CO_2-e emissions modelled in this study include emissions related to energy use, which is treated as usual in many previous literatures. Electricity, coal, oil and natural gas are used as energy intermediate inputs by the Leontief function. CO_2-e emissions can be obtained through energy demand and corresponding emission factors. Regardless of where carbon emissions come from, the implementation of ETS affects the production costs of sectors involved.

2.3 Model outline

The CGE model typically includes a production module, a price and trading module, an income and expenditure module, a dynamic module and market clearing and closure conditions. In this study, it also simulated land factor as a heterogeneous input, and considered the substitution between different land types. Besides, it modelled NZ ETS module with land use and timber growth.

2.3.1 Production module

The production module includes 3 factor inputs (labour, capital and land), intermediate inputs and product outputs. The CES production is nested by a composite value-added factor and the intermediate inputs; labour, capital and land form a composite value-added factor; the intermediate inputs are divided into intermediate energy inputs, and non-energy intermediate inputs. However, the inside parts of these two intermediates adopt Leontief function to input and produce. The structure of production, as shown in the above Figure 4. The equations of this module involved many equations are presented in the appendix A.1.

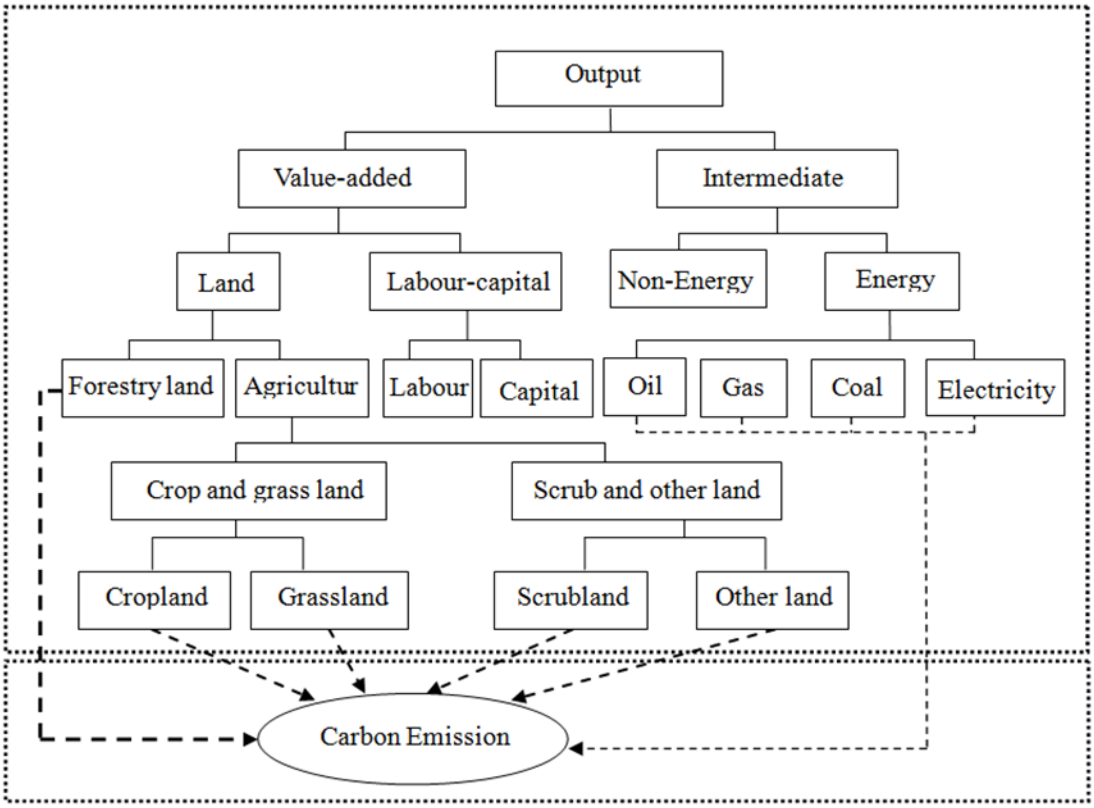


Figure 4 The overall structure of production module

2.3.2 Price and trading module

The price module is a core part of the model, connecting other modules within the economy. There are many prices in the model: the price of labour, the price of capital, the price of the import and export goods, the price of the intermediate inputs, the output price, the consumer price, and the government consumer price. This study takes the exchange rate of New Zealand dollars to US dollars as the numeraire, which equals 1 in the benchmark year.

The total output is sold to domestic market and foreign countries according to the principle of profit maximization, and the CET function decides the distribution between the domestic and foreign market. Each producer (represented by an activity) is assumed to pursue profit maximization.

$$QA_i = aT_i \left[e_i QE^{\frac{\sigma-1}{\sigma}} + (1 - e_i) QD^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \tag{2-1}$$

$$\frac{PE_i}{PD_i} = \frac{e_i}{1-e_i}\left(\frac{QD_i}{QE_i}\right)^{\frac{1}{\sigma}} \tag{2-2}$$

Where，aT_i is scaling parameter of CET function, $e_i$denotes the share parameter, σ means the transformation elasticity, PE_i price of domestically produced goods exported to foreign markets, PD_i is the price of domestically produced goods sold on the domestic market. Referring to Figure 5 below for other letters meaning.

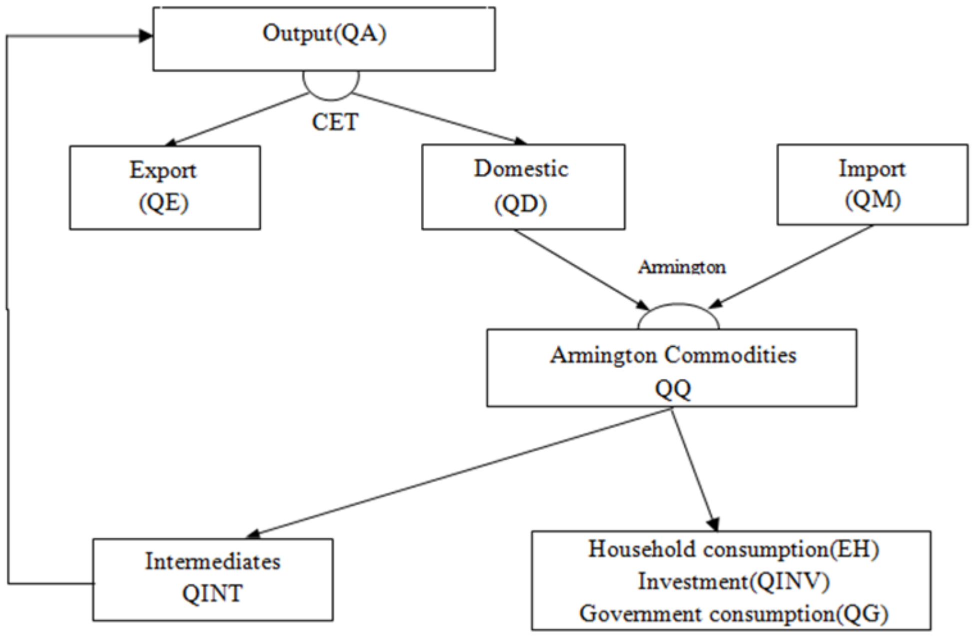


Figure 5 Trading commodities circulation

Local goods come from domestic production and imports, which meets the substitution relationship of the Armington condition. When modelling, we assume Armington function to represent the imports and domestic products, which are not entirely substituted. Also, New Zealand is assumed to be a global commodity price-taker (Daigneault, 2015); the price of import and export goods is determined by the international market price.

$$QQ_i = aM_i\left[\delta_i QD^{\frac{\mu-1}{\mu}} + (1-\delta_i)QM^{\frac{\mu-1}{\mu}}\right]^{\frac{\mu}{\mu-1}} \tag{2-3}$$

$$\frac{PD_i}{PM_i} = \frac{\delta_i}{1-\delta_i}\left(\frac{QM_i}{QD_i}\right)^{\frac{1}{\mu}} \tag{2-4}$$

In equations (2-3) and (2-4), aM_i is scaling parameter of Armington function, δ_i means a share parameter, μ is Armington elasticity, PM_i is the price of imported goods.

2.3.3 Land-use emissions and forestry sequestration

Constructing a dynamic CGE model for agriculture land, it is necessary to enable the model to reflect land supply constraints and land use changes due to land heterogeneity, and important for land-based emissions and forestry sequestration. According to Lennox and van Nieuwkoop (2009), land allocation is through a nest of constant elasticity of transformation (CET) function. In Figure 4, land is divided into agricultural land and forestry land, then agricultural land is CET nested by four types: cropland, scrubland, grassland and other lands. Under this framework, it is assumed that different land types are incomplete alternatives to producing a given agricultural product, resulting in different land types with different rental rates. This module is mainly used to study the impact of the carbon price on the use of five different land types and their mutual conversions. The CET elasticities are taken from the global trade model (Lee, 2005), and New Zealand-specific version GTAP-ENZ (Rae, Strutt, & Cassells, 2008).

The NZ ETS encourages forest owners to grow trees to get carbon credits that generate additional income for forest growers. In the carbon ETS, carbon emitters need to pay the cost for CO_2-e emissions, and forest owners can benefit from selling CO_2-e emission units derived from carbon sequestration (Ministry of Primary Industry, 2018). In the NZ ETS, the distinction between pre-1990 and post-1989 forest land lies in participants' obligations about deforestation and harvest and their eligibility to earn NZUs. Under the ETR Act (Emissions Trading Reform), post-1989 forest land will be categorised as standard or permanent forest registered in the NZ ETS from 1 January 2023, banned from deforestation and clear-fell harvesting for at least 50 years (Acosta, Grimes, & Leining, 2020). Therefore, this study does not consider the felling of trees when dealing with biological growth, but only considers the impact of carbon sequestration caused by the continued growth of trees. The dynamic change of forest net carbon storage depends on the biological characteristics of eligible trees and the planting area of trees. Policy makers only need to refer to the changes in forest area and the biological characteristics of trees to ensure the annual carbon sequestration requirements.

New Zealand's forestry industry is primarily based on managed plantations, with approximately 90% of the plantations being *Pinus radiata*. So, this study simulates tree growth based on The National Exotic Forest Description (NEFD) regional yield tables of *Pinus Radiata* and estimate the annual carbon sequestration multiplying the timber biomass by the percentage of carbon content in the trees. Following Conrad (1999), this study assumes tree biomass continues to grow over time as follows:

$$\mathrm{V(t)} = \exp(a - \mathrm{b/t}) \quad (2\text{-}5)$$

Where a =7.63, b=40.32. We assume that the trees keep growing without decline but at last the volume will tend to be an absolute constant e^a, when adopting this function. The amount of carbon forestry sequestration gained per hectare due to tree growth as shown in Equation (2-6).

$$Carbon_{sink} = k * \Delta V(t) \quad (2\text{-}6)$$

According to the look-up tables for post-1989 forest land of *Pinus Radiata*, this study adjusted carbon content coefficient *k*. The widely used method for estimating forest carbon storage is to calculate by multiplying the forest biomass by the carbon content coefficient (Stainback & Alavalapati, 2002).

2.3.4 NZ ETS module

The carbon price determinants in this module include not only the unique features-forestry carbon sequestration mentioned in the above section, but also ETS features: emissions cap, free allowance allocation and coverage. The NZ ETS initially operated without a nationwide cap, and there were unlimited international offsets from the Kyoto Protocol's clean development mechanism (CDM) as well as forestry carbon sequestration. However, with the emission credits supply restricted to domestic NZU units since 2015, the NZ ETS is running as a closed trading scheme towards an effectively fixed cap that equals the annual free allocations plus forest carbon removals issued (ICAP, 2017).

Table 1 Variables of ETS policy

ETS design		Variables of ETS		
Carbon cap		Total reduction rate	$tcer$	11-70%
		Total carbon permit	Equation (2.5)	
Allowance allocation	Free allocation	Free quota rate	fp	10%;24-47%
		Total free allocation	Equation (2.7)	-
		Total auction	Equation (2.8)	-
	Rules of free allocation	Free allocation of industry i	FPi	-
		Output-based grandfathering	Equation (2.9)	-
		Emission-based grandfathering	Equation (2-10)	-
Coverage		Emissions of all sources	-	-

The exogenous reduction cap of this research is set according to New Zealand's carbon emission reduction target. The international goal is to reduce CO_2-e emissions by 30 per cent below the 2005 levels by 2030, which is equal to 11 per cent below 1990 levels ($tcer$=11%). Domestically, the government aims to reduce emissions to net-zero by 2050, excluding biogenic methane emissions to net-zero by 2050 (MfE, 2020a). However, with current instruments only, the net emissions are estimated to decrease 59 per cent of 2020's net emission level (58.5 Mt CO_2-e) to 23.8 Mt CO_2-e in 2050 (MfE, 2021). While, this study sets net-emissions cap equal to 20 Mt and 25 Mt CO_2-e, respectively by 2050, and the corresponding $tcer$ is between 60-70% of 1990 gross emission level in 2050, to explore how carbon price changes response to different carbon emission cap. The simple presentation of NZ ETS mechanism is as Figure 6 shows.

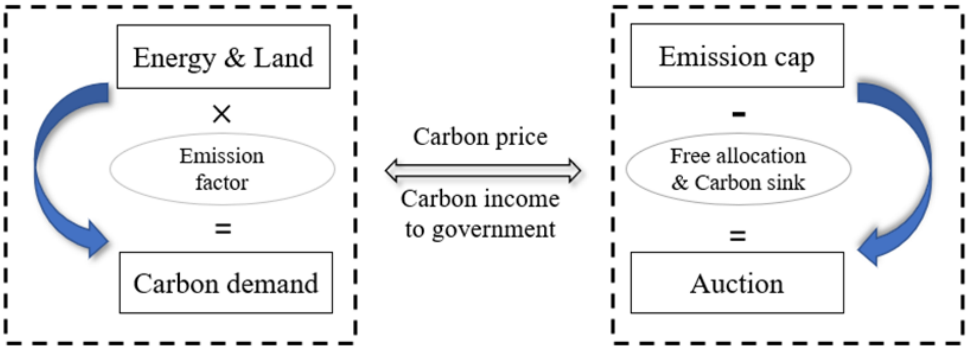


Figure 6 NZ ETS mechanism

The setting of the carbon cap is mainly on the corresponding emission reduction goals. The specific equation is set as follows:

$$\text{Carbon}_{cap} = (1 - tcer\ )\ TCO2_t,\ \ t = 1, \tag{2-7}$$

Where, $\text{Carbon}_{\text{cap}}$ represents the total carbon emission cap on the carbon trading market at time *t*, $TCO2_t$ means the total carbon emissions of all industries at period *t*, and the base year in this study is 2013, and $t = 1$ represents 2013. $tcer$ is the carbon emission reduction rate set based on government's reduction targets. And the total carbon emission calculation formula is as follows：

$$TCO2_t = \sum_{i=1}^{49} CO2_{i,t} = TFP_t + TAP_t \tag{2-8}$$

$$TFP_t = fp * Emission_{cap} = \sum_{i=1}^{49} FP_{i,t} \tag{2-9}$$

$$TAP_t = (1 - fp) Emission_{cap} = \sum_{i=1}^{49} AP_{i,t} \tag{2-10}$$

Among them, TFP_t and TAP_t respectively indicate the total free distribution quota and the total auction amount in the period t, and $FP_{i,t}$ represents the free payment of the industry i in the period t. According to the formula (2-10), the total auction volume increases, when the free distribution allocation ratio fp decreases, the carbon-intensive sector needs to purchase more emission credits to ensure production and operation, and at the same time, it will generate higher carbon emission costs, thereby suppressing sector output.

In terms of free distribution, the allocation of emissions allowances is usually considered independent of the emissions reduction, free allocation can affect the performance and fairness of allowance trading (Burtraw & McCormack, 2017). Two grandfathering clauses allocate free permits. One is output-based allocation (Lennox & Van Nieuwkoop, 2010), see equation (2-11).

$$FP_{i,t} = \frac{QA_{i,t}}{TQA_t} * TFP_t \tag{2-11}$$

The other one is emission-based allocation. According to Böhringer and Lange (2005), allocation allowance links to historical emissions are best in a closed ETS. Here, in this study, unlike (Lennox & Van Nieuwkoop, 2010), it follows the grandfather clause based on carbon emissions, the amount of free quota is calculated from the historical carbon emissions of industry i.

$$FP_{i,t} = \frac{CO2_{i,t}}{TCO2_t} * TFP_t \tag{2-12}$$

According to the Climate Change Commission's requirements, agriculture reduces biomethane emissions by 10% by 2030, 24-47% by 2050 compared to 2017's biogenic methane emissions, 33.13 Mt CO_2-e (Zero Carbon Act 2050 target calculations). The reduction equates to between 3.31 by 2030, and 7.95-15.57 Mt CO_2-e by 2050. The study assumes that only this part of emissions are free, and *fp* ranges from10% to 47%. Besides, According to MfE (2020), has announced new price restrictions intended to prevent unacceptably high or low auction carbon prices. The government has acknowledged limiting the price floor at NZ$20 after 2020 and increased by two per cent for each following year. However, the government can stipulate the expected total carbon emissions, price celling and flooring, but cannot determine the actual carbon price in the market. The focus of this study is to explore the carbon price effect of emission reduction targets, agricultural emissions are included in NZ ETS without explicitly setting a sub-cap for biomethane emissions.

When carbon sinks are a commodity linked to prices, the price equilibrium in the carbon trading market can be written as:

$$\sum_{i=1}^{49} CO2_{i,t} = \sum_{i=1}^{49} FP_{i,t} + \sum_{i=1}^{49} AP_{i,t} - Carbon_{sink} = Carbon_{cap} \tag{2-13}$$

The carbon price occurs when CO_2-e emissions are capped (Yu et al., 2018). When calculating the cost of production, the part of the free allowance is deducted, that is, the free allowance avoids pay the carbon price. The carbon cost of agriculture sectors will decrease its cost of output. Formulated as follows:

$$PX_{i,t} * X_{i,t} = PP_{i,t} * X_{i,t} + P_c\left(CO2_{i,t} - FP_{i,t}\right) \tag{2-14}$$

Where, $PX_{i,t}$ represents the carbon price of the output products of industry i at period t, $PP_{i,t}$ represents the production price without carbon costs, P_c is carbon price in the carbon trading market.

2.3.5 Data input and scenario settings

The New Zealand 2013 input-output table issued in 2016 was the core data source of the CGE model and the basis of the social accounting matrix (SAM). The account settings of the SAM table mainly include activities, commodities, labour, capital, land, households, enterprises, governments, and the rest of the world (ROW). In addition, the model needs three other types of data. The first is the land carbon emission coefficient and energy carbon emission coefficient. The different land carbon emission coefficients refer to Timar and Kerr (2014), and the energy carbon emission coefficients come from Ministry of Business, Innovation and Employment (MBIE, 2019). The second type are elasticities, such as Armington's substitution elasticity, CET conversion elasticity and substitution elasticity among the factors of production, moreover, the different share parameters and scaling parameters. The transformation conforms to the CET function, and the elasticities of transformation gained from Lennox and van Nieuwkoop (2010), and the Armington's elasticity refers to Daigneault (2015). Shares and technical parameters are calibrated according to the SAM table. Substitution elasticities are given in Appendix A.2.

Under the market equilibrium state, in the dynamic recursive CGE approach, the emissions prices are endogenously determined–the model calculates the emission prices, given a specific emission cap and free allocation. As explained in section 2.3.4, scenarios are provided as below:

Table 2 Different scenarios of emissions reduction and free allocation

Scenario	2030	2050	2020-2030	2030-2050
	Total carbon emission reduction rate *tcer* (%)		Free allocation to agriculture (*fp*)	
ETS-R1	11%	60%	0%	0%
ETS-R2	11%	60%	10%	24%
ETS-R3	15%	70%	10%	47%

2.4 Results

This study sets up three scenarios based on different levels of carbon emission reduction targets and free emissions allocation to agriculture.

2.4.1 Carbon prices in NZ ETS

From Figure 7, in Scenario ETS-R1, the carbon emission reduction target is 11% of 1990's emissions level by 2030 and 60% by 2050 with net emissions of 25 Mt CO_2-e, including agricultural emissions. In this case, the price of carbon emissions increased from NZ$43.02 in 2020 to NZ$82.25 per ton in 2030. In 2050 the price of carbon is NZ$177.56 per ton.

In ETS-R2, as the emission reduction rate keeps the same, but the agricultural sector will receive 10% free CO2-e emissions of 2017's biogenic methane by 2030, and 24% of 2017 by 2050, the carbon prices go lower slightly than that in ETSR1, and experience a small drop in 2031, with price of NZ$ 66.31. Nevertheless, by 2050, carbon price has increased to NZ$136.37. The price changes indicate that free emissions allocation to agricultural emissions can curb carbon price increase.

In Scenario ETS-R3, the carbon emission reduction target is 15% of 1990's emissions level by 2030 and 70% by 2050 with net emissions of 20 Mt CO_2-e, including agricultural emissions. The free payment of emissions to agricultural sector keeps the same by 2030 as scenario ETS-R2. However, by 2050, the free quota for the agricultural sector will increase to 47% of 2017's biogenic methane (7.62 Mt CO_2-e more for fee than that of ETS-R2). The price of carbon emissions increased from NZ$54.45 in 2020 to NZ$102.99 per ton in 2030. When net emissions by 2050 are 20 Mt, the agricultural free quota is 47%, the carbon price rise to NZ$325.74 per ton. The free quota did not inhibit the increase in carbon prices, indicating that carbon prices are more sensitive to net emission caps less than 25 Mt net emissions. It is in line with the latest New Zealand's projected greenhouse gas emissions to 2050, which announced that with current instruments only, the net emissions are estimated to 23.8 Mt CO_2-e in 2050 (MfE, 2021).

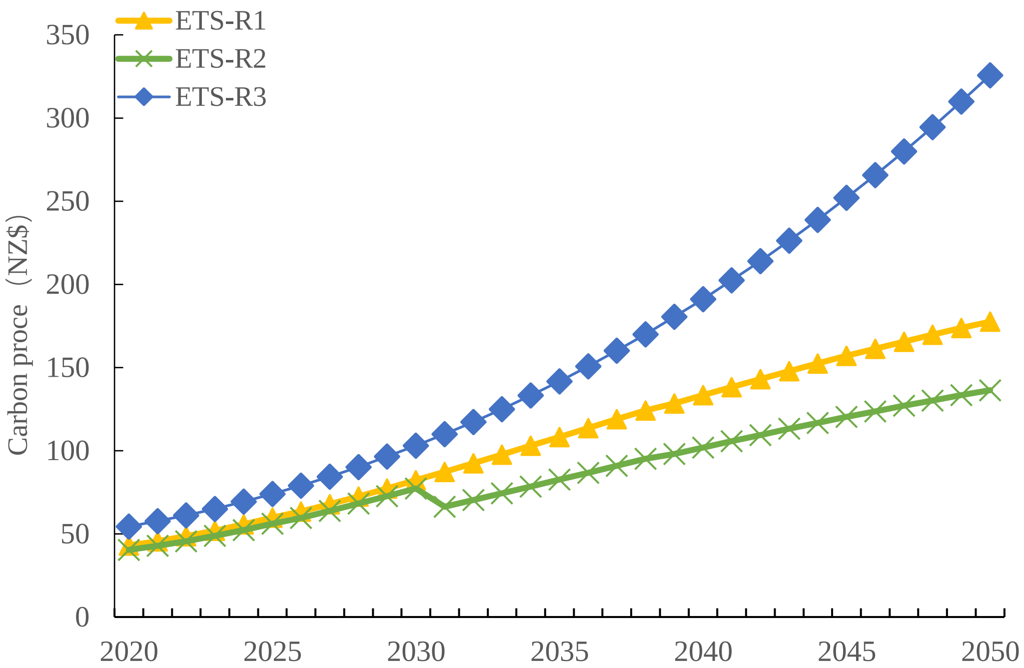


Figure 7 Carbon prices under different ETS scenarios

In the model, the equilibrium prices of carbon emissions are determined endogenously by total supply and demand. When the carbon emission reduction target remains unchanged, the demand for carbon credits decreases, and the carbon prices fall slightly after 2030 (See scenario ETS-R2). Nevertheless, due to the gradual realization of emission reduction targets, carbon demand has increased, it results in the continuous rise of carbon prices.

2.4.2 Land use and land-use changes

Of all 49 industries in this study, only five sectors take land use as an input factor to produce goods, which are Horticulture and fruit growing (HFRG), Livestock and cropping farming (SHBF), Dairy cattle farming (DAIF), Other farming (OTHF) and Forestry (FOLO) sector. Although the area of land supply is fixed, land use and land changes depend on land rents, and land-use types that are associated with higher CO_2-e emissions will bear higher carbon price.

Based on the principle of cost minimization, rational producers will choose more land with a small carbon emission coefficient or carbon stock, such as forest land, for production activities. As carbon prices rise, forest owners expand timber planting area. Although rising carbon prices have increased the cost of other intermediate inputs in the forestry sector, forestry land has increased as expected. In scenario ETS-R1, the forest planting area has increased by 31.26% by 2050, compared with the base year 2013. In ETS-R2, the emission reduction rate keeps the same, although the agricultural sector got free emissions, carbon prices change slightly, land use has not changed much compared with the ETS-R1 scenario. However, in scenario ETS-R3, the emission reduction target is increased, and the carbon price is from NZ$54.45 in 2020 to NZ$325.74 per ton in 2050. Higher carbon prices prompt grassland to switch to forest land. The grassland has decreased by 4.67% compared to the area in base year 2013. While, the forest area has increased by 37.04%. Carbon emission coefficients differ across land use categories, grassland has a high carbon emission coefficient because of farming methods and fertilizer use. When the carbon price increases, the land with a high carbon emission coefficient bears a higher carbon cost, the use of this type of land is reduced.

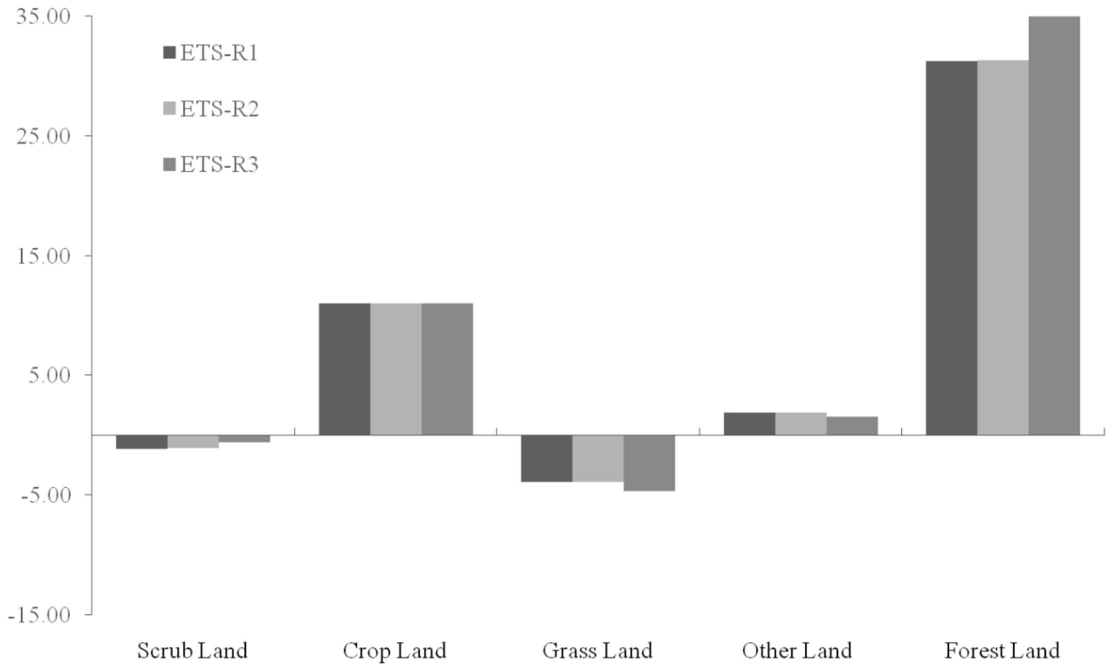


Figure 8 Land use changes under different scenario in 2050 compared with BAU (%)

2.4.3 GDP changes

The setting of carbon emission reduction targets directly affects the price of carbon emissions, and its impact is mainly reflected in increasing the production costs of industries, reducing their output, and causing GDP growth to decline.

As can be seen from Figure 9, achieving New Zealand's carbon emission reduction targets under NZ ETS reduces GDP. In the ETS-R1 scenario, the GDP reduction rate from 2020 to 2050 is 0.29%-0.81% and in 2050, reducing by NZ$3580 million compared with the BAU scenario. In Scenario ETS-R2, when the carbon emission reduction target keeps the same as that of ETS-R1, the agricultural sector received a 24% free quota of agricultural CO_2-e emissions in 2017, although, the free allocation can decrease the carbon cost of agricultural sectors and protect their competitiveness, the negative GDP growth rate, -0.85% by 2050, is slightly larger than that in ETS-R1. This phenomenon can be analysed from the perspective of GDP expenditures approach, which consists of resident and government spending, investment, and net exports. The free allocation to agricultural sectors decreases the government's auction revenue and spending, resulting in GDP loss.

In Scenario ETS-R3, the GDP growth rate is reduced by 1.31%-3.16%. Under this scenario, GDP will be reduced by NZ$14034 million by 2050. Overall, the emission reduction targets have harmed New Zealand's GDP. In general, the more ambitious the emission reduction target, the greater the damage to New Zealand's GDP. The reason behinds this phenomenon, in my view, is that with the increase of the total carbon reduction rate, the carbon price has been rising rapidly, which has caused an increase in production costs and abatement costs. Besides, the higher free allocation to agriculture sectors decreases more of the government's auction revenue and spending. Therefore, the GDP loss is much higher than that of ETS-R1 and R2. Luckily, the GDP loss caused by reducing so much carbon emissions is relatively small compared to other countries. For example, Nong et al. (2017) assessed the impact of Australia's ETS on the economy and the environment there; they found that when the carbon price was AU$13.1 per ton, GDP fell by 0.85% in 2020, while carbon prices rose to AU$ 41.3 per ton, it can be achieved 28% emissions reduction in 2030 compared to 2005 with 1.6% GDP loss.

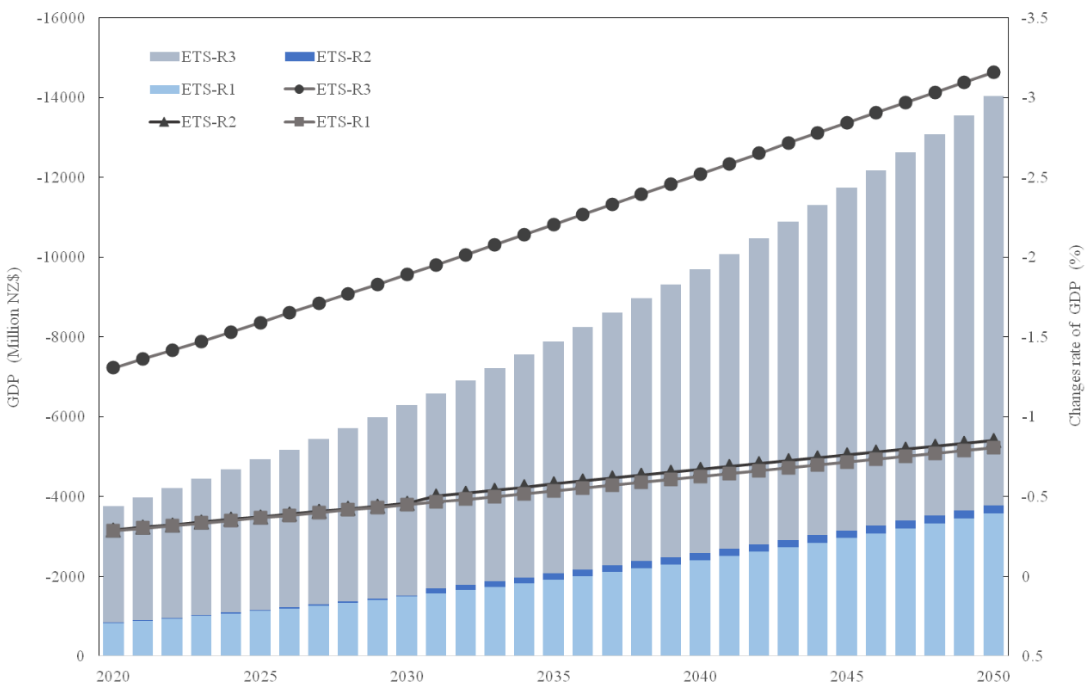


Figure 9 GDP Changes under different scenarios

2.5 Conclusions and suggestions

This study compiles a SAM table containing 49 production sectors to data support the recursive dynamic CGE model. Using labour, capital, and land as three value-added input factors, the emission reduction target scenarios selected were justified based on the government's target, which emphasizes the impact of New Zealand's emission reduction targets on carbon prices of NZ ETS, land-use changes and the economy with carbon sequestration included. This chapter draws the following conclusions:

First, the setting of the total emission reduction target is price sensitive. That is, a small emission reduction rate may bring a greater carbon price and the carbon price changes in the same direction as the emission reduction rate changes. When the net emissions less than 25Mt, the greater of free emissions payment to the agricultural sector could not lower the carbon price. The corresponding price is up to NZ$325.74 per ton, which exceeds that of the New Zealand Productivity Commission's prediction-by raising carbon price from $21 per ton to between $ 75 and $ 152. Furthermore, to achieve net-zero emissions, except biomethane emissions, the carbon price needs to rise from $ 200 to $ 250 per ton for New Zealand's transition to a low-carbon economy by 2050. The cost of forest-based carbon sequestration ranges widely from US$3 to US$550 per ton (Stavins & Richards, 2005; van Kooten & Sohngen, 2007). Carbon prices in this study keep within a reasonable range and work for carbon emissions reduction. However, from scenario ETS-R3, it can be known that New Zealand's net emissions in 2050 achieved through forest carbon sinks have a critical point. Carbon prices will increase rapidly by less than 25 Mt net emissions cap, and marginal emission reduction costs will increase.

Second, the relationship between carbon prices and forest carbon sequestration change in the same direction. Carbon sequestration is a carbon-credit pool in New Zealand to contract climate change. The impact of increasing carbon prices on forestry is mainly reflected in the forest expansion. However, the rapid increase in prices is not a panacea to encourage forestry planting, mainly due to the long timber growth, and is slow when adjusting the planting area. However, the expansion of forest area lags behind the carbon price, mainly due to the longevity of wood, and the response is slow when adjusting the planting area. In scenario ETS-R1 and ETS-R2, the net emissions are the same, the forest planting area has increased by 31.26% by 2050 with carbon price NZ$177.56 per ton. In scenario ETS-R2, the forestry planting keeps all most the same with NZ$136.37 per ton by 2050. However, when the net emission cap becomes more ambitions 20 Mt by 2050, the marginal cost of abatement begins to grow rapidly in scenario ETS-R3, and the forestry planting increased by 37.04%, less than 6% higher than the previous two scenarios. It means that higher carbon prices are not always effective in encouraging forest planting and carbon sequestration. As Pradhan et al. (2017)'s finding shows that a carbon price higher than US$75/t$CO_2$-e was not very effective in achieving a notable additional GHGs of Nepal's agriculture, forestry and other land-use (AFOLU) sectors.

Third, in the long run, realizing New Zealand's net emission target, including agricultural emissions, it is worth noting that free emission quotas allocated to the agricultural sector curb the increase in carbon prices but does not help to reduce the GDP loss (Scenario ETS-R2). Other study also claimed that the free emission quota directly impacts carbon trading prices, but will not have a direct impact on GDP and other economic and environment indicators (Li & Jia, 2016). Besides, the existence of free carbon allowances makes emission reduction in the agricultural sector full of uncertainty unless an additional sub-cap is set on.

Based on the analysis results, there are several policy recommendations. First, comprehensively considering the economic losses and emission reduction costs, it is necessary to set a mandatory total emission reduction target. Second, free carbon emissions from the agricultural sector should be distributed carefully to avoid large economic losses. It is recommended to accelerate the operation of NZ ETS with agriculture sector included, ensuring the smooth and effective operation of the carbon market.

Some uncertainties exist both in forest biomass and land-use changes. The sequestration modelled is essentially a "step change" removal when land is converted from agriculture to forestry, although it may gloss over important transitional dynamics, depending on how the NZ ETS actually operates and how forest owners/managers respond. Forestry growth conflicts with a standard production model in a recursive dynamic CGE model that outputs produced by these sectors depend on the inputs applied in the same year. This study assumed that new plantations will not be harvested during the simulation time span (2013-2050). That could be a reasonable simplification in the long run.

The results are affected to some extent by the limitations of the CGE model itself. This study adopts a dynamic recursive CGE model. In the short term, it is relatively easy to ensure the rationality of the model. However, in the long run, technological change could work to dampen the negative economic impact of higher priced carbon.

Appendix A.1 The remain modules and equations in the dynamic CGE model

Detailed equations of production structure and expenditure preferences

a. Output: Intermediate inputs + added value inputs nested based on CES production function

$$QA_i = \lambda_a \left[\mu_a QVA^{\frac{\sigma_1 - 1}{\sigma_1}} + (1-\mu_a) QINTA^{\frac{\sigma_1 - 1}{\sigma_1}}\right]^{\frac{\sigma_1}{\sigma_1 - 1}} \quad \text{(A.1)}$$

$$\frac{PVA_i}{PINTA_i} = \frac{\mu_a}{1-\mu_a}\left(\frac{QINTA_i}{QVA_i}\right)^{\frac{1}{\sigma}} \quad \text{(A.2)}$$

$$PA_i * QA_i = QVA_i * PVA_i + QINTA_i * PINT_i \quad \text{(A.3)}$$

b. b1. Value-added composite bundle: labor and capital composite bundle + land is nested through the CES production function

$$QVA_i = \lambda_{va} \left[\mu_{va} QLK^{\frac{\sigma_2 - 1}{\sigma_2}} + (1-\mu_{va}) QLAND^{\frac{\sigma_2 - 1}{\sigma_2}}\right]^{\frac{\sigma_2}{\sigma_2 - 1}} \quad \text{(A.4)}$$

$$\frac{PLK_i}{PLAND_i} = \frac{\mu_{va}}{1-\mu_{va}}\left(\frac{QLAND_i}{QVA_i}\right)^{\frac{1}{\sigma_2}} \quad \text{(A.5)}$$

$$PVA_i * QVA_i = QLK_i * PLK_i + QLAND_i * PLAND_i \quad \text{(A.6)}$$

b2. Intermediate inputs: Intermediate commodities of different industries are nested according to Leontief 's production function.

$$QINT_{ij} = \lambda_{int} * io_{ij} * QINTA_i \quad \text{(A.7)}$$

$$PINTA_{ij} = \sum io_{ij} * PQ_i \quad \text{(A.8)}$$

2.3.6 Dynamic module

This model adopts the recursive dynamic mechanism, which realizes the dynamics through the dynamic changes of labour growth and capital accumulation. The establishment of a recursive dynamic relationship mainly includes two paths. The first path is the traditional path, which implements the recursive dynamics of the model with the inter-temporal investment-savings evolution equation.

The capital stock in period *t+1* is mainly composed of two parts. The first part is the capital stock in period *t* minus capital depreciation, which represents the stock capital of the previous period. The second part is the total investment in period *t*, which represents the incremental capital of the previous period. Hence, previous stock and incremental capital together form the current capital stock. The equations for the recursive dynamic relationship of the traditional paths over time are detailed in the following formula:

$$KST_{t+1} = (1 + g_k) * (1 - dep) * KST_t + INVPS_t \quad (A.9)$$

Among them, KST_t and KST_{t+1} represent the capital stock in periods *t* and *t + 1*, $INVPS_t$ represents the total investment in period *t*, dep dep is the depreciation rate of macroeconomic capital, and g_k is the capital growth rate. The second path is a population growth path that is supplemented and improved on the basis of the traditional path. $gpop_t$ is the annual population growth rate for period *t*.

$$LST_{t+1} = (1 + gpop_t) * LST_t \quad (A.10)$$

Where, LST_{t+1} represents the labour supply level in year t+1. This model assumes that the labour growth rate is equal to the annual population growth rate. The labour growth rate in 2013-2050 is available according to the population growth rate provided by Statistics NZ. According to Statistics NZ, New Zealand's Overall gross fixed capital formation is 0.1 per cent.

2.3.7 Enterprise income and expenditure

Enterprise pre-tax income: mainly the portion of capital income allocated to the enterprise

$$YENT = shif_{ent_k} * PK * KS \quad (A.11)$$

Enterprise savings: Enterprise pre-tax income deducts income tax paid to the government and transfer payments to residents.

$$ENTS = (1 - t_{ent})YENT - transf_{h_{ent}} \quad \text{(A.12)}$$

Enterprise investment: The total investment of each sector forms the total investment, that is, capital formation (exogenous given).

$$ENTS = \sum_c PQ_c * \overline{QINV_c} \quad \forall\, c \in Commodities \quad \text{(A.13)}$$

2.3.8 Household income and expenditure

Household income: mainly includes labor income, capital gains, land rents, enterprise-to-resident transfer payments, and government-to-resident transfer payments.

$$YH = PL * QLS + PK * QKS * shif_{hk} + PLAND * LANDS * shif_{hland} + transf_{h_{ent}} + transf_{h_{gov}} \quad \text{(A.14)}$$

Household expenditure for goods demand: Expenditure on different types of goods is based on household disposable income (family income after deduction of personal income tax). The household utility function is assumed to be a Cobb Douglas utility function, so household consumption expenditures for different types of goods can be written as follows.

$$EH = shrh_c * mpc_h * (1 - t_h) * YH \quad \forall\, c \in Commodities \quad \text{(A.15)}$$

Household saving:

$$HS = (1 - mpc_h) * (1 - t_h) * YH \quad \text{(A.16)}$$

2.3.9 Government income and expenditure

Government revenue: it mainly includes the part of government revenue derived from production tax, domestic commodity consumption tax, income tax, and import tariffs.

$$YG = \sum_i t_p * PA_i * QA_i + t_h * YH + t_{ent} * YENT + \sum_C tm_c * pwm_c * QM_c * EXR$$

(A.17)

Government expenditure for commodities demand: the government utility function is assumed to be the Cobb Douglas utility function, so the government's consumption expenditure for different types of goods can be written as follows.

$$PQ_c * QG_c = shrg_c * mpc_g * \left(YG - transfr_{hg} - transfr_{ent_g}\right) \quad \text{(A.18)}$$

Government saving:

$$GS = (1 - mpc_g) * \left(YG - transfr_{hg} - transfr_{ent_g}\right) \quad \text{(A.19)}$$

2.3.10 Market clearing and closure conditions

When the market reaches a general equilibrium, all markets clear and supply equals demand. Investment equals savings and balance of payments are in equilibrium. Ultimately, the entire macroeconomic system is in equilibrium.

In the current economic development of New Zealand, the labour factor, capital factor and land supply are relatively sufficient. Assuming the total factor supply of all industries is equal to total demand.

Appendix A.2 Substitution elasticity

Table 3 Substitution elasticity

Symbol	Name	Nesting form	Values
σ1	Value-added and Intermediate	CES	0.75
σ2	Land and Labour-capital	CES	0.7
σ3	Non-Energy and Energy	Leontief function	-
σ4	Labour and Capital	Leontief function	-
σ5	Oil, gas, coal and electricity	CES	0.3
σ6	Crop-grass land and Scrub-other land	CES	5.8
σ7	Cropland and Grassland	CES	5.8
σ8	Scrubland and Other land	CES	5.8
σ9	Armington elasticity	-	-4
σ10	CET elasticity	-	2.5

Sources: Daigneault (2015), Fernandez and Daigneault (2015), Lee (2005), and Rae et al. (2008)

Appendix A.3 The abbreviation for 49 sectors

No.	Code	Sectors
1	HFRG	Horticulture and fruit growing
2	SHBF	Livestock and cropping farming
3	DAIF	Dairy cattle farming
4	OTHF	Other farming
5	FOLO	Forestry and logging
6	FISH	Fishing
7	AFFS	Agriculture, forestry, and fishing support services
8	COAL	Coal
9	OIL	Oil
10	OMIN	Other mining and quarrying
11	MEAT	Meat manufacturing
12	DAIR	Dairy manufacturing
13	OFOD	Other food manufacturing
14	BEVT	Beverage, malt and tobacco manufacturing
15	TCFL	Textiles and apparel manufacturing
16	WOOD	Wood product manufacturing
17	PARP	Paper and paper product manufacturing
18	PPRP	Printing, publishing, and recorded media
19	GAS	Gas
20	CHEM	Fertiliser and other industrial chemical manufacturing
21	RBPL	Rubber, plastic, and other chemical product manufacturing
22	NMMP	Non-metallic mineral product manufacturing
23	BASM	Basic metal manufacturing
24	FABM	Structural, sheet and fabricated metal product manufacturing
25	MAEQ	Machinery and other equipment manufacturing
26	OMFG	Furniture and other manufacturing
27	EGEN	Electricity generation and transmission and distribution
28	WATS	Water supply
29	WAST	Sewerage, drainage, and waste disposal services
30	CONS	Construction
31	TADE	Wholesale and retail trade
32	ACCR	Accommodation, restaurants and bars
33	RDTR	Road transport
34	RAIL	Rail transport
35	WATR	Water transport
36	AIRS	Air transport and transport services
37	COMM	Communication services
38	FIIN	Finance and insurance
39	REES	Real estate
40	EHOP	Equipment hires and investors in other property
41	OWND	Ownership of owner-occupied dwellings
42	SRCS	Scientific research and computer services
43	OBUS	Other business services
44	GOV	Central government administration and defence
45	SCHL	Pre-school, primary and secondary education
46	OEDU	Other education
47	HOSP	Hospitals and nursing homes
48	OHCS	Other health and community services
49	PERS	Personal and other community services

Chapter 3 Carbon tax and technological progress in agriculture sectors

Overview

The New Zealand government has introduced legislation to reduce agricultural CO_2-e emissions as part of its policy to transition to a low carbon economy by 2050. In 2018, New Zealand's agriculture emitted 37.7 Mt CO_2-e emissions, accounting for 48% of the total emissions. To this end, the government has set a target of reducing emissions from agriculture by 24%-47% of 2017 levels by 2050. It is challenging to implement policies to reduce emissions without damaging the interests of the agricultural sector. This chapter examines the impact on agriculture and the economy through a combination of a carbon tax and technological progress. Eight scenarios include five different tax rates and three alternative assumptions about technological progress: labour-augmenting, capital-augmenting, and land-augmenting. In the absence of technological progress, a carbon tax lowers GDP but does not cause a substantial reduction in CO_2-e emissions. However, we show that technological progress can offset the adverse impact on the agricultural sector. Land-augmenting progress outperforms labour and capital augmenting technological progress. Finally, we propound policy recommendations on how to promote New Zealand's transition to a low-carbon economy through carbon tax and technological progress in the agricultural sector.

3. 1 Introduction

Climate change caused by greenhouse gas emissions is one of the most severe issues facing the international community (Jiang, Zhu, Chevallier, & Xie, 2018). Reducing emissions from agricultural is a challenging issue (George et al., 2019). The World Food and Agriculture Organization (FAO) released the "State of Food and Agriculture 2016" report confirming that agriculture contributes about 20% of the world's GHGs. In order to achieve the ambitious goals agreed to in the Paris Agreement, agricultural GHG emissions should be reduced (Reisinger & Ledgard, 2013). New Zealand is in a unique position internationally as it is the only developed country whose agricultural

GHG emissions play a crucial role in the national emissions profile (Clark et al., 2011). Furthermore, New Zealand is also the only country in the world that integrates forestry into a carbon emissions trading scheme (Adams & Turner, 2012). In 2019, New Zealand's agriculture emitted 39.6 Mt CO_2-e emissions, which is the largest emission source and accounts for 48% of New Zealand's total emissions (MfE, 2020a). Hence, controlling agricultural CO_2-e emissions will make a massive contribution to achieving the government's emission reduction target. In particular, implementing relevant emission reduction policies without damaging the interests of the agricultural sector will be a huge challenge.

Because carbon price will increase the cost of agricultural products, and thus weaken New Zealand's agricultural international competitiveness, agriculture is the last sector to be included in the NZ ETS. At present, the policy about the agriculture sector is cautious and conservative. Agricultural emissions have been postponed into ETS (Leining et al., 2017). The government has set a target of net-zero emissions of all GHG emissions, except biogenic methane by 2050. For agriculture, the reduction target for biogenic methane is between 24% to 47% of 2017 emissions by 2050, with an interim 10% reduction below 2017 biogenic methane emissions by 2030 (MfE, 2019a). Meanwhile, NZ ETS encourages forest owners to increase forest plantation areas by receiving payment for carbon sequestration. However, reducing biogenic methane emissions from livestock has proved to be a major scientific challenge to which there are no effective solutions, other than reducing livestock numbers. Also, NZ ETS will cause the price of agricultural products in deprived areas to rise (Frank et al., 2017), and the agriculture-related emission reduction policies may be contrary to food security policies (Stevanovic et al., 2017).

A carbon tax is an alternative option for New Zealand reducing CO_2-e emissions. Fan et al. (2018) used an economic-energy-environment CGE model to analyse the impact of different rates of carbon taxes on China's economy and agricultural sector over 2020-2050. They found that the short-term effect of a carbon tax is more effective in reducing CO_2-e emissions, weakening carbon intensity and improving energy efficiency. Mardones and Lipski (2020) found that the impact of carbon taxes on agricultural CO_2-e emissions alone, ranging from US$5 to US$131 US dollars per ton, would not significantly reduce emissions. Mardones and Muñoz (2018) analysed the impact of Chile’s carbon tax on CO_2-e emission reduction by using the environmental expansion of the Leontief price model and found that the power sector has to bear a tax rate 20 times higher than the current level to achieve 30% emission reductions in 2030. In short, there are two difficulties in assessing the implications of the carbon tax. First, there may be uncertainty over achieving emissions reductions; second, there will be a challenge to set a tax rate that has minimal adverse economic impact on the agriculture sector.

The CGE model is well suited to explore the economic impact of carbon tax policies. Using a CGE model, Meng (2015) showed that a carbon tax would negatively impact all agricultural sectors. Incorporating the agricultural sector into the carbon tax plan was shown to result in a substantial decline in real GDP, and significant emissions reductions. Ntombela et al. (2019) used a dynamic CGE model to assess the potential impact of carbon tax policies on agriculture, food and other sectors in South Africa. Their results show that a carbon tax would reduce emissions by 33% compared to the benchmark by 2035. However, the carbon tax also leads to a welfare loss of US$5.9 billion. Other CGE studies conclude that a carbon tax contributes to carbon emission reduction but is not conducive to macroeconomic development (Benavente, 2016; Lu, Tong, & Liu, 2010; Sam Meng, Siriwardana, & McNeill, 2013).

Technological progress can work to mitigate the impact of a carbon tax. Wollenberg et al. (2016) point out that agricultural GHG emissions reduction requires a combination of transformative technologies (by improving livestock management, cropland management, and paddy rice management) and policy options to reduce emissions. Mosnier et al. (2019) used four bio-economic models to study the French dairy sector. Their results show that promising strategies of farms emissions abatement include measures to enable animals to realize their production potential and fully moderate land management. Shahbaz et al. (2016) analysed how technological improvement influenced carbon emissions in Malaysia from 1790 to 2011. They found that technological development, described by improving trade openness, leads to economic growth and eventually boosts carbon emissions. However, technological progress in these studies mainly refers to the improvement of “soft technology” such as management concepts and economic structure, which expands the connotation of technological progress. Technical progress in Solow’s economic growth model refers to the marginal productivity or factor-augmenting technology progress (Solow, 1957). One input factor is more conducive to improving the marginal output than the other (Hicks, 1963). Acemoglu (2002) furtherly pointed out that labour-augmenting technical progress, and capital-augmenting technical progress, are manifested by changes in the efficiency of production factors.

Studies point to the fact that technological progress shows different growth patterns in different countries and industries (Geylani & Stefanou, 2011; Oh et al., 2012). In most cases, technological progress may be biased towards one of the factors of production (Acemoglu, 2007; Acemoglu, Akcigit, Hanley, & Kerr, 2016; Caselli & Coleman II, 2006). For example, Chen, Oxley, Xu, Wang, and Ma (2013), using DEA, found that gains in capital and land productivity dominated China's wheat output rather than labour-intensive operations. In contrast, Key (2019) found that labour-augmenting technological progress facilitates greater productivity on American farms. Zhang, Sun, Wu, and Deng (2016) used a multi-regional CGE model to investigate the effects of labour-augmenting and capital-augmenting technological progress on China's food production. Their results show that labour-augmenting progress outperforms capital-augmenting progress in food production. Other research used CGE model in agricultural sector from the view of the total factor productivity (Ianchovichina, Darwin, & Shoemaker, 2001), in this literature, they studied the impact of a slowdown in agricultural total factor productivity (TFP) on agriculture, forest resources, and the global economic and population growth. The results showed that a decrease in agricultural TFP growth might lead to higher crop prices in all regions. However, these studies did not consider climate change or CO_2-e emissions in agriculture sector. The recent research of Tokunaga, Okiyama, and Ikegawa (2020) used the CGE model to simulate global warming with adaptation technology on Japan's rice production and economic effects. They found that adaptive technologies such as high-temperature-tolerant rice varieties are developed, the impact of climate change on rice production will be reduced.

Research on technologies to reduce agricultural GHG emissions in New Zealand has focused on animal, feed, soil and management interventions (Beauchemin et al., 2008; De Klein & Eckard, 2008; Kirschbaum et al., 2015; McNally et al., 2017). Few studies focus on the impact of factor-augmenting technical progress and the introduction of a tax on agricultural emissions in New Zealand but emphasize specific technologies. For example, Carroll and Daigneault (2019) used a New Zealand economic land-use model to estimate the benefits and costs of implementing land-based GHG emissions reduction practices with gross GHGs reduction by 2% to 62%. Their results show that the cost and effectiveness of modelled practices are highly variable. Methane inhibitors are estimated to be highly effective but costly, while targeted urine patch treatments are cheap but less effective. Afforestation and methane vaccines cost less than \$50/tCO_2-e and could reduce NZ's GHG emissions by 20%. When the reduction targets range from 10% to 50%, the marginal costs could be between \$15 and \$162/tCO_2-e and well within the range of estimates of achieving low emissions pathways, which is lower than the estimated costs for NZ's energy and transportation costs to meet similar GHG targets (Ballingall, Pambudi, & Corong, 2018).

This chapter uses a land based dynamic CGE model to comprehensively analyze the macroeconomic and land use effects of a carbon tax levied on agricultural emissions, given alternative scenarios of technological progress: labour-augmenting, capital-augmenting progress and land-augmenting technological progress. The results show that land-augmenting technological progress can reduce the adverse impacts of a carbon tax on agriculture from a macro perspective. As to the specific practices, this study did not model them into the CGE model, However, the technology progress related to land productivity should be considered as the priority in the long run, such as stock reduction for fallow and afforestation on marginal land, CH_4 and N_2O inhibitor adopted.

This study contributes to the literature as follows. First, it analyses the impact of a tax on agricultural emissions and the economy using a dynamic recursive land-based CGE model. Second, it combines an agricultural carbon tax with agricultural factor-augmenting technology progress. This fills the gap in the existing literature that does not comprehensively consider the impact of agricultural emission reduction on the competitiveness of agricultural sectors from the perspective of the economic system, such as the GDP growth, agricultural output, domestic prices, imports and exports. Agricultural technological progress is characterised as: labour-augmenting, capital-augmenting, and land-augmenting. This classification enables us to explore the differential impacts of technological progress, given an emissions tax, on the economy and agricultural GHG emissions reduction. Third, unlike previous studies, CO_2-e emissions related to agriculture are mainly methane emissions from enteric activity, nitrous oxide emissions from manure and nitrous oxide emissions from fertilizer use (Kerr & Zhang, 2009). Following Timar and Kerr (2014), this chapter defines land-use intensity as the volume of a selected activity on different land types; for example, dairy land use includes milk production, the slaughter of dairy cattle and synthetic fertiliser use. Therefore, CH_4 and N_2O can be treated as CO_2-e emissions associated with land-use intensity and adjusted to make sure aggregate emissions determined via the use of emission factors are consistent with New Zealand's Greenhouse Gas Inventory emissions.

The chapter is structured as follows, section 3.2 explains the land-based CGE model and data input. Section 3.3 provides an explanation of the different scenarios of technological progress and agricultural CO_2-e emissions tax scenarios. Section 3.4 presents the simulation results and discussion. Sensitivity analysis is presented in Section 3.5. Conclusions and suggestions follow in Section 3.6.

3.2 Land-based CGE model and data input

In this study, the New Zealand land-based CGE model includes production modules, land use modules, trade modules, dynamic mechanisms, macro closure and other modules.

3.2.1 Production modules

Factor inputs include labour and capital. For the agricultural sector, it includes land along with labour and capital. The model assumes that the market is completely perfect competitive, and all sectors make decisions about factor input and product output based on the principle of cost minimization under constant returns to scale. They use multi-level nested production functions under the principle of cost minimisation. The first level combines the total intermediate inputs (INT) with the total factor inputs (Value-added) Combined. The constant elasticity of substitution (CES) production function is nested between labour-capital and land to form a composite production factor. The composite production factor and intermediate inputs produce total output according to the CES production function. The structure is shown in Figure 10 below.

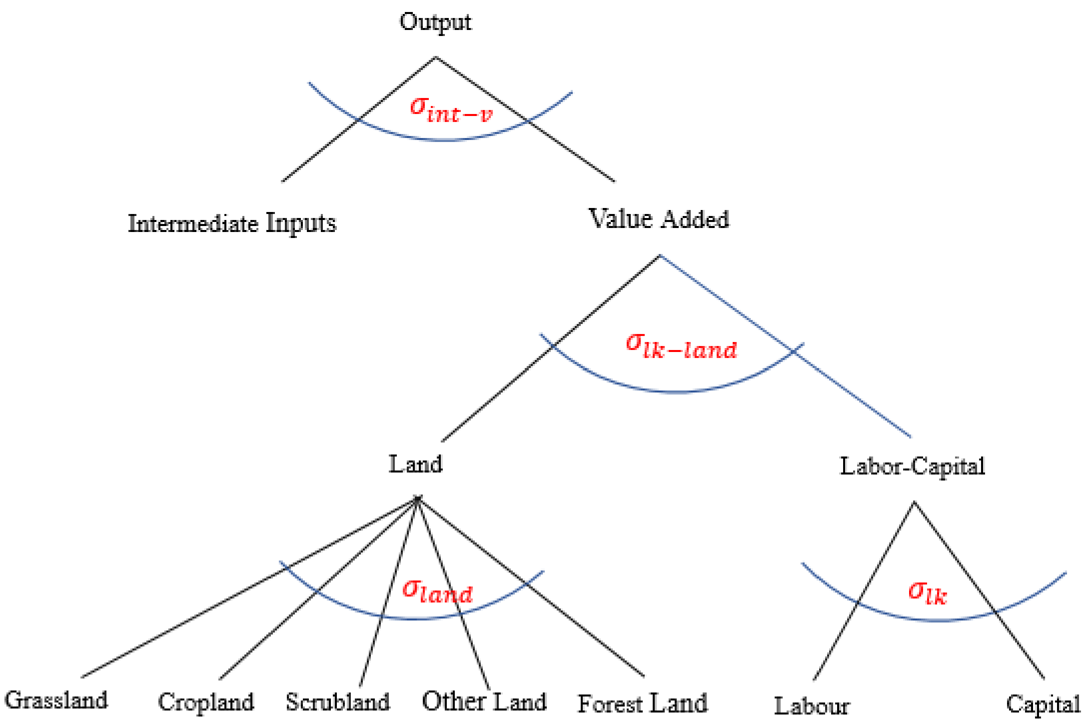


Figure 10 The structure of production block

3.2.2 Land-based block

Land input as a factor of production is geographically immovable, but it is possible to change land use. This module is useful for studying the effects of the changes of different land-use under exogenous shocks on the achievement of New Zealand's agricultural CO_2-e emission reduction targets. The agricultural CO_2-e emission module is reflected in land use. CO_2-e emissions are obtained by multiplying different patterns of land use by the corresponding land use carbon emission coefficient.

$$QLAND_a = \lambda_{land} \cdot (\sum_{a \in A} \delta^a_{land} \cdot land_a{}^{-\rho_q})^{\frac{1}{\rho_q}} \quad (3\text{-}1)$$

$$PLA_a = (1/\lambda_{land}) \cdot (\sum_{a \in A} \delta^a_{land} \cdot PLAND_a{}^{1-\rho_q})^{\frac{1}{1-\rho_q}} \quad (3\text{-}2)$$

$$AGCO2_a = LAND_a \cdot emf_a \quad (3\text{-}3)$$

$$TXAGCO2 = \sum_{a \epsilon A} tco2 \cdot AGCO2_a \quad (3\text{-}4)$$

Where, $AGCO2_a$ is the CO_2-e emissions of the agricultural sector, emf_a is the corresponding land carbon emission coefficient. $PLAND_a$ and $LAND_a$ are the price and input quantities of different types of land, respectively. $tco2$ is the carbon tax rate per unit of CO_2-e emissions in the agricultural sector.

3.2.3 Trade module

Commodities supplied come from domestic production and imports, which together meet the needs of domestic consumers, Non-Profit Institutions Serving Households (NPISH) and the government. The substitution relationship between domestic production and imports that satisfies the Armington condition. In order to achieve the lowest consumption cost, rational consumers will optimize the combination of domestic and imported goods when purchasing goods. In the modelling, the Armington hypothesis adopts the constant substitution elasticity (CES) function; that is, the relationship between imported products and domestic products is incomplete substitution. The model assumes that the price of imported goods is given exogenously. Because of the small economy of New Zealand, the price of imported goods is determined by the international market price, and New Zealand is the price taker (Daigneault, 2015).

Similarly, under the assumption of a small economy, export commodities are also determined exogenously by international market prices. The total domestic output is sold at the local market and abroad following the principle of maximizing profit. Producers optimize the combination of domestic sales and export, and the combination relationship is allocated using the constant elasticity of transformation (CET).

3.2.4 Dynamic mechanism

Variables in the dynamic equations are divided into two categories. The first category is exogenous growth, which is driven by the labour supply. In the long run, the labour force and the population keep increasing or decreasing in the same direction, and the population is affected by economic policies. Therefore, in the dynamic CGE model these variables are exogenous. The other category is the supply of capital. The growth rate of the capital stock is driven by investment, whose size is affected by the rate of return on capital. The dynamic model adopts the form of recursive dynamics, which are realized through labour force growth and capital accumulation. Among them, the labour force of each sector in the base year is given exogenously. The current capital stock is equal to the previous capital stock plus new capital, minus depreciation. The distribution of new capital among different sectors is endogenous and determined by a constant transformation elasticity (CET) function so as to maximize capital gains.

3.2.5 Macro closure module

The CGE model embodies the principle of general equilibrium. This chapter uses neoclassical closure, including product market equilibrium, factor market equilibrium, and equality of investment and savings. The equilibrium state of the economy refers to a stable state of the relative balance between supply and demand. When the economy reaches an equilibrium state, the supply and demand of each commodity in the commodity market are equal; in the factor market, the supply and demand of labour, capital and land are equal. There are mutual influences between various products and production factors, and they are continuously adjusted to achieve a simultaneous equilibrium between the product market and the factor market.

The total supply of labour, capital, and land is given exogenously at the benchmark year. The allocation among different sectors is automatically adjusted according to the profit maximization of each sector. That is, the total supply of factors in all industries is equal to the total demand for factors. The equilibrium price can be calculated under market equilibrium conditions, which represents the solution of the nonlinear equation system.

3.2.6 Data input

This study uses 2013 as the base year, and the primary data for the model draws from the following sources. First, the New Zealand Social Accounting Matrix (SAM), compiled according to New Zealand's 2013 Input-Output table, the period of this model is selected as 2013-2050. The input of land as a factor input of the agricultural sector is divided into cropland, scrubland, grassland and other land. Second, the land emission coefficient is estimated by Timar and Kerr (2014). Third, the elasticity of substitution is exogenous, adopted from some previous literature, including the elasticity of substitution between inputs in the production function, the elasticity of substitution between imports and domestic products in the CES function of the trade module, and the export and domestic products in the CET function (Fernandez & Daigneault, 2015; Paltsev et al., 2005).

3.3 Scenario settings

The New Zealand government set a target of reducing emissions by 11% of 1990 levels by 2030 and proposed a long-term climate change policy to reduce all greenhouse gases other than biogenic methane emissions by 2050. In 2017, agricultural biomethane emissions were 73.3% of total agricultural emissions. According to the Climate Change Commission's requirements, the agricultural sector needs to reduce biomethane emissions by 10% by 2030 compared to 2017, and 24%-47% by 2050. To protect the competitiveness of the agricultural sector, farmers and producers are not currently obliged to surrender the biological emissions from agricultural activities. However, the government is considering to find the best way to include biological emissions into NZ ETS (MPI, 2020). Leining et al. (2020) reported on the policy insights of NZ ETS. It is expected that agricultural bio-emissions will be priced from 2025. Land use-related emissions remain a strategic issue for the future. According to MfE (2020b), has announced new price restrictions intended to prevent unacceptably high or low auction carbon prices. The government has acknowledged limiting the price floor at $20 after 2020 and increased by two per cent for each following year.

This study simulates the use of a carbon tax on agricultural carbon emissions. Here, it treats the flooring carbon price as determined under the ETS as the carbon tax and examines the effect on agricultural CO_2-e emission reduction, the change in land use and its impact on the macroeconomy. First, the energy and forestry sector are already included in the ETS, both emissions and sequestration are priced, so the study includes this as business as usual (BAU). Thus, if the ETS carbon price floor is NZ$20 per tonne in 2020, carbon tax levied on agriculture emissions is NZ$20 per ton in the SA1 scenario. To study the use of tax revenue, we also set scenario SA2 to see what is different from SA1. In Scenario SA3, the carbon tax is assumed to increase at a rate of 2% annually. To explore the sensitivity to carbon tax rates, this study also set another two different tax rates: $50, $100. The detail scenario settings are shown in Table 4 below.

Second, according to Acemoglu (2007), technological progress is divided into neutral technological progress, labour-augmenting technical progress, and capital-augmenting technical progress. When setting scenarios, the study also includes land-augmenting technological progress in order to examine the effect of technological progress on carbon emissions. According to the IEA (2018), New Zealand's energy intensity has improved at an average annual rate of 1.4% since 1990. Table 4 shows three scenarios (SAT1, SAT2, SAT3) that include technological change at a constant 2% annual growth rate from 2020.

Table 4 Scenario settings

Scenario		Carbon Tax levied	Carbon Subsidy	Tax or Subsidy Rate (change from 2020)	Technology type	Annual efficiency change rates (%)	Revenue assigned to:	
							Household	Government
Base case	BAU	Energy	Forest	20$ per ton of CO_2-e	-	-	-	
Scenario A	SA1	Energy and Agriculture	Forest	20$ per ton of CO_2-e	-	-	YES	-
	SA2	Energy and Agriculture	Forest	20$ per ton of CO_2-e	-	-		YES
	SA3	Energy and Agriculture	Forest	Price increased at a rate of 2% per year based on $20 per ton	-	-	YES	
Scenario AE	SAE1	Energy and Agriculture	Forest	50$ per ton of CO_2-e	-	-	YES	
	SAE2	Energy and Agriculture	Forest	100$ per ton of CO_2-e	-	-	YES	
Scenario AT	SAT1	Energy and Agriculture	Forest	20$ per ton of CO_2-e	Labour-augment	2013-2019:0%; 2020-2050:2%	YES	-
	SAT2	Energy and Agriculture	Forest	20$ per ton of CO_2-e	Capital-augment	2013-2019:0%; 2020-2050:2%	YES	-
	SAT3	Energy and Agriculture	Forest	20$ per ton of CO_2-e	Land-augment	2013-2019:0%; 2020-2050:2%	YES	-

Note: labour augment technological progress increased by 2% means marginal production of labour increased by 2%.

3.4 Simulation results

3.4.1 Impact on the macroeconomy

We first analyse the impact of carbon tax policies on the macroeconomy. It can be seen from Table 5 that different rates of the carbon tax imposed on the agricultural sector have different effects on major economic indicators and CO_2-e emissions. Compared with the BAU scenario, the percentage changes of main macroeconomic variables vary over time. When the carbon tax is equal to $20 (SA1 and SA2), the negative impact on New Zealand's GDP growth rate decreases over time. For example, in Scenario SA1, GDP will be 0.208% lower than that without an agriculture carbon tax (BAU) in 2030. In 2050, GDP will drop by 0.156%. When the carbon tax is greater than $20 per ton, the negative impact increases. For Scenario SA3, when the carbon tax rate increases at a rate of 2% from the base of $20 per ton, GDP will drop slightly more than that in SA1, 0.358% and 0.638% by 2030 and 2050, respectively. When the carbon tax is $50 in Scenario SAE1, GDP will drop by 0.359% in 2030, which is similar to SA1. However, as time goes on, the GDP decline increases to 0.622% by 2050. In Scenario SAE2, the GDP will decline by 0.437% in 2030 and decline to 0.870% by 2050.

Tax revenue collected by government in Scenario SA2 reduces total consumption, investment and net export, thereby increasing carbon tax damage to GDP above that that in Scenario SA1. Emission reduction is similar under SA1 and SA2. Regardless of the form of taxation, final consumption, government and NPISH expenditure and imports are reduced by the carbon tax. Although, the effect of a carbon tax (less than $50) on household consumption is positive but not large. For example, the decline in household consumption is 0.090% in 2030 compared to the BAU scenario, and the consumption rate increases 0.352% in 2050 in Scenario SA1. When tax revenue is assigned to the government in SA2, household consumption falls slightly.

The effect of a carbon tax on household consumption and government consumption depends on how the carbon tax revenue is distributed. Consumption is affected by two variables: commodity prices and income. When commodity prices rise, consumption falls; when income increases, consumption goes up, it depends on which variable has more effect. From these scenarios we simulated, higher carbon taxes are as negative to the economy as expected.

Table 5 Changes of macroeconomic indicators from the BAU baseline (%)

	SA1		SA2		SA3		SAE1		SAE2	
	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
GDP	-0.208	-0.156	-0.206	-0.164	-0.358	-0.638	-0.359	-0.622	-0.437	-0.870
Final Consumption	-0.136	-0.387	-0.136	-0.395	-0.263	-0.596	-0.263	-0.576	-0.328	-0.674
Household	0.090	0.352	0.088	0.341	0.015	0.099	0.019	0.123	-0.018	-0.007
NPISH	-2.014	-1.606	-2.010	-1.612	-2.065	-1.772	-2.051	-1.749	-2.053	-1.810
Government	-2.024	-1.674	-2.018	-1.676	-2.063	-1.804	-2.052	-1.790	-2.049	-1.833
Investment	0.063	0.981	0.063	0.971	-0.055	0.488	-0.056	0.504	-0.119	0.235
Export	0.696	0.982	0.674	0.930	0.516	0.628	0.569	0.760	0.474	0.582
Import	-0.563	-0.394	-0.555	-0.385	-0.739	-0.884	-0.755	-0.911	-0.847	-1.167
Domestic demand	0.307	0.521	0.298	0.495	0.191	0.242	0.213	0.306	0.152	0.164
Agricultural emissions	-0.741	-2.006	-1.933	-2.062	-1.866	-4.548	-1.866	-4.400	-2.453	-5.655
Energy emissions	-0.011	-0.032	-0.025	-0.068	-0.087	-0.243	-0.089	-0.170	-0.188	-0.331
Forestry sequestration	2.158	8.065	1.089	5.886	3.171	10.189	6.322	16.540	7.329	18.588

As the carbon tax increases, total investment decreases because the total investment is determined by total household savings, NPISH, enterprise, government and the rest of the world, according to the closure rule. Economic agents do not generate enough savings to sustain the previous investment level of the economy due to the tax burden (Mahmood & Marpaung, 2014). However, with development of the economy, investment increases but at a decreasing rate.

It can be seen from Table 5 that the reduction effect has been achieved by taxing CO_2-e emissions in agriculture sectors. In Scenario SA1, when the carbon tax rate is $20 per ton, the impact on agricultural emissions reduction is 0.741% in 2030, 2.006% in 2050. However, in this scenario, it has slight effect on energy-related CO_2-e emission, the reduction is 0.011% in 2030, 0.032% in 2050. Even when the tax rate is increased to $100 per ton in Scenario SAE2, the energy-related emission reduction is small compared to the reduction of agricultural sector production. Emission reductions are 2.453% in 2030, 5.655% in 2050, respectively, compared to the BAU scenario. These reductions do not meet the government's target reducing biomethane emissions by 10% by 2030 compared to 2017, and 24%-47% by 2050. In the long run, the carbon tax will reduce New Zealand's export competitiveness.

As to forestry sequestration, in Scenario SA1, when the payment to forestry is $20 per ton of CO_2-e, the carbon sequestration will increase 2.158% in 2030, 8.065% in 2050. In table 2, with the increase in subsidy rate, carbon sequestration is expanding. For example, in scenario SAE2, the subsidy rate increased to $100 per ton, carbon sinks will increase by up to 18.588%. The reason behind this phenomenon is that carbon subsidies stimulate the expansion of forest planting. At the same time, the agricultural carbon tax has converted grassland and cropland with high carbon intensity into forest land.

3.4.2 The output changes of agriculture and related industries

The economic effects of carbon taxes are reflected in the macroeconomy and the output levels of various industries. Here, we analyse the changes in the output level of sectors related to the agricultural primary product and agricultural product processing. In Figure 11, compared with the BAU scenario, no matter what level the carbon tax rate is imposed on agriculture sectors, the output from the dairy sector falls through 2050. In Scenario SA3, the output of dairy manufacturing falls. Except for these two sectors, the output of other agricultural sectors increases. It may be closely related to the land use of dairy cattle farming and dairy manufacturing -grassland, which has a high CO_2-e emission intensity according to Timar and Kerr (2014). Taxation will increase the sectors' cost and increase the output price, which in turn will result in profit squeezed and output decreased. On the contrary, the output of the forestry and logging sector increases the fastest because the carbon credits received from sequestration reduce production costs, which promote the expansion of output. Also, the output of other industries has increased to varying degrees.

Under the SA1 scenario, the agricultural sector has the lowest tax revenue, and its positive impact on output is more significant than that of SA2 and SA3. In the SA2 scenario, after the government levied the tax, agricultural output is lower than in the other two scenarios. The possible reason is that due to the reduction in household income, the demand for agricultural products has weakened.

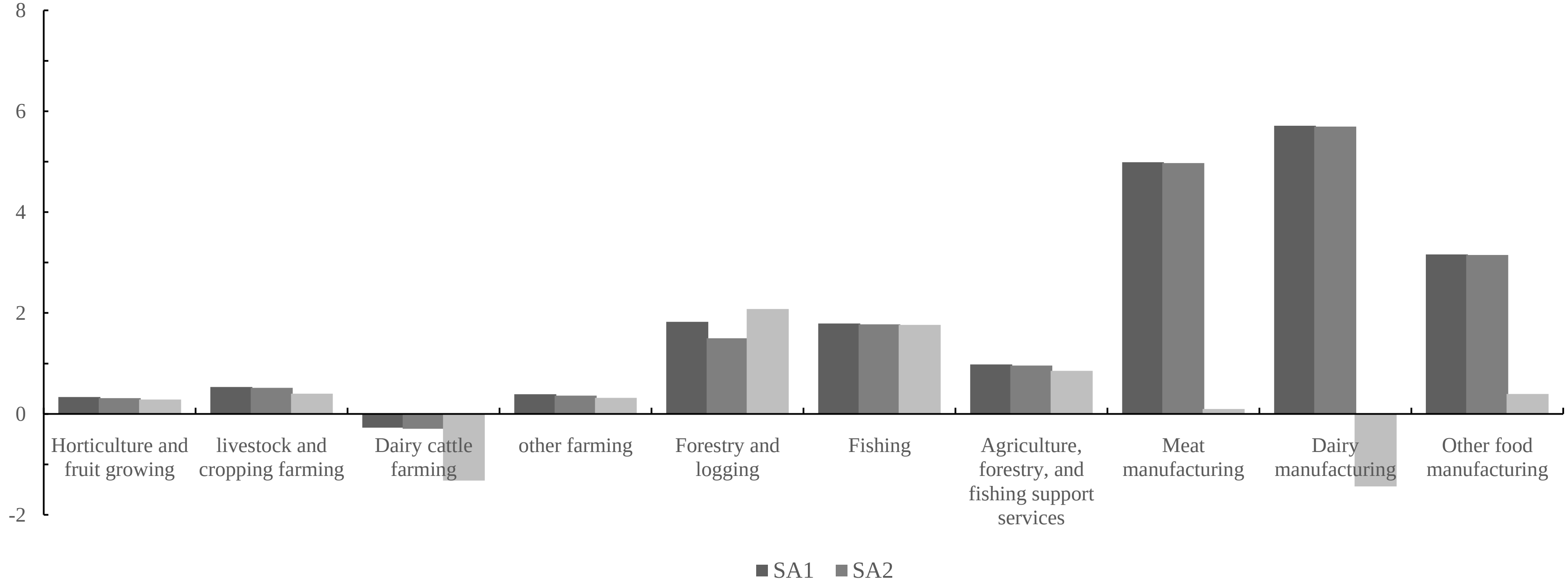


Figure 11 the output of agriculture and related industries under different taxes in 2030

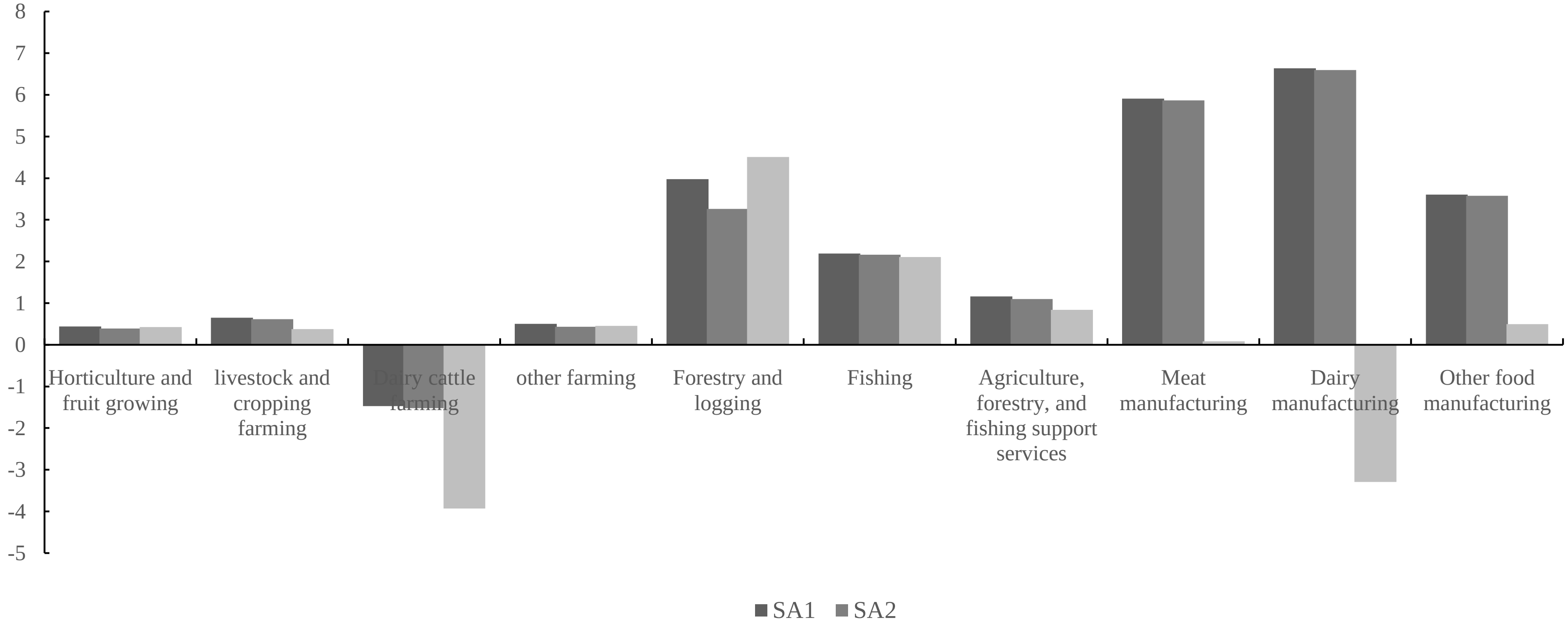


Figure 12 the output of agriculture and related industries under different taxes in 2050

3.4.3 Land use and land changes

In Figure 13, compared with the BAU scenario, no matter what level of carbon tax, grassland is converted to forest land, but the degree of change differs. The main reason is that the tax has different impacts on conversion of land use. Land-use types that are associated with higher CO_2-e emissions will bear the tax. Based on the principle of cost minimization, rational producers will choose more land with a small carbon emission coefficient (such as scrub\forest) for production activities. The higher the carbon tax, the more grassland will be converted to Forestry land. For example, in Scenario SAE2, grassland is reduced by 6.832% in 2050, and the forestry land is increased by 18.588%. Carbon emission coefficients differ across land use categories, grassland has a high carbon emission coefficient because of farming methods and fertilizer use. When the carbon tax policy is implemented, the land with a high carbon emission coefficient bears a higher carbon tax cost, the use of this type of land is reduced. Decreased grassland results in reducing livestock numbers[1].

Our results provide insights into the relationship between CO_2-e emissions and land-use change. The conversion of grassland to forestry land directly leads to a net reduction of CO_2-e emissions. However, as mentioned in the above section, the different carbon tax rates on agricultural sector contribute slightly to abate agricultural CO_2-e emissions. As general fiscal revenue, subsidizing carbon tax revenue to the forestry sector will change the pattern of land use to and provides new ideas for the agricultural sector to deal with climate change.

[1] The Climate Change Commission has released a draft blueprint in Feb 2021 with one of recommendations to slash livestock numbers by about 15 percent. The result is consistent with this study, which has been doing with the dynamic CGE model since November 2019.

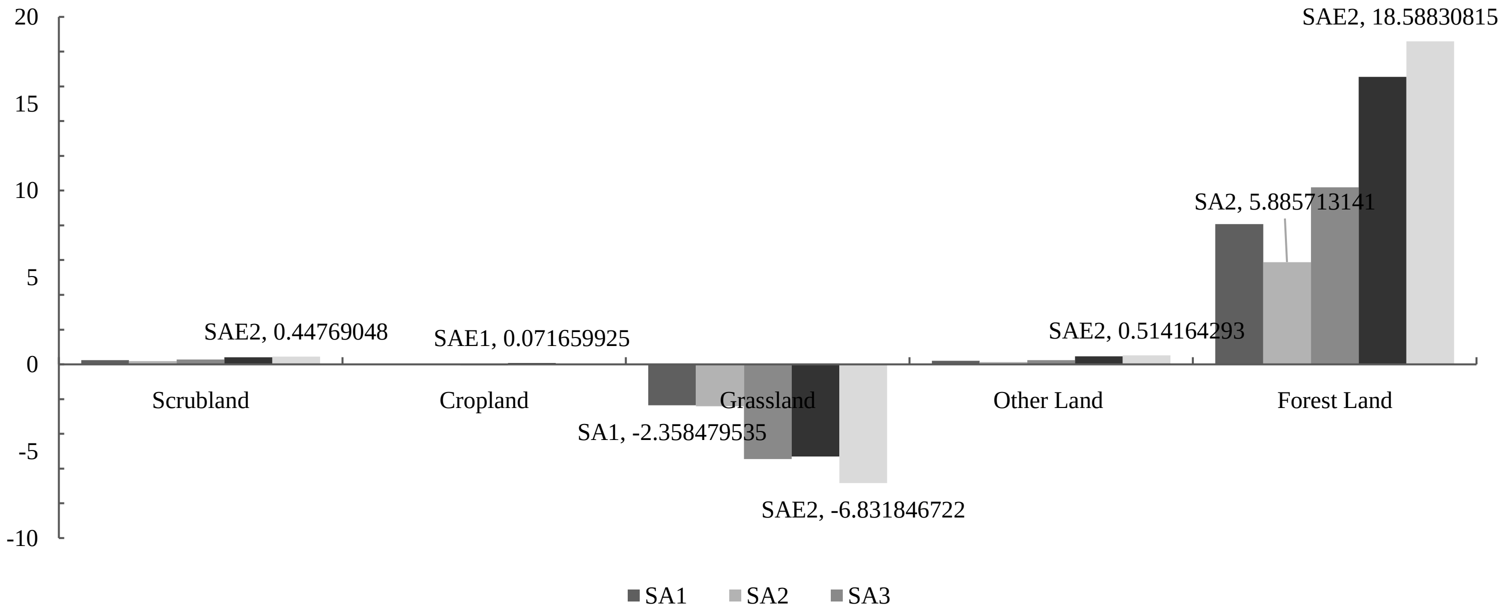


Figure 13 Land use changes under different carbon taxes in 2050

Based on a carbon tax of NZ$20/ton in Scenario SA1, it can be seen from Figure 14, when different types of technological progress impact the agricultural sector, the conversion of land use is further affected. Under Scenario SAT1, when labour-enhancing technology progresses by 2% per annum, the use of scrubland and other land and forest land increases, while the use of cropland and grassland decrease. Similar results are found under Scenario SAT2.

Furthermore, the impact of labour-enhancing and capital-enhancing technological progress (SAT1 and SAT2) on Grassland is not different. In scenario SAT3, when the land-enhancing technology progresses by 2% per annum, the area of cropland and grassland falls, the area of other land uses increase, especially forest land which increases by 7.603% in 2050.

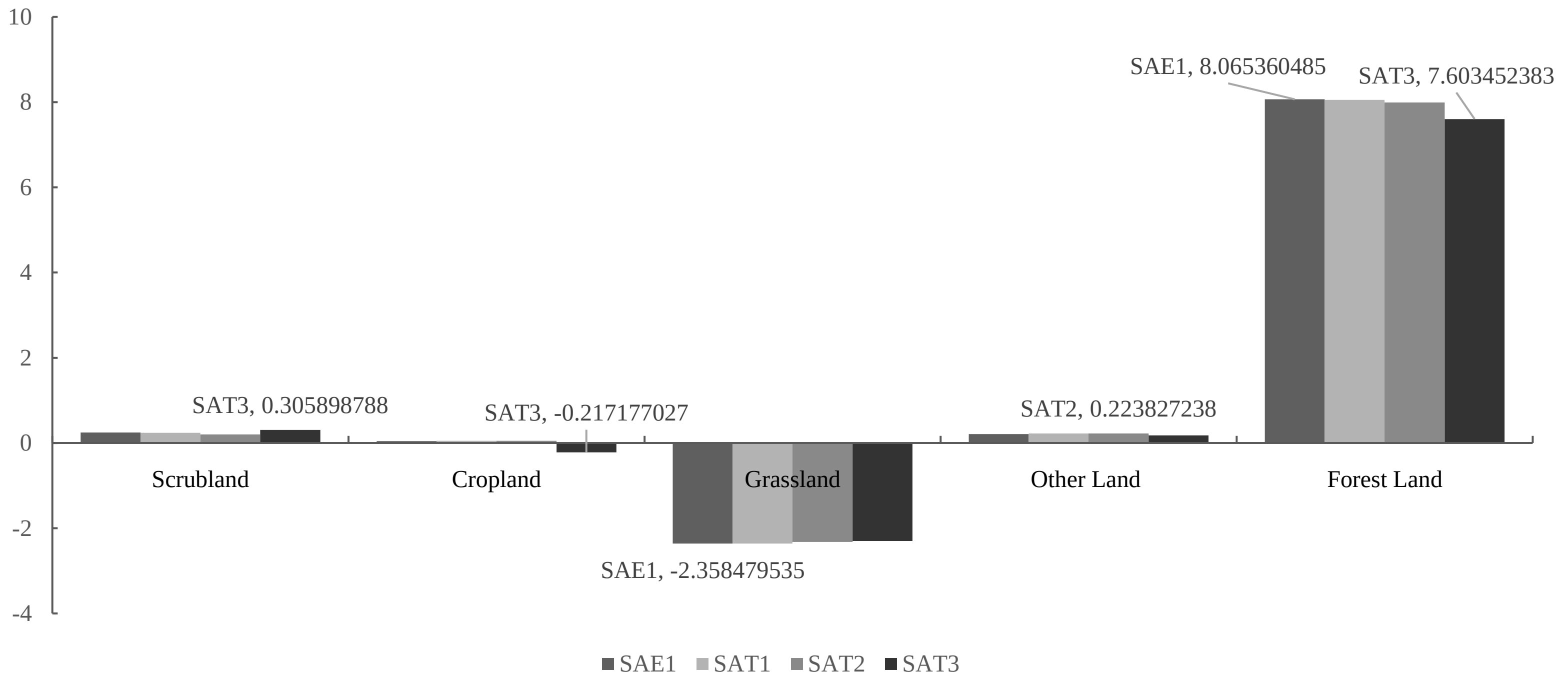


Figure 14 Land use changes under different technologies in 2050

3.4.4 The impact of different technological progress

Typically, the improvement of technological innovation is conducive to the reduction of emissions. However, when accounting for the substitution effect, it leads to increased CO_2-e emissions. Amri et al. (2019) claimed that whether technological progress effectively helps carbon reduction is still controversial. It can be seen from Table 6, compared to SA1, technological progress promotes the development of the macroeconomy by buffering the negative impact of the carbon tax but increases CO_2-e emissions.

In the three technological simulations SAT1, SAT2 and SAT3, the CO2-e emissions increased by about 0.002%, 0.025%, and 0.041% by 2050. Table 5 presents the combined effect of the carbon tax and agricultural technological progress. It is evident that the impact of increasing costs brought about by tax levied in the production sector has been offset to some extent by technological progress, SAT1, SAT2 and SAT3 increase GDP by 0.055%, 0.129% and 1.238% by 2050, respectively. Technological progress also contributes to other macroeconomic improvements. Among them, in Scenario SAT3, macroeconomic variables have increased the most, which means the improvement of land-augment productivity is the most effective in alleviating the agricultural carbon tax’s harmful effects, followed by capital-augment productivity improvement.

Table 6 Changes of macroeconomic variables in different scenarios from SA1 (%)

	SAT1			SAT2			SAT3		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
GDP	0.030	0.044	0.055	0.065	0.098	0.129	0.625	0.889	1.238
Final Consumption	0.026	0.040	0.037	0.057	0.091	0.084	0.506	0.771	0.648
Household	0.017	0.032	0.043	0.039	0.075	0.101	0.230	0.500	0.759
NPISH	0.011	0.023	0.031	0.019	0.046	0.066	0.158	0.363	0.546
Government	0.011	0.020	0.026	0.016	0.037	0.053	0.156	0.306	0.445
Investment	0.028	0.035	0.053	0.061	0.076	0.124	0.720	0.773	1.338
Export	0.043	0.052	0.055	0.111	0.133	0.137	0.269	0.447	0.583
Import	0.033	0.046	0.054	0.072	0.103	0.125	1.127	1.398	1.726
Domestic demand	0.028	0.040	0.046	0.063	0.090	0.105	0.286	0.493	0.681
Agricultural emissions	0.002	0.002	0.002	0.024	0.025	0.024	0.020	0.025	0.041
Energy emissions	0.021	0.035	0.044	0.048	0.080	0.103	0.012	0.254	0.483

Figure15 and 16 show the import and export changes in specific sectors caused by different technological simulations-the import and export of most sectors all increase. However, the importation of agricultural commodities has decreased in SAT1 and SAT2, which is due to the cost of domestic production caused by the carbon tax has been offset by the improvement of labour and capital productivity. This makes domestic products more competitive against international products. Land-enhancing technological progress in SAT3 can reduce domestic commodity prices to the greatest extent, compared with the other two types, exports of agriculture have increased by 1.06%. In contrast, agricultural imports have increased by 0.67%. Because agriculture is New Zealand's pillar industry, the advancement of land-enhancing technology results in an increase in its exports.

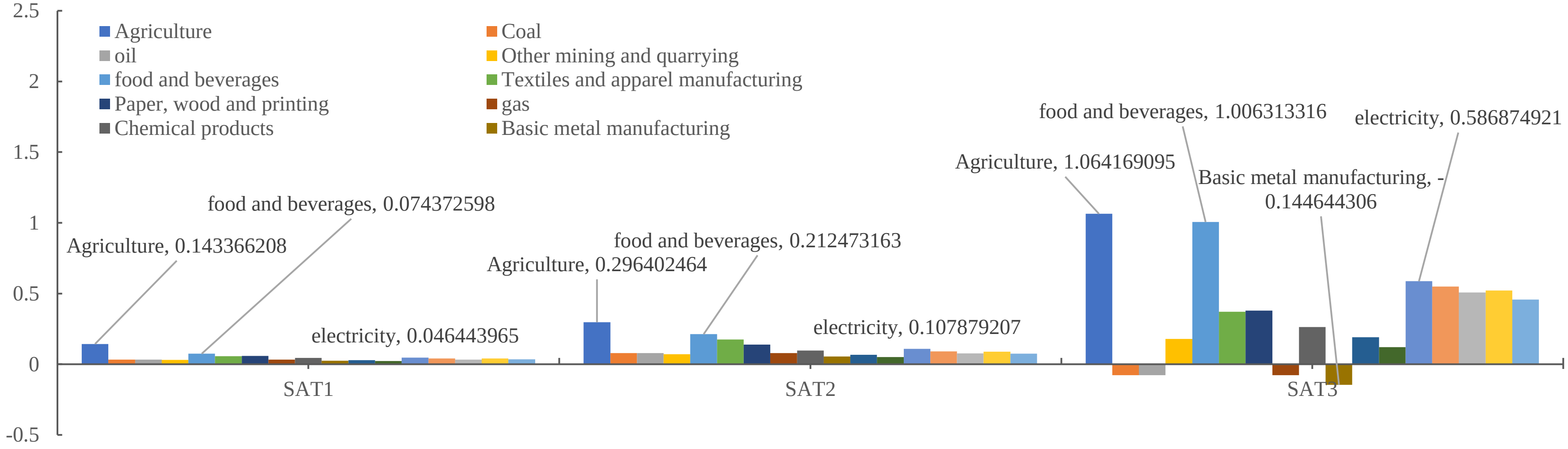


Figure 15 Export changes from the SA1 in different technological simulations in 2050 (%)

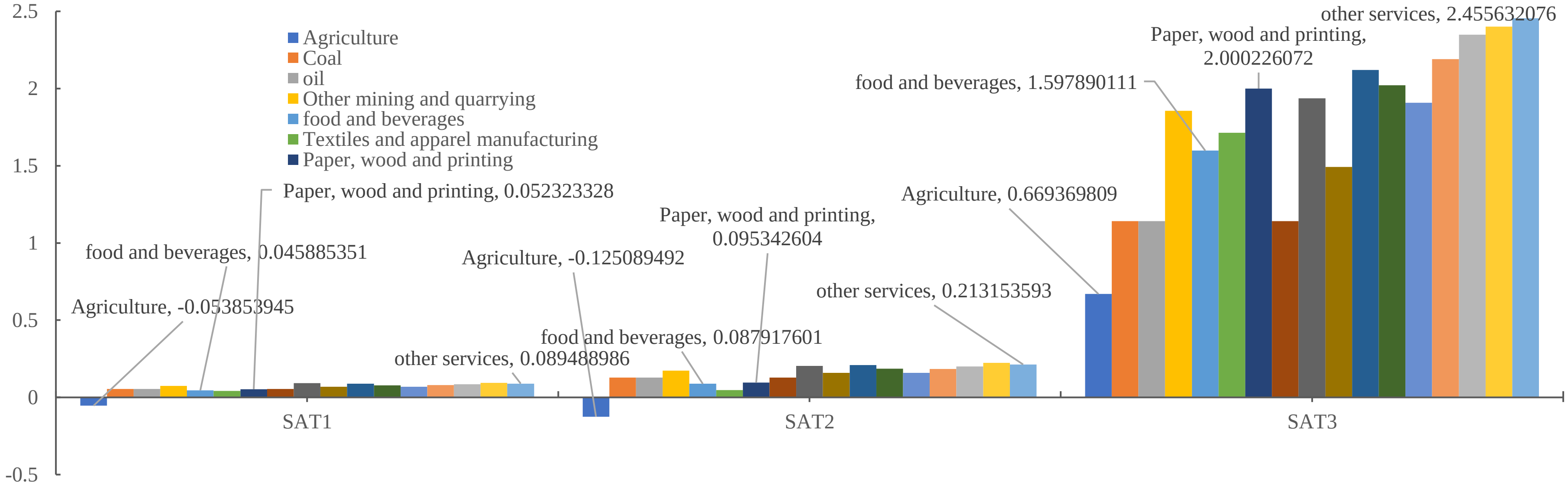


Figure 16 Import changes from the SA1 in different technological simulations in 2050 (%)

3.5 Sensitivity analysis

To check the model's stability, the study focuses on the substitution elasticity between labour-capital and land composition ($\sigma_{lk-land}$), and land inter-substitution elasticity among scrubland, cropland, grassland, other land, forest (σ_{land}). Elasticity values are reduced or increased by 20% in three different scenarios. The results of Table 7 show that the rates of change of GDP and other macroeconomic variables are not sensitive to changes in the elasticity of substitution, which shows that our model is stable.

Table 7 Sensitivity analysis of substitution elasticity

Scenarios	Selected indicators	Parameters			
		$\sigma_{lk-land}$		σ_{land}	
		+20%	-20%	+20%	-20%
SA1	GDP	-0.0013	0.0016	0.0008	-0.0011
	Output	0.0003	-0.0003	-0.0001	0.0001
	Import	-0.0004	0.0004	0.0002	-0.0003
	Export	0.0001	-0.0001	-0.0001	0.0001
	CO_2 emission	0.0000	0.0000	0.0000	0.0000
SAE1	GDP	-0.0013	0.0016	0.0008	-0.0011
	Output	0.0003	-0.0003	-0.0001	0.0001
	Import	-0.0004	0.0004	0.0002	-0.0003
	Export	0.0001	-0.0001	-0.0001	0.0001
	CO_2 emission	0.0000	0.0000	0.0000	0.0000
SAT1	GDP	-0.0016	0.0016	0.0008	-0.0011
	Output	0.0003	-0.0003	-0.0001	0.0001
	Import	-0.0004	0.0004	0.0002	-0.0003
	Export	0.0001	-0.0001	-0.0001	0.0001
	CO_2 emission	0.0000	0.0000	0.0000	0.0000

3.6 Conclusion and suggestion

Agriculture is an important sector in the New Zealand economy with dairy and meat products as leading exports. The reduction of agricultural CO_2-e emissions plays a vital role in the sustainable development of agriculture and contributes to the development of a low-carbon economy. In this study, we used the land-based CGE model to estimate the impacts of the carbon tax of agricultural emissions and technology improvement. We find that they do not cause substantial emissions reductions as estimated in Mardones and Lipski (2020)'s findings, who estimated that the impact of carbon taxes (from US$5 to US$131 per ton) on CO_2-e emissions from agriculture would not substantially reduce emissions, and reduce GDP. The higher the carbon tax rate, the greater the negative impact on New Zealand's GDP growth rate, which is consistent with Fan et al. (2018). Our conclusion is in line with that of Ntombela et al. (2019), who found that a carbon tax would reduce GDP by 0.91%

We find that output from dairy cattle farming and dairy manufacturing falls. However, the output of Forestry and Logging, Fishing and Agriculture, forestry, fishing support services and other sectors increases. Because dairy cattle farming and dairy manufacturing are the two main emitters, this kind of sector adjustment would contribute to the reduction of biogenic methane emissions. From this perspective, the implementation of a carbon tax ccontributes to the transition to a low-carbon economy.

There is an interesting finding in this study that although different types of technological progress can dampen the adverse impact of an agricultural carbon tax on GDP and other macroeconomic variables, the advancement of agricultural technological progress works to increase carbon emissions. Shahbaz et al. (2016) analysed how technological improvement influenced carbon emissions in Malaysia from 1790 to 2011. They found that technological development leads to economic growth and eventually boosts carbon emissions. We also find that all factor-augmenting technological improvement contributes to agricultural emissions, but land-augmenting technological improvement contributes the most to the macro economy.

It is necessary to accelerate the advancement of agricultural technological progress. In practice, it is vital to distinguish the difference in the effect of different types of technological progress. Land-augmenting progress is most useful when it comes to boosting economic development but it results in higher emissions. Because, land-augmenting progress is about the productivity improvement not the emission-reduction technology. Policymakers should pay attention to the priority of promoting productivity improvement under existing constraints, to make more significant contributions to the low-carbon economy transition. It is also to be noted that there is potential to reduce GHG emission from the agriculture sectors through carbon taxation ($100 per ton in Scenario SAE2, the emission reduction is 2.45% in 2030, 5.66% in 2050). However, it has a negative impact on the macroeconomy. Technological progress can alleviate this damage, especially land-augmenting progress. In agriculture, it will require a large amount of capital investment, and multi-lateral cooperation between government enterprises and scientific research institutions to reach land-augmenting productivity improvement.

The chapter modelled technological progress here refers to factor-saving productivity not the specific technological practices used (such as methane inhibitors or methane vaccines) in agricultural emissions reduction. The focus of this chapter simulated a production process and its effects on macroeconomy and carbon emissions in response to factor augmenting-technological progress. Clearly, exogenous technological progress is a simplification. Endogenous technical changes would be a good topic for future research.

Appendix B

New Zealand land based CGE Model equations

Production module

Production function for goods

$$QA_i = \lambda_a \left[\mu_a QVA^{\frac{\sigma_1 - 1}{\sigma_1}} - + (1-\mu_a) QINTA^{\frac{\sigma_1 - 1}{\sigma_1}}\right]^{\frac{\sigma_1}{\sigma_1 - 1}} \quad \text{(B.1)}$$

$$PA_i \cdot QA_i = QVA_i \cdot PVA_i + QINTA_i \cdot PINT_i \quad \text{(B.2)}$$

Production function for intermediate inputs

$$QINT_{ij} = \lambda_{int} \cdot io_{ij} \cdot QINTA_i \quad \text{(B.3)}$$

$$PINTA_{ij} = \sum io_{ij} \cdot PQ_i \quad \text{(B.4)}$$

Value-added function

$$QVA_i = \lambda_{va} \left[\mu_{va} QLK^{\frac{\sigma_2 - 1}{\sigma_2}} - + (1-\mu_{va}) QLAND^{\frac{\sigma_2 - 1}{\sigma_2}}\right]^{\frac{\sigma_2}{\sigma_2 - 1}} \quad \text{(B.5)}$$

$$PVA_i \cdot QVA_i = QLK_i \cdot PLK_i + QLAND_i \cdot PLAND_i \quad \text{(B.6)}$$

Labor & Capital aggregate function

$$QKL_i = \lambda_{kl} \cdot L_i^{\lambda^l} \cdot K_i^{\lambda^k} \quad \text{(B.7)}$$

$$PLK_i * QLK_i = L_i * w_i + K_i * r_a \quad \text{(B.8)}$$

Land aggregate function

$$QLAND_a = \lambda_{land} \cdot \left(\sum\nolimits_{a \in A} \delta_{land}^a \cdot land_a{}^{-\rho_q}\right)^{\frac{1}{\rho_q}} \quad \text{(B.9)}$$

$$PLA_a = (1/\lambda_{land}) \cdot \left(\sum\nolimits_{a \in A} \delta_{land}^a \cdot PLAND_a{}^{1-\rho_q}\right)^{\frac{1}{1-\rho_q}} \quad \text{(B.10)}$$

Trade Module

Armington function between imports and domestic goods

$$QQ_c = \alpha_c^q \left[\delta_c^q QD_c^{\rho_c^q} + \left(1-\delta_c^q\right) QM_c^{\rho_c^q}\right]^{\frac{1}{\rho_c^q}} \quad \text{(B.11)}$$

CET function between exports and domestic goods

$$QA_a = \alpha_a^t \left[\delta_a^t QDA_a^{\rho_a^t} + (1-\delta_a^t) QE_a^{\rho_a^t}\right]^{\frac{1}{\rho_a^t}} \quad \text{(B.12)}$$

Wage curve:

$$PQ_c \cdot QQ_c = PD_c \cdot QD_c + PM_c \cdot QM_c \quad \text{(B.13)}$$

$$PA_a \cdot QA_a = PDA_a \cdot QDA_a + PE_a \cdot QE_a \quad \text{(B.14)}$$

$$PM_c = pwm_c \cdot (1 + tm_c) \cdot EXR \quad \text{(B.15)}$$

$$PE_a = pwe_a \cdot EXR \tag{B.16}$$

Closure rule

$$\sum_c pwe_c \cdot QE_c = \sum_c pwm_c \cdot QM_c + FINV \tag{B.17}$$

Income and expenditure module

Household

Household income

$$YH = PL \cdot QLS + PK \cdot QKS \cdot shif_{hk} + PLAND \cdot LANDS \cdot shif_{hland} + transf_{gov_h} \tag{B.19}$$

Household expenditure

$$EH = shrh_c \cdot mpc_h \cdot (1 - t_h) * YH \tag{B.20}$$

Household saving

$$HS = (1 - mpc_h) \cdot (1 - t_h) * YH \tag{B.21}$$

Enterprise

Enterprise pre-tax income:

$$YENT = shif_{ent_k} \cdot PK * KS \tag{B.22}$$

Enterprise savings:

$$ENTS = (1 - t_{ent})YENT - transf_{ent_g} \tag{B.23}$$

Enterprise investment

$$ENTS = \sum_c PQ_c \cdot \overline{QINV_c} \tag{B.24}$$

NPISH

NPISH income

$$YN = \ transfr_{g_{np}} \tag{B.25}$$

NPISH consumption

$$EN = shrn_c \cdot mpc_n \cdot YN \tag{B.26}$$

Government

Government revenue

$$YG = \sum_i t_p \cdot PA_i \cdot QA_i + t_h \cdot YH + t_{ent} \cdot YENT + \sum_C tm_c \cdot pwm_c \cdot QM_c \cdot EXR + TXAGCO2 \tag{B.27}$$

Government expenditure for commodities demand

$$PQ_c \cdot QG_c = shrg_c \cdot mpc_g \cdot \left(YG - transfr_{g_h} - transfr_{g_n}\right) \tag{B.28}$$

Government saving

$$GS = (1 - mpc_g) \cdot \left(YG - transfr_{g_h} - transfr_{g_n}\right) \quad \text{(B.29)}$$

Carbon module

$$AGCO2_a = LAND_a \cdot \ emf_a \quad \text{(B.30)}$$

$$TXAGCO2 = \ \sum_{a \epsilon A} tco2 \cdot AGCO2_a \quad \text{(B.31)}$$

Dynamic module

Capital stock growth

$$KST_{t+1} = (1 + g_k) \cdot (1 - dep) \cdot KST_t + INVPS_t \quad \text{(B.32)}$$

Labour supply growth

$$LST_{t+1} = (1 + gpop_t) \cdot LST_t \quad \text{(B.33)}$$

Market balance

Goods and services market balance

$$QQ_c = \sum_a QINT_{ca} + QH_c + QG_c + QINV_c \quad \text{(B.34)}$$

Saving/investment balance

$$EINV = \sum_c PQ_c \cdot QINV_c + EXR \cdot FINV \quad \text{(B.35)}$$

$$EINV = HSAV + GSAV \quad \text{(B.36)}$$

Chapter 4 Rebound effect of energy efficiency in New Zealand

Overview

Fossil energy use accounts 65% of New Zealand's energy consumption. New Zealand's government is committed to improving energy efficiency to conserve energy and realize the transition to a low-carbon economy. However, the reduction of energy consumption can be moderated by the rebound effect. It is important that policy makers measure the rebound effect and track its source at macro and sector levels. This study uses a recursive dynamic CGE model with 49 sectors to study the impacts of New Zealand's energy efficiency improvement on the economy, calculate energy consumption and decompose the rebound effect into production side and the economy-wide level. Results show the economy-wide rebound effects brought by four energy types (coal, oil gas and electricity) are all much greater than 100%, which leads to an increase in the final demand for energy consumption. Improving electricity efficiency by 5% has the most significant positive impact on reducing energy use and CO_2-e emissions on the production side and contributes to 0.3% growth in GDP.

4.1 Introduction

Fossil energy use is the leading cause of global climate change and one of the most pressing problems facing all humankind (Cifci & Oliver, 2018). Improving energy efficiency is considered to be an effective measure to reduce energy consumption, and mitigate greenhouse gas emissions (Weizsäcker, Lovins, & Lovins, 1998). The International Energy Agency (IEA) emphasized the importance of energy efficiency redefining it from "hidden fuel" to "first fuel" (IEA., 2014).

The New Zealand Parliament recently passed the Zero Carbon Amendment Act, which formalizes its intention to have net zero emissions for all greenhouse gases except for biogenic methane by 2050 (Ministry for the Environment, 2019). Transitioning to a low-carbon economy is a challenge for New Zealand. In 2017, New Zealand's total energy consumption was 596 Petajoules, of which the consumption of fossil energy (including oil, gas and coal) accounted for 65%, and the consumption of electricity accounted for 24%. According to the IEA (2018), New Zealand's energy intensity has improved at an average annual rate of 1.4%

since 1990.However New Zealand's energy intensity remains high. It is the 6th highest in the OECD and 18% above the OECD average. New Zealand energy sector emissions have increased over the last few decades from 24 Mt CO_2-e in 1990 to 33 million tons Mt CO_2-e today, representing 41 per cent of New Zealand's gross emissions[2]. This suggests that energy efficiency increases in fossil energy and electricity can contribute to New Zealand's carbon reduction targets.

Improving energy efficiency is seen as an affordable and sustainable energy policy and an important step towards a low-carbon economy. This is consistent with the government's prospective target to develop an affordable, resilient and sustainable energy system. New Zealand is the only country with an "Energy Efficiency and Conservation Act" (Verma et al., 2018), and its energy policy is linked to emissions reduction targets. The Energy Efficiency and Energy Conservation Authority is responsible for the implementation of a carbon reduction plan, aimed at achieving improvements in efficiency and reductions in emissions at least cost (EECA, 2018).

However, energy savings brought by increased energy efficiency can be offset by increased energy demand. This is the so-called "rebound effect" (Bentzen, 2004) that comprises direct, indirect and economy-wide effects. The micro-economic direct rebound effect occurs when an energy efficiency innovation reduces the cost of providing an energy service, such as heating, lighting, or transport, and, as a result, users increase the use of the service offsetting some of the energy efficiency improvement. But there are also changes in the use of complementary and substitute goods or inputs and other flow-on effects that affect energy use across the economy known as indirect rebound effects. Together these constitute the economy-wide rebound effect.

The microeconomic direct rebound effect is a result of an increase in energy efficiency makes energy services cheaper such as lighting which leads to an increase in demand offsetting some of the energy efficiency gains. The indirect rebound effect is associated with the income effect when lower energy costs, due to increased efficiency, increase household consumption of other goods and services. The economy-wide rebound effect arises from the economy-wide increased use of resources. In particular, if energy efficiency is improved, production in the economy can

[2] Agricultural GHG emissions make up about 50% of NZ CO_2^e emissions.

expand and economic growth increase (Bentzen, 2004; Greening et al., 2000; Steve Sorrell, 2007). Estimates of price elasticity and cross-price elasticity of demand provide insights into the first two effects. However, estimating the economy-wide rebound effect requires a macroeconomic approach that includes resource prices changes and how these changes affect energy demand (Matos & Silva, 2011).

This chapter uses a recursive dynamic CGE model to estimate the impact of New Zealand's energy efficiency policy as an exogenous factor on energy use and carbon emissions because of rebound effect. The recursive dynamic mechanism is based on dynamic changes of labor growth and capital accumulation. Estimates of changes in energy consumption and the rebound effect derive from the rate of improvement in energy efficiency. The effectiveness of energy efficiency improvement is also evaluated in terms of its impact on CO_2-e emissions and macro economy variables.

The rest of the study is organized as follows. Section 4.2 reviews the literature and describes the contribution. Section 4.3 describes the CGE model and how the rebound effect is measured and decomposed. Results and discussion are presented in section 4.4 presents. Section 4.5 does sensitivity analysis. Section 4.6 concludes the study and provides some suggestions.

4.2 Literature review

Jevons introduced the idea of an energy rebound effect (RE) in 1866. He pointed out that improved energy efficiency may lead to increased energy use and called this phenomenon the "backfire" effect (Jevons, 1866). However, Jevons did not estimate the magnitude of the rebound effect. In 1978, the famous Khazoom-Brookes Postulate affirmed the existence of the energy rebound effect, claiming that if the energy price remains the same, an increase in energy efficiency caused by technological progress will increase energy consumption (Brookes, 1978). However, Khazzoom (1980) showed that improvements in energy efficiency would not reduce energy consumption, confirming the Khazoom-Brookes Postulate.

The existing literature about the assessments of the rebound effect varies widely from super-conservation to backfire, and the corresponding amount of RE ranges from negative to greater than 100% (Haas & Biermayr, 2000). In addition to these two extreme cases, the size of RE is between 0 and 100%, part of the reduction in energy consumption caused by the improvement of energy efficiency is offset by the rebound effect (Frondel & Vance, 2013; Wei, Zhou, & Zhang, 2019).

Generally, the direct micro energy rebound effect is easier to calculate and smaller than the economy-wide rebound effect. Yang and Li (2017) used data from 30 provinces in China to quantitatively analyze the relationship rebound effect and CO_2-e emissions. They concluded that the rebound effect of carbon emissions in China's provinces varies between 10%-60%. Mizobuchi (2008) studied the rebound effect of Japanese households and found the rebound effect is 27%. He pointed out that the original rebound formulation used by Khazzoom would exaggerate the rebound effect. Wang and Lu (2014) used double logarithmic regression equations to calculate the direct rebound effect of the transport sector using panel data of 31 provinces in China from 1999 to 2011. Hong, Oreszczyn, Ridley, and Group (2006) estimated the rebound effect caused by the improvement of heating technology in low-income households in the UK. The common feature of these existing papers is to study direct RE from the micro perspective. They could not capture the complementary and substitute effects of commodities or inputs that affect energy consumption known as the in-direct RE. Therefore, the estimated micro-level RE is relatively small compared to the economy-wide RE.

It is controversial to estimate the size of the economy-wide rebound effect (Gillingham, Kotchen, Rapson, & Wagner, 2013; Saunders, 2000). Turner (2009) studied the rebound effect for the UK by a macro CGE model, the size of which varies from negative to more than 100%. He emphasized that the assumption of parameter values in the CGE model is crucial for calculating economy-wide RE. The CGE model is broadly adopted in studies of the economy-wide or macro-level rebound effect (Hanley, McGregor, Swales, & Turner, 2009). Freire-González (2020) used the Spanish energy dynamic CGE model to estimate economy-wide RE from the whole society brought by energy efficiency improvement in energy sectors and the entire economy-wide rebound effect is 83% but did not track the RE of specific sector and involve the consumer consumption. Another Spanish study, Duarte, Sánchez-Chóliz, and Sarasa (2018) used a dynamic CGE models to calculated economy-wide RE from the consumer side brought about by the improvement of efficient technologies on electricity consumption and energy use in transportation services and found economy-wide rebound effects between 51%-71%, which did not involve RE from the production side. Some literature found that the size of an economy-wide RE varies with country and sectors analyzed. Studies in China include

Lu et al. (2017) and Zhou, Liu, Feng, Liu, and Lu (2018), who used a dynamic CGE model to estimate the discomposed economy-wide RE, and they concluded that there is no "backfire" effect, but the short-term rebound is larger than the long run rebound. Du et al. (2019) established a static CGE model to study the rebound effect in the Chinese construction industry. They concluded that the rebound effect of improving natural gas efficiency was an average of 99.2%. While the rebound effect brought by improvements in electricity efficiency use was with an average of 83.5%. Studies in other countries, Anson and Turner (2009) used Scotland's Energy-Economy-Environment CGE model. They revealed that a 5% efficiency increased in oil use in the transport sector leads to a short-term rebound effect of 36.5%, while the long-term rebound effect is 38.3%. This result is line with Lu et al. (2017)'s finding that the short-term rebound effect is greater than the long-term rebound effect. However, it conflicts with (Saunders, 2008)'s study that the long-term RE is larger than that in short term. In our view, it may because the fixed capital and some fuel could not be adjusted freely and resulted in an understatement of short-term RE.

In addition, there are disputes about energy-related CO_2-e emissions reduction due to the rebound effect of energy efficiency. Some argued that that improving energy efficiency is a cost-effective way to reduce energy use, improve energy supply security, and reduce carbon dioxide emissions (Ang et al., 2010; Belaïd et al., 2018). However, much empirical research shows that the improvement of energy efficiency has the opposite effect on CO_2-e emissions. Brännlund et al. (2007) studied the energy choices of Swedish households and CO_2-e emissions. They showed that a 20% increase in energy efficiency will increase CO_2-e emissions by about 5%. However, these studies based on micro level and they did not calculate the energy rebound effect, but only the rebound effect of CO_2-e emissions. Because the relationship between energy efficiency improvement and carbon emissions occurs in the economic system, and it will naturally be affected by other economic factors, such as energy prices, economic growth, energy policies, population growth and capital investment. Therefore, it is necessary to study energy efficiency improvement in the entire economic system. Not surprisingly, the CGE models are suited to the task of analyzing the impacts of improvements in energy efficiency (Ciaschini et al., 2012; Orlov & Grethe, 2012; Sancho, 2010; Solaymani & Kari, 2014).

To sum up despite many studies on this issue, there is still not a definitive answer to how large is the economy-wide rebound effect, with estimates varying between 50%-100%. Although, as seen above, studies vary somewhat as to the size of the economy wide rebound effect recent evidence suggest that it is likely to be large. Stern (2020) in his review of the rebound effect points to historical evidence finding a large rebound effect and cites recent econometric studies for the US which find the rebound effect of around 100% (Bruns, Moneta, & Stern, 2021; Rausch & Schwerin, 2018).

There are only a few studies of the rebound effect associated with improvements in New Zealand's energy efficiency and energy-related emissions. Most of New Zealand's research studies a specific energy sector, lacking a systematic analysis of carbon emissions reductions related to overall energy use, nor do they study the rebound effect from the national macroeconomic level. Jones (2015) studied New Zealand's light transport fleets (private passenger cars) and claimed that improving their energy efficiency can reduce carbon dioxide emissions. However, it mainly investigated whether New Zealand had formulated a framework for introducing energy efficiency laws and regulations from a legal perspective. Atkins et al. (2010) introduced the expansion of Carbon Emissions Pinch Analysis (CEPA), which took into account the close relationship between the increase in demand in New Zealand's electricity industry and carbon emissions. It also illustrated some of the issues in achieving meaningful emission reductions, but there was no mention of energy efficiency improvement in electricity. Although Scrimgeour et al. (2005) utilized the New Zealand CGE model, the model only emphasized the relationship between environmental taxes and other related taxes. It was specially designed for the energy sector and imposed energy and carbon taxes on all fossil fuels. The results showed that energy taxes are not as significant as carbon taxes to reduce carbon emissions, but carbon taxes hurt the capital stock. This article did not mention the energy structure changes by different taxes, which has a significant impact on emission reduction, let alone energy efficiency improvement and rebound effect.

Based on the aforementioned review and information, few studies use the dynamic CGE model to analyze the rebound effect of New Zealand's energy efficiency on macro-economy, energy consumption and energy-related emission reduction. It attempts to fill three knowledge gaps: (1) Calculating the rebound effect of energy efficiency in the production side and the economy-wide level dynamically in the medium and long term; (2) Distinguishing four energy sources (coal, oil, gas and electricity) and track each sector's energy-specific rebound effect; (3) the energy module and the dynamic module are embedded to establish a multi-sector dynamic CGE model with the SAM table based on the latest released New Zealand's Input-Output table (2013). It incorporates CO_2-e emissions into the analysis framework of energy efficiency. This study provides some evidence for the rebound effect of energy consumption as well as analyzing the impact on a range of macro variables. The results reported here have import implications for possible government policy measures to achieve a transition to a low-carbon economy.

4.3 Methodology

4.3.1 New Zealand Energy CGE model

CGE models stem from the general equilibrium theory in which supply and demand are equalized across all of interconnected markets in the economy (Walras, 1954). The CGE model is calibrated on real data and a complex system of equations. It examines changes in the prices, quantities, and market supply and demand relationships of all commodities and factors within the entire economic system caused by changes in an exogenous variable and studies the impact of the transition of the economic system from one equilibrium state to another on the macroeconomic level (Sue Wing, 2011).

To date, there is no agreement on where energy composite should be introduced in the production structure (Lecca, Swales, & Turner, 2011). Some scholar modeled into the value-added nest (Wei & Liu, 2017), others introduced into the intermediates nest (Steve Sorrell, 2014). Since this chapter only considers the rebound effect of improving fossil energy efficiency, the energy structure is subdivided into coal, oil, gas and electricity, and does not include renewable energy. Energy input is a produced input, which is different from value added input. Here, this chapter nests energy input an intermediate input. It refers to the approach of Lofgren, Harris, and Robinson (2002), Turner and Hanley (2011) and Zhou et al. (2018) to build a New Zealand CGE model with the energy and carbon emission modules, which includes 49 industries, three inputs (Labor, Capital and Land), and five economic entities: households, Non-Profit Institutions Serving Households (NPISH), enterprises, government and the rest of the world. This model assumes that the market is perfectly competitive and all companies make cost minimizing decisions. The production module uses a three-layer nested design form to reflect the more complex substitution relationship between multiple inputs.

The first level of the hierarchical production function combines in fixed proportions the aggregate intermediate input (INT) with the aggregate factor input (VA). At the second level, intermediate inputs are combined in fixed proportions and an aggregate land is combined with other factor inputs in a CES function. At the third level, capital and labor are assumed to be perfectly mobile between sectors using a CD function since the long-run equilibrium. The structure of this energy CGE model is shown in Figure 17.

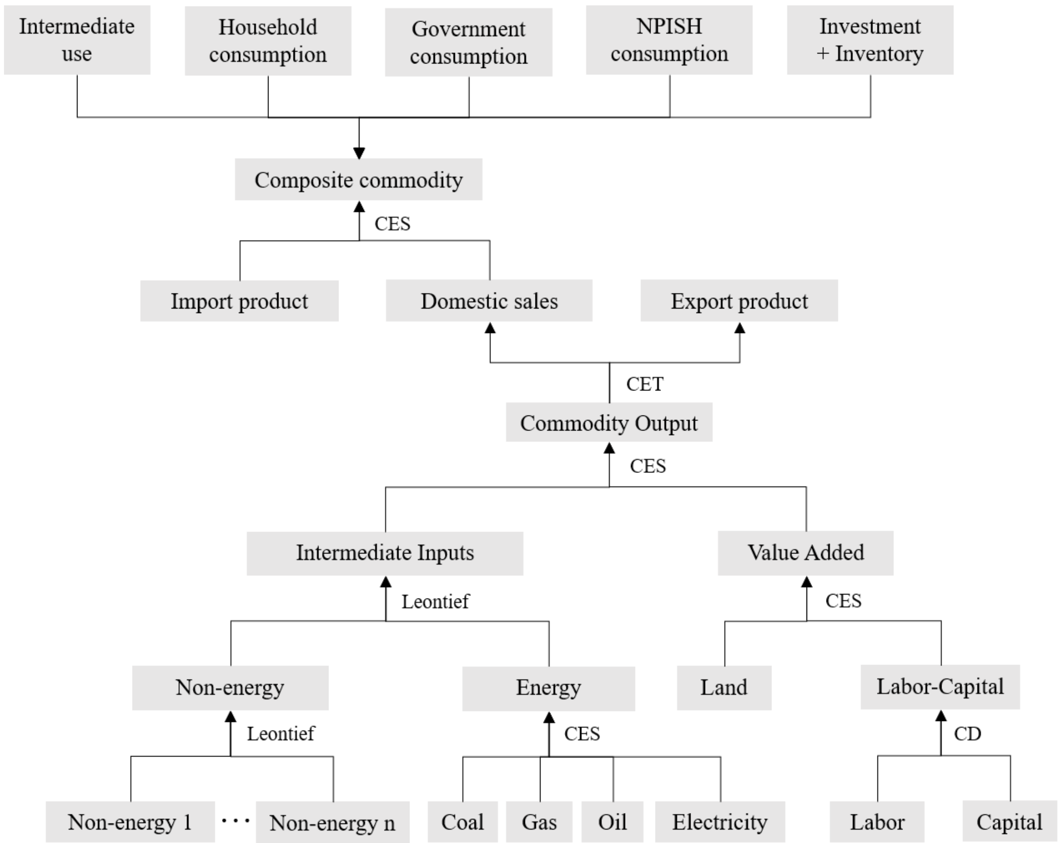


Figure 17 The structure of New Zealand CGE model

Households, enterprises, Non-Profit Institutions Serving Households (NPISH) and government, maximize their utility from the consumption of final goods, following a Cobb–Douglas utility function in the income and expenditure module. Household income is used for consumption or savings, deriving from all primary factors' compensation and transfers from government. Enterprise income includes production profits, capital investment and government transfers and its expenditure on intermediate inputs and investment needs. Government income is composed of various taxes and transfer-payment from the rest of world, and its expenditures include purchase, transfer payments and the surplus. NPISH income comes from government transfer payments, and its expenditures are used to purchase goods and services.

International trade is a significant module of this model. The Armington assumption is applied for combining imported goods with domestic goods, representing the imperfect substitution with different elasticities. At the same time, the total domestic output is distributed to domestic use and exports through a Constant Elasticity of Transformation (CET) function.

This chapter calculates energy-related carbon emissions, which is the sum of carbon emissions from electricity, coal, oil and natural gas using the carbon emission coefficients of each energy source. Primary information on emissions has been obtained from the Ministry for the Environment (MfE, 2019c).

The model calculates changes in the rebound effect and its impact on New Zealand's transition to low-carbon economy from 2013 to 2050. In order to achieve this goal, it used a recursive dynamic mechanism through exogenously changing labor growth and capital accumulation. The choice of the closure conditions defines the direction of causality in a model and determines how equilibrium is reached after policy shocks (Burfisher, 2017). Neoclassical closure includes equilibrium in commodity and factor markets and balance of payments budget equilibrium.

4.3.2 Quantifying rebound effect in CGE model

Berkhout, Muskens, and Velthuijsen (2000) proposed a systematic definition of the rebound effect at both micro- and macro-levels. The starting point is that when energy efficiency increases, the energy consumption for per unit product should decrease (Expected savings). However, producers tend to use more energy instead of other inputs, and consumers tend to consume more energy services, resulting in part of the energy savings generated by energy efficiency improvements counterbalanced by additional energy consumption (Actual savings). Haas and Biermayr (2000), suggest the formula for calculating the energy rebound coefficient (RE) as follows:

$$RE(\%) = \frac{Expected\ savings - Actual\ savings}{Expected\ savings} \qquad (4\text{-}1)$$

At the macro level for the economy-wide rebound effect, this study follows the approach suggested by Lecca et al. (2014) and Koesler, Swales, and Turner (2014), which quantifies the difference of energy consumption brought by the change in energy efficiency. R represents the economy-wide rebound effect, in the equation below:

$$R = \left[1 + \frac{\dot{E}}{\gamma}\right] \cdot 100 \tag{4-2}$$

Where, $\dot{E}$ is the percent change in energy consumption caused by the efficiency improvement γ $(0 < \gamma < 1)$ in energy use, where γ is given exogenously. R is not the direct rebound, rather it takes all general equilibrium effects into account (Koesler et al., 2014).

When efficiency improvement γ is specific to part of the economy, like production side, it should add $\beta = E_P/E$ into Eq. (4-2). It is noted that β is the initial proportion of production energy consumption in the economy-wide energy use and subscript P represents all production sectors. Then economy-wide rebound effect should be calculated as:

$$R = \left[1 + \frac{\dot{E}}{\beta\gamma}\right] \cdot 100 \tag{4-3}$$

Therefore, in order to calculate the economy-wide rebound effect in New Zealand, it considers the total energy use on aggregate production and the final consumption of the economy in this study. And it redefines R_T as economy-wide rebound effect and subscript T denotes total economy, measuring by Eq. (4-4):

$$R_T = \left[1 + \frac{\dot{E_T}}{\beta\gamma}\right] \cdot 100 = \left[1 + \frac{\frac{\Delta E_T}{E_T}}{\frac{E_P}{E_T} \cdot \gamma}\right] \cdot 100 = \left[1 + \frac{\Delta E_T}{\gamma E_P}\right] \cdot 100 \tag{4-4}$$

In which $\dot{E_T}$ is the economy wide energy use. The study uses a two-stage decomposition approach (Zhou et al. (2018) where it decomposes energy consumption into two parts, the production sectors (P) and final demand (C). Therefore, it can rewrite ΔE_T into Eq. (4-5):

$$\Delta E_T = \Delta E_P + \Delta E_C \tag{4-5}$$

where, ΔE_p is the absolute change of energy use in all production sectors; ΔE_c is final consumption demand which include household consumption (hc), government consumption (gc), NPISH consumption (nc), export (ex), Investment (iv), Change in inventories (sc). Therefore, it can decompose ΔE_c into Eq. (4-6):

$$\Delta E_C = \Delta E_{hc} + \Delta E_{gc} + \Delta E_{nc} + \Delta E_{ex} + \Delta E_{iv} + \Delta E_{sc} \tag{4-6}$$

Finally, the economy-wide rebound effect can be calculated as:

$$\begin{aligned} R_T &= \left[1 + \frac{\Delta E_P + \Delta E_{hc} + \Delta E_{gc} + \Delta E_{nc} + \Delta E_{ex} + \Delta E_{iv} + \Delta E_{sc}}{\gamma E_P}\right] \cdot 100 \\ &= R_P + \left[\frac{\Delta E_{hc} + \Delta E_{gc} + \Delta E_{nc} + \Delta E_{ex} + \Delta E_{iv} + \Delta E_{sc}}{\gamma E_P}\right] \cdot 100 \end{aligned} \tag{4-7}$$

Where, $R_P = \left[1 + \frac{\Delta E_P}{\gamma E_P}\right] \cdot 100$ is the rebound effect in production side. In this study, it has 49 production sectors. Here, it can rewrite ΔE_p into Eq. (4-8) as:

$$\Delta E_P = s_i \cdot \Delta E_i \tag{4-8}$$

where $s_i = \frac{E_i}{E_p}$ is the proportion of energy use of sector i which sees the efficiency gain. It substitutes sector rebound effect, $R_i = \left[1 + \frac{\dot{E_i}}{\gamma}\right] \cdot 100$, into equation (4-7), then the economy-wide rebound effect can be decomposed as follows:

$$R_T = \left[R_i \cdot \frac{E_i}{E_P}\right] + \left[\frac{\Delta E_{hc}}{\gamma E_P} + \frac{\Delta E_{gc}}{\gamma E_P} + \frac{\Delta E_{nc}}{\gamma E_P} + \frac{\Delta E_{ex}}{\gamma E_P} + \frac{\Delta E_{iv}}{\gamma E_P} + \frac{\Delta E_{sc}}{\gamma E_P}\right] \cdot 100 \tag{4-9}$$

The first term on the right-hand side of equation is the weighted sector rebound effect, which is the product of sector rebound effect and share of sectoral energy use in industrial energy use. Eq. 4-8 implies that the economy wide depends on the weighted sector rebound effect as well as. Following Zhou et al. (2018), this study defines the contribution of each energy user to the total rebound effect δ_j as:

$$\delta_j = \begin{cases} \frac{R_i}{R_T} \cdot \frac{E_j}{E_P} & j \in Production\ sectors \\ \frac{\Delta E_j}{\gamma E_p} \cdot \frac{1}{R_T} \cdot 100 & j \in final\ demand \end{cases} \tag{4-10}$$

Which allows us to identify key contributors to the rebound effect for each energy type. It is noted that the study will calculate the rebound effect of specific energy like coal, oil, gas and electricity, rather than total energy use. For example, it will measure the rebound effect of electricity on the macro and sector level.

4.3.3 Data and scenario design

The social accounting matrix (SAM) table is the core data source of CGE model, which is a comprehensive description of the economy of a country (or a region) within a specified period (usually one year). In the process of constructing the CGE model, this study makes the model an accurate representation of real economy, within the constraints of data availability. The SAM data compiled in this article is mainly from the 2013 New Zealand input-output table. Statistics NZ and The Ministry for the Environment are also primary data sources. In addition to the substitution elasticity, this study uses trade coefficients described by Fernandez and Daigneault (2015), the remaining parameters in the CGE model are calibrated using the 2013 SAM.

Figure 18 below shows the structure of the four types of energy consumption by various activities or entities in 2013. Electricity consumption accounted for the highest share in production, residential consumption, NPISH consumption and government consumption. Exports and investment have different structures of energy consumption, and a significantly larger proportion of their energy consumption arise primarily from oil.

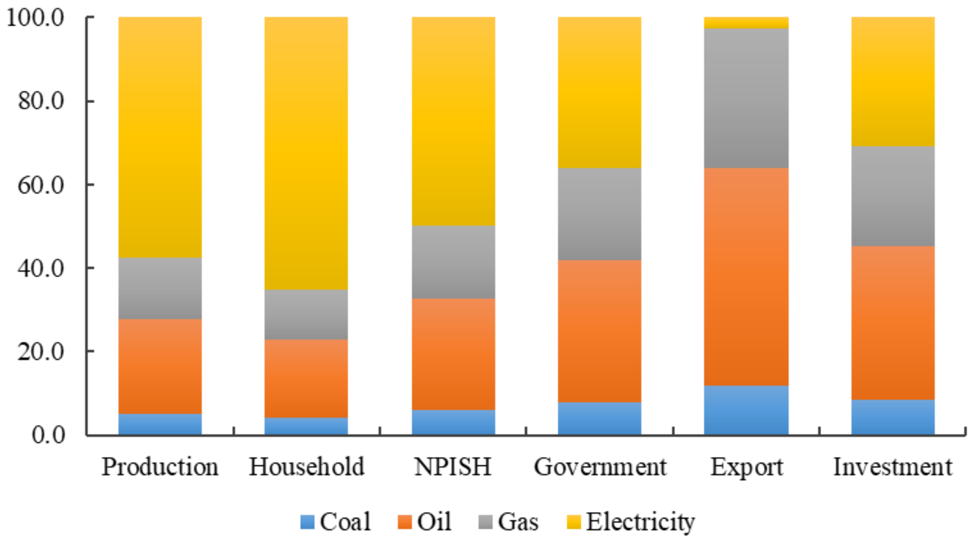


Figure 18 Structure of energy-specific consumptions in 2013 (%)

It specifies four energy sources: coal, oil, natural gas, and electricity. The most common approach used by many researchers to measure the rebound effect is to assume that energy efficiency is exogenous without any economic cost. The energy efficiency shock is applied to the second nest of the production function (See Appendix C2). Based on the BAU scenario, one or several policy shocks are set as simulated scenarios. For the sake of simplicity, the study assumes that exogenous energy technological progress is completed at one time, and the improvement of energy efficiency remains constant during the simulation period. Therefore, when performing simulations, the study sets energy-specific efficiency improvement to 2%, 3%, 5 % in order for all production sectors. As the below table shows, for example, the efficiency of electricity is improved by 2%, 3% and 5% for all production sectors in Scenario 4 showed in S4-a, S4-b and S4-c. Based on the SAM table, about 73.8% is consumed for 49 production sectors. Therefore, in this study, β is 73.8%, the initial proportion, as the denominator of Eq. (4-2). It means that a 5% efficiency improvement of using electricity in all the production sectors is supposed to reduce the consumption of electricity in the whole economy by 3.7% (see Table 8).

Table 8 Scenarios setting for energy efficiency improvement

Scenarios	Sub-scenarios	Energy Type	Annual energy efficiency change rates (γ)	Initial share of energy use affected by efficiency improvement (β)	Expected energy savings from efficiency improvement (βγ) in 2013
BAU		-	-	-	-
	S1-a	Coal	2%	58.850%	1.177%
Scenario 1	S1-b	Coal	3%	58.850%	1.766%
	S1-c	Coal	5%	58.850%	2.943%
	S2-a	Oil	2%	58.816%	1.176%
Scenario 2	S2-b	Oil	3%	58.816%	1.765%
	S2-c	Oil	5%	58.816%	2.941%
	S3-a	Gas	2%	58.832%	1.177%
Scenario 3	S3-b	Gas	3%	58.832%	1.765%
	S3-c	Gas	5%	58.832%	2.942%
	S4-a	Electricity	2%	73.834%	1.477%
Scenario 4	S4-b	Electricity	3%	73.834%	2.215%
	S4-c	Electricity	5%	73.834%	3.692%

4.4 Results and discussion

4.4.1 Impact of energy efficiency improvement

In this section, it presents the results of 5% improvements in energy efficiency. In Table 9, it can be seen that energy efficiency improvement has an impact on macroeconomic variables. Among them, the increase in the energy efficiency of electricity contributed about 0.30% growth rate in GDP growth rate compared to the BAU scenario (Specifically, 0.2969% in 2020, 0.3103% in 2030, 0.3137% in 2050). When the efficiency of coal, gas increased by 5%, the contribution to increased GDP was about 0.029%, 0.082% at the most during the whole period, respectively, neither contributed to the GDP growth rate by more than 0.1%, while the contribution of oil efficiency improved to GDP is up to 0.126%. The improvement in any energy efficiency has a positive impact on GDP growth. Nevertheless, GDP growth rate caused by electricity efficiency improvement was the most considerable. The reasons behind this phenomenon: first, the increase in final consumption and net exports. The increased cost-effectiveness brought about by improved energy efficiency created a competitive export advantage, resulting in expanding in the total net exports. Second, the increase in energy efficiency has led to an increase in sector output, which requires more factor input, that is, labour and capital demand increased, therefore, the wage rate and return on capital have increased. Energy productivity of GDP, measuring in dollars of GDP per unit of energy, increases by the average rate of 0.016%, 0.069%, 0.045% and 0.078% respectively in four scenarios. That is, energy productivity is positively related to energy efficiency improvement.

The CPI rise is caused by the increase in production cost brought by the rise in factor prices. In the short term, due to the fixed capital stock, the expansion of production causes a rise in capital prices. Furthermore, in the long run, even though capital can be adjusted with economic growth. At this time, the increasing labour demand will push up the wage rate. Overall, the 5% increase in energy efficiency has a more significant impact on CPI changes in the medium and long-term. Generally speaking, as the energy efficiency of each sector improved, New Zealand's products are more competitive than similar imported products, and also results in lower prices of intermediate inputs, which decreases production costs and raises competitiveness in the international market. The most noticeable is that the increase in electricity efficiency will lead to an increase in imports to 0.33% and the contribution to exports has slightly decreased to 0.22% in 2050. However, the increase in the energy efficiency of coal, oil, and gas is not significant for imports and exports promotion (less than 0.1%). Because its wage rate and return on capital have increased compared to the BAU scenario, leading to factor prices increased, which offsets the cost reduction caused by the increase in energy efficiency.

Table 9 Macroeconomic impact of 5% energy efficiency improvement (%)

	Scenario 1: Coal			Scenario 2: Oil			Scenario 3: Gas			Scenario 4: Electricity		
	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
GDP	0.028	0.029	0.029	0.123	0.125	0.126	0.080	0.081	0.082	0.297	0.310	0.314
CPI	0.022	0.023	0.023	0.096	0.098	0.099	0.062	0.064	0.064	0.068	0.080	0.081
Final consumption	0.009	0.009	0.009	0.040	0.041	0.041	0.026	0.027	0.027	0.288	0.292	0.293
Household	0.578	0.587	0.561	0.614	0.623	0.597	0.597	0.607	0.581	0.935	0.949	0.925
NPISH	0.007	0.007	0.007	0.031	0.031	0.032	0.020	0.020	0.020	0.151	0.156	0.158
Government	0.008	0.008	0.008	0.029	0.029	0.029	0.019	0.020	0.020	0.113	0.117	0.119
Imports	0.018	0.019	0.019	0.080	0.083	0.083	0.052	0.054	0.054	0.314	0.327	0.330
Exports	0.012	0.012	0.012	0.052	0.052	0.053	0.034	0.034	0.034	0.212	0.221	0.224
Investment	0.010	0.011	0.011	0.046	0.046	0.047	0.030	0.030	0.031	0.139	0.144	0.148
Wage rate	0.028	0.029	0.029	0.123	0.126	0.127	0.080	0.081	0.082	0.352	0.366	0.370
Capital price	0.019	0.019	0.019	0.082	0.083	0.083	0.053	0.054	0.054	0.090	0.095	0.094
Energy productivity of GDP	0.016	0.016	0.016	0.070	0.069	0.069	0.045	0.045	0.045	0.076	0.080	0.077

The impacts of energy efficiency improvements on the output levels of different sectors are not the same. As a free-market economy, New Zealand's diversified economic structure includes three major segments. The sizable service sectors, the large manufacturing sectors and the primary sectors. Impacts are analyzed from the perspective of these three different types of sectors, the sizable service sectors, the large manufacturing sectors and the primary sectors. See Table 13 and 14 in Appendix C1, when coal efficiency is increased by 5%, compared with the BAU scenario, the overall output level of the service sector has positive increases. Simulation results show that the average increase in the service sector is up to 0.0073% by 2050. Oil efficiency improvement contributes higher to the growth rates of the corresponding industries' outputs, which is by 0.03% approximately. When the 5% increase in energy efficiency occurs to gas use, the overall outputs of the service sectors increase by 0.02% on average. In contrast, an increase in electricity efficiency makes a 0.22% contribution to the average outputs of the whole service sectors. This shows that the improvement of electricity efficiency has the most significant impact on the output of the service sectors.

Table 15 and 16 in Appendix C1 shows that when the four energy efficiencies are increased by 5% respectively, the impact on primary sector output is positive, and the increase in electricity efficiency has the immense contribution to the increase in output in three different periods, respectively 0.142%, 0.144% and 0.145%. The increase in coal efficiency has the least impact on output growth, and the growth rate declined slightly in the long run. However, the average growth rate of output has remained at about 0.004%. Similarly, the improvement of gas and oil efficiency is beneficial to the output of the entire primary industry, with average output growth rates of about 0.012% and 0.018%, respectively. The increase in output of primary and service sectors is mainly because companies in these sectors are very flexible in adjusting outputs and inputs. The improvement in energy efficiency has lowered labour and capital costs, encouraging companies to use more energy to replace labour and capital, which stimulated the output of these sectors.

As can be seen from Table 17 and 18 in Appendix C1, the output changes the study analyzes are industries that are undoubtedly related to the daily lives of domestic residents. Firstly, it analyzes the production changes in the four energy sectors. The results show that the efficiency improved, energy sector will increase its output, while the other three energy industries will decrease their production, which can be explained by the combination of the price effect and the substitution effect. For example, when coal energy efficiency increases by 5%, its output increases by 0.610%, 0.615% and 0.618%, respectively at different time, and under this situation, the output of the other three energy sectors declines.

Secondly, when the energy efficiency of coal, oil and gas is improved by 5%, the output of Dairy Manufacturing, Textiles and apparel manufacturing, Fertilizer and other industrial chemical manufacturing, Machinery and other equipment manufacturing all decrease to some varying extent. Among them, due to the increase in oil efficiency, the output of these sectors has been negatively the most affected. However, when the energy efficiency of electricity is increased by 5%, not only does it not reduce the output of these sectors, but also increases the output.

Except for the above mentioned, in Table 17, all the industries have improved output resulting from energy efficiency improved. The sector with the most positively affected production is Basic metal manufacturing while the least favorable affected is the Dairy manufacturing, which shows that the increase in energy efficiency has a more significant impact on the heavy industry. In contrast, the light industry has a relatively smaller impact. However, the output impact brought by the improvement of electricity efficiency is the largest, and the average increase rate of output in 2020 is 0.280%, 0.285% in 2030, and 0.288% in 2050.

Compared with the service and primary sectors, some manufacturing sectors show signs of shrinking outputs because energy costs account for a large proportion of these sectors. However, due to the particularity and durability of production equipment, manufacturing sectors lack flexibility in the adjustment of production inputs. Even if the improvement of energy efficiency will reduce energy costs by a considerable amount, it is difficult for them to decrease production costs. Because the wage and capital price increased (See Table 9). In addition, the improvement of energy efficiency may promote structural adjustment and increase the output of the industry. However, this kind of change may not be able to guarantee the low carbon development of the industries. It needs to analyze the rebound effect and energy-related carbon emissions.

4.4.2 The rebound effect of energy efficiency and energy-related emissions

This section first analyzes the changes from 2013 to 2050 in the energy rebound effect on energy use and carbon emissions when New Zealand's energy efficiency increased by 2%, 3% and 5%, compared with BAU scenario. It calculated the rebound effect in all production sectors R_P and the economy-wide rebound effect R_T in four scenarios. The results show that the rebound effect of energy is not sensitive to the changes in the improvement of different energy efficiency, and the overall change of the rebound effect under three different energy efficiency is not significant. The efficiency improvement gain of different energy types does not always decrease or increase with efficiency improved, which is in line with Duarte et al. (2018) 's findings.

Table 10 shows changes in energy consumption and corresponding economy-wide RE in all the scenarios in 2050. It presents that the actual energy savings are negative and huge rebound effect. It can be seen that the economy-wide RE is very different due to different energy types. The largest rebound effect occurs when the efficiency of electricity is improved. The heterogeneity can explain such difference in input-output relationships or distribution structures across the five energy sources. Energy products are consumed by producers, households, government and exported. In the rebound effect mechanism, the improvement in energy efficiency lowers the price of energy, which results in the substitution effect, the income effect and the effect of economic growth. First is the substitution effect, which means that energy consumption may increase to replace other factor inputs, and the cost of energy decreases, which offsets the initial energy-saving potential. The second mechanism is the income effect, which means producers tend to increase energy demand and produce more production of goods due to the increase of real income. The third is called the effect of economic growth. As an important driving force for economic growth, the improvement of energy efficiency will bring an increase in overall economic productivity.

Table 10 Economy-wide RE and corresponding energy saving in 2050(%)

Energy Type	Sub-scenarios	Expected energy savings	Actual energy savings	Economy-wide RE
Coal	S1-a	24.00	-4.15	117.28
	S1-b	35.99	-6.17	117.15
	S1-c	59.99	-10.14	116.91
Oil	S2-a	104.83	-12.97	112.37
	S2-b	157.25	-19.27	112.25
	S2-c	262.08	-31.53	112.03
Gas	S3-a	67.85	-9.92	114.61
	S3-b	101.78	-14.75	114.49
	S3-c	169.64	-24.19	114.26
Electricity	S4-a	268.17	-48.94	118.25
	S4-b	402.25	-72.52	118.03
	S4-c	670.41	-118.00	117.60

From the production side, improving energy efficiency can lead to a reduction of energy consumption in specific energy sources in New Zealand and the energy rebound effect shows a slight upward trend (see Table 10). The rebound effect coefficient of coal from 2013 to 2050 is higher than 100%, which means that the actual energy saving of coal is less than zero. That is, the energy-saving effect of energy efficiency is harmful and “backfire” appears. For oil, gas and electricity, improvement in energy efficiency has all caused a “partial rebound” effect. However, energy efficiency improvement is still conducive to New Zealand’s energy conservation. Among them, the rebound effect coefficient of electricity is the smallest, changing from 84.37% in 2020 to 85.00% and 85.23% in 2030 and in 2050, which shows that the improvement of electricity efficiency can achieve better energy saving than other energy types. Similarly, it can see rebound effect of gas from production side increases over time, going from 99.13% in 2020 to 99.23% and 99.26% in 2030 and 2050, respectively.

The difference in the proportion changes of four energy types consumption depends on the level of improving energy efficiency, and the results show a non-linear relationship between autonomous energy efficiency improvement and energy use. However, energy use decreases or increases depending on different energy sources. When efficiency is improved by 5% in Table 11, in Scenario 1, the growth rate of coal consumption compared to the BAU scenario has enhanced by approximately 0.07% during the whole period. However, the use of oil and gas in production declined in Scenario 2 and 3 by -0.14% and -0.04% respectively. In Scenario

4 the reduction rate of electricity consumption is maximal and of significance (more than 0.75%) compare to the BAU scenarios. The possible reason is that coal is not the primary fuel in New Zealand (about 5.2% in production energy use). The price elasticity of coal demand is higher than that of the other three energy types, and changes in coal demand are very sensitive to price changes. When the efficiency of coal increases, the price of coal decreases, which directly promotes the growth of coal consumption. Due to the substitution relationship between coal and other energy types, the increase in coal efficiency also affects the reduced demand for oil and natural gas.

In Table 11, it can also be seen the economy-wide rebound effect and the change of energy use of different scenarios. First, the use of all four energies increases and the growth rate of the other three energy types except electricity remains stable, about 0.5%, 0.35% and 0.42% respectively. In Scenario S4, Electricity consumption rises by 0.64% to 0.66% from 2020 to 2050, due to the importance of the weight of electricity use in total energy use (see Figure 19 above). Thus, as the efficiency of electricity use increases, electricity demand in all production sectors decreases, which exceeds reductions in energy consumption of the other three energy types. However, it increases in total energy use mainly due to more household consumption. Second, it can be observed that the improvement in energy efficiency leads to “backfire” in energy usage on economy-wide. Among that, the rebound effect of coal is still the largest, and it increased to 101.48% in 2050 in the production side. It is significate that the change in the price of electricity products expanded in the energy efficiency of 2% to 5%, which shows that the improvement of energy efficiency can achieve better energy saving.

Table 11 Rebound effect on production and macroeconomy of 5% efficiency improvement (%)

x = coal, oil, gas, electricity	Scenario 1:Coal			Scenario 2: Oil			Scenario 3: Gas			Scenario 4: Electricity		
	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
Technical energy-efficiency imprivment (γ)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Initial share (E_P/E_T)	0.58	0.59	0.59	0.58	0.59	0.59	0.58	0.59	0.59	0.74	0.75	0.75
Change in total energy $\boldsymbol{x}$ use (ΔE_T)	9.88	9.60	10.14	30.16	29.72	31.53	23.38	22.85	24.19	111.01	110.58	118.00
Production sectors (ΔE_P)	0.84	0.83	0.89	-7.10	-6.57	-6.83	-1.41	-1.23	-1.25	-100.45	-95.17	-99.01
Final demand (ΔE_C)	9.04	8.77	9.26	37.26	36.29	38.36	24.78	24.08	25.45	211.45	205.75	217.00
Rebound effect in production side (R_P)	101.46	101.47	101.48	97.17	97.35	97.39	99.13	99.23	99.26	84.37	85.00	85.23
Total economy-wide rebound effect (R_T)	117.22	116.92	116.91	112.03	111.99	112.03	114.40	114.24	114.26	117.28	117.43	117.60

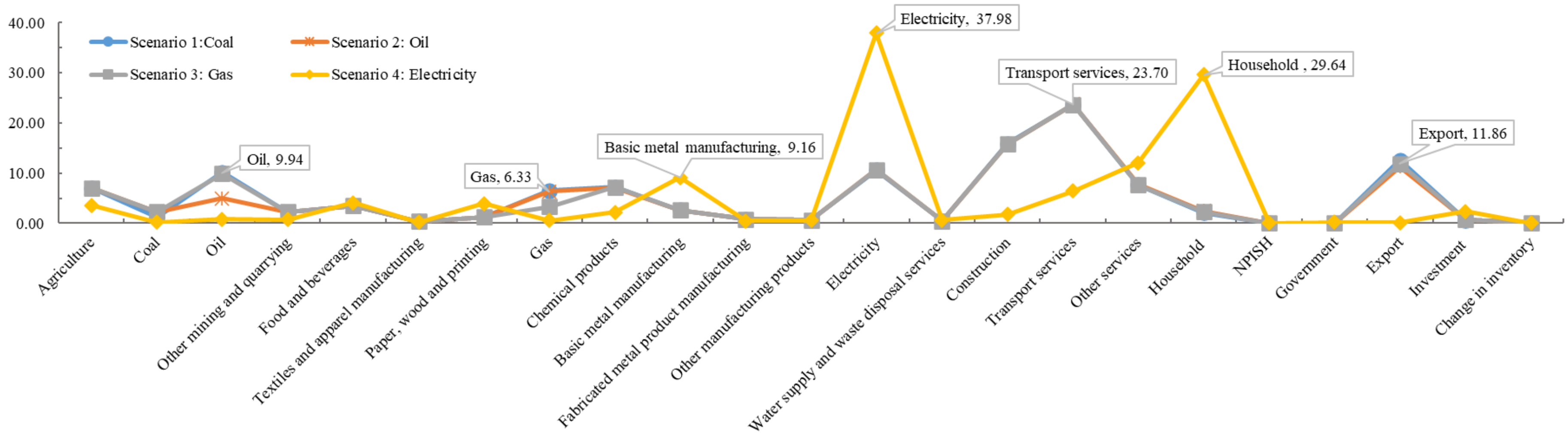
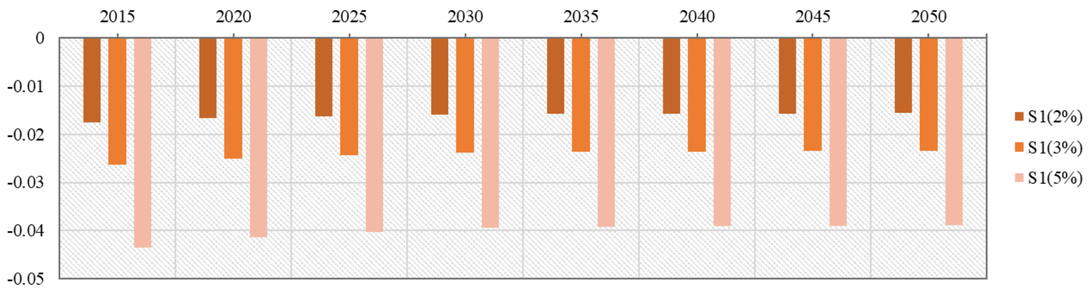


Figure 19 Decomposition of energy-specific rebound effect in 2050 (Scenario 5%)

Figure 19 shows the decomposition of the energy-specific rebound effect. Take electricity for example (yellow line), the weighted rebound effect in the electricity sector is largest (37.98%), which implies the contribution of this sector to total rebound is positive, and the share is 32.29%. In contrast, the top 5 weighted rebound effect in S1, S2 and S3 is transport services, construction, oil, other services and agriculture. Besides, the rebound effect of final demand takes a large part in total rebound effect (more than 30%) though final demand is not directly affected by energy efficiency in this study. Significantly, the total rebound effect of electricity is lower if it excludes energy use in final demand. These results are the same as the studies by Broberg, Berg, and Samakovlis (2015) and Koesler et al. (2016). Besides, it also finds that export demand contributes 10% to the rebound in final demand.

Figure 20 shows under the four scenarios, there is no significant reduction in energy-related CO_2-e emissions compared with BAU, particular in Scenario 1. Reductions in CO_2-e emissions in electricity efficiency are more significant than other scenarios, and the highest production energy efficiency (5%) leads to a total reduction of 0.41% in CO_2-e emissions by 2050, representing a cut of 5768kt of CO_2-e. In Scenario 4, the emissions from household consumption increase due to the improvement in the consumption of coal, gas, oil and electricity products. Thus, rebound effects triggered by electricity savings partially offset the production declines and some additional emissions associated with final consumption. From this point of view, to effectively achieve the CO_2-e emission reduction, policy should focus on improving electricity efficiency, while taking into account the improvement of the efficiency of the other three energy sources. Nevertheless, the existence of New Zealand's energy rebound effect impacts the CO_2-e abatement effect of energy policy; the improvement of four energy efficiencies is not ideal for CO_2-e emissions reduction.



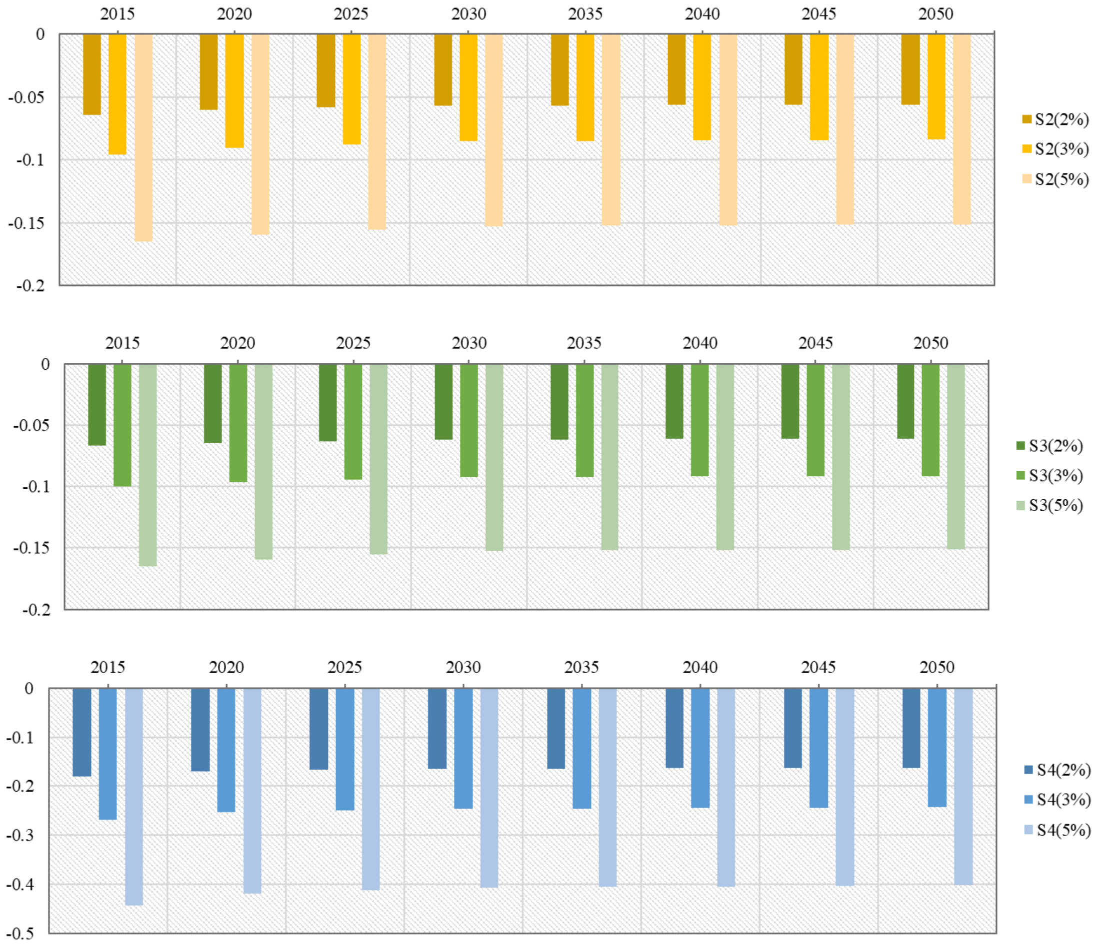


Figure 20 CO_2-e emissions of energy efficiency improvement (%)

4.5 Sensitivity analysis

In order to check the stability of this model, it focuses on the inter-fuel elasticities of substitution. Elasticities of substitution among the energy inputs are small ($\sigma_{en} = 0.3$). Here, the study explores the impact of a higher elasticity of 0.8 and a lower elasticity of 0.2. Table 12 shows the impact on macroeconomic variable and rebound effect with different values of inter-fuel substitutability. Results show that the ratio of change of GDP is insensitive to the change of substitution elasticity. Besides, there is a slight increase in the rebound effect along with the higher values of elasticity, considering the influence exerted by the substitution effect, which is consistent with Khosroshahi and Sayadi (2020)'s finding.

Table 12 Sensitivity analysis of inter-fuel substitutability in 2013 (5% scenario)

Inter-fuel substitutability	Energy	GDP	Output	R_P	R_T
0.2	Coal	0.024	0.004	100.52	115.35
	Oil	0.103	0.018	96.34	110.09
	Gas	0.067	0.012	98.25	112.49
	Electricity	0.242	0.166	80.05	111.39
0.3	Coal	0.024	0.004	101.34	116.42
	Oil	0.103	0.018	96.93	110.87
	Gas	0.067	0.012	98.95	113.40
	Electricity	0.245	0.167	83.55	114.90
0.8	Coal	0.024	0.004	102.98	118.55
	Oil	0.103	0.018	98.12	112.42
	Gas	0.067	0.012	100.34	115.22
	Electricity	0.252	0.170	90.52	121.93

4.6 Conclusions and Suggestions

In this chapter, the dynamic CGE model with 49 sectors is used to analyze the economy-wide rebound effect of specific energy caused by the energy efficiency improvement of 2%, 3% and 5%. Simulation results show that the improvement in energy efficiency results in a slight decrease in energy use, indicating that there is a considerable energy rebound effect. The energy-saving effect of improved coal efficiency results in rebound effect in production of 101.4%, and when the final consumption is taken into account, the economy-wide energy rebound effect is about 117%. It is the phenomenon of “backfire”, as Turner (2009) found that the rebound effect was greater than 100% in the UK. Improvements in electricity efficiency cause a partial rebound effect on production, and the rebound effect is the smallest, the short-term is 84.37%, and the medium- and long-term is 85% and 85.23% respectively, which is very close to the rebound effect of electricity efficiency in China, 83.4%, found by Du et al. (2019). The rebound effects of the other two energies (oil and gas) are close to 100% on production.

In my view, the main reason for coal's backfire effect is because the demand for coal is price sensitive in New Zealand. Improved coal efficiency encourages more use of coal as an input. Because when coal efficiency increases, the production cost of coal decreases, resulting in a decrease in the price of coal-related products. In contrast, the prices of other energy products remain unchanged, which means the prices of these energy products are relatively high. It is ultimately increasing the use of coal and coal-related products (the substitution effect). As a small open economy, the substitution effect plays a more important role in New Zealand. Because New Zealand is not a coal self-sufficient country. Some large users choose to import coal for numerous reasons, including the coal quality they require for their processes and cost competitiveness (Energy in New Zealand, 2020). When New Zealand's coal prices decrease, world coal prices remain unchanged. In this case, the world coal prices will be relatively high, resulting in a decrease in New Zealand coal imports and an increase in domestic coal use. The rebound effect will be higher than that of the global economy or other big economies. Besides, the prices of coal and coal-related products have fallen, resulting in the actual purchasing power of households increasing, and more products can be purchased with the same income (the income effect). Compare to the coal's rebound effect, electricity efficiency improved caused a relatively small rebound effect, which due to the electricity supply and other three energy inputs have a smaller substitution than that of coal, oil or gas. The magnitude of the energy rebound effect depends not only on the elasticity of substitution between energy and non-energy commodities and the energy intensity of commodity production but also by changes in consumer income, changes in relative prices of consumer goods. Therefore, the final rebound effect caused by different energy efficiency improvements is not very different, given that the other factors do not change much.

Improving electricity efficiency has the most positive impact on reducing energy use and CO_2-e emissions from production. Besides, the rebound effect is not sensitive to the efficiency change. This finding is line with the conclusion of Duarte et al. (2018). However, the economy-wide rebound effects brought by these four energy sources are all much greater than 100%, resulting from an increase in the final demand for energy consumption (the income effect). Hence, it is necessary for government to account for the rebound effect when formulating energy conservation and emission reduction policies. Compared with other developed countries, New Zealand's energy rebound effect is relatively high, Scotland's 5% energy efficiency improvement brings about an oil rebound effect of less than 40% (Anson & Turner, 2009). When Spain's energy efficiency increases by 5%, the economy-wide rebound effect is

82.82% (Freire-González, 2020), which is close to that of New Zealand's production side. In addition, the increase in energy efficiency has contributed positively to the output level of the service and primary sectors, but a negative impact on some manufacturing sectors. It is difficult for these sectors to decrease production costs and reduce their CO_2-e emissions. As for macroeconomic dictators, the improvement of energy efficiency is conducive to the development of New Zealand's economy. The results show that improvements in electricity efficiency have the greatest and positive effect on the growth rate of GDP. Moreover, imports, exports and consumption are all simulated to expand.

In conclusion, our results add weight to more recent studies that find strong economy wide rebound effects of around 100% (Stern, 2020). Based on the above conclusions, the study offers the following policy proposals to achieve the goal of an energy productive and low-emissions economy in New Zealand. First, there is no doubt that improving electricity efficiency can reduce CO_2-e emissions and reduce energy consumption on the production side. Policymakers should pay more attention to encourage electricity companies to introduce energy technology innovation, increase R&D investment aimed at developing cleaner advanced energy technologies. Also, from the results, the increase in energy consumption of the final demand is the main reason hindering the decrease in overall energy consumption. Therefore, it is also necessary to accelerate the technological revolution on the final consumption side, which also means that the role of residential and commercial sectors in realizing a low-carbon economy cannot be underestimated.

Second, the improvement in electricity efficiency has the most significant impact on output. Improving low-emission energy efficiency in electricity generation can reduce CO_{2-e} emissions more relative to the other three energy types. This result is contrary to (Li, Gao, Hou, Song, & Chen, 2020) because New Zealand's economy is dominated by the services sector, a major user of electricity. Our results show that improving electricity efficiency is more advantageous than other energy sources in reducing rebound effect and carbon dioxide emissions.

Third, it is necessary for the government to implement carbon reduction policies to limit the increase in energy consumption due to the improvement of energy efficiency. Consistent to achieve a low-carbon economy, such policies should be aimed at reducing the energy rebound effect by increasing energy prices (Brännlund et al., 2007). In addition, fossil energy, such as coal and oil are the primary sources of CO_{2}-e emissions in New Zealand, policy-makers should consider supporting measures to reduce the negative impact of the energy rebound effect, such as energy tax, to reduce CO_{2}-e emissions and promote renewable energy use.

From the simulation results, there may be some discrepancies in the expected effects of improved energy efficiency because the complexity of the economy makes it difficult for the CGE model to describe the entire national economy. For example, the limitations of the CGE model data availability. For future research, as energy-related carbon emissions are New Zealand's second-largest source of carbon emissions, reducing energy consumption and emissions is challenge for New Zealand to achieve a low-carbon economy. Promoting the use of clean energy and the development of low-carbon technologies should be the focus of New Zealand's energy policy.

Appendix C1

Table 13 Output changes of the service sectors (% changes from the baseline)

The Service Sectors	Coal (5%)			Oil (5%)		
	2025	2035	2050	2025	2035	2050
Agriculture, forestry, and fishing support services	0.0050	0.0050	0.0050	0.0216	0.0217	0.0217
Air transport and transport services	0.0123	0.0123	0.0124	0.0537	0.0536	0.0542
Communication services	0.0045	0.0045	0.0046	0.0198	0.0197	0.0201
Finance and insurance	0.0091	0.0091	0.0092	0.0397	0.0399	0.0402
Real estate	0.0094	0.0094	0.0095	0.0411	0.0412	0.0416
Equipment hires and investors in other property	0.0143	0.0142	0.0144	0.0623	0.0620	0.0626
Ownership of owner-occupied dwellings	0.0084	0.0084	0.0085	0.0364	0.0366	0.0370
Scientific research and computer services	0.0124	0.0124	0.0125	0.0541	0.0542	0.0547
Other business services	0.0074	0.0074	0.0075	0.0321	0.0324	0.0329
Central government administration and defence	0.0029	0.0029	0.0030	0.0125	0.0128	0.0130
Pre-school, primary and secondary education	0.0023	0.0024	0.0024	0.0102	0.0105	0.0106
Other education	0.0063	0.0063	0.0064	0.0273	0.0275	0.0279
Hospitals and nursing homes	0.0022	0.0023	0.0024	0.0097	0.0101	0.0104
Other health and community services	0.0058	0.0058	0.0059	0.0252	0.0254	0.0257
Personal and other community services	0.0054	0.0054	0.0055	0.0234	0.0236	0.0239
Average increase rate of output	0.0072	0.0072	0.0073	0.0313	0.0314	0.0318

Table 14 Output changes of the service sectors (% changes from the baseline)

The Service Sectors	Gas (5%)			Electricity (5%)		
	2025	2035	2050	2025	2035	2050
Agriculture, forestry, and fishing support services	0.0140	0.0140	0.0141	0.2357	0.2397	0.2411
Air transport and transport services	0.0348	0.0348	0.0351	0.2582	0.2624	0.2650
Communication services	0.0128	0.0128	0.0130	0.2582	0.2622	0.2648
Finance and insurance	0.0258	0.0258	0.0261	0.2636	0.2681	0.2704
Real estate	0.0266	0.0267	0.0269	0.2946	0.2997	0.3026
Equipment hires and investors in other property	0.0404	0.0402	0.0406	0.3086	0.3131	0.3159
Ownership of owner-occupied dwellings	0.0236	0.0237	0.0240	0.2002	0.2036	0.2061
Scientific research and computer services	0.0351	0.0351	0.0354	0.3015	0.3062	0.3088
Other business services	0.0208	0.0210	0.0213	0.2694	0.2741	0.2767
Central government administration and defence	0.0081	0.0083	0.0084	0.0815	0.0837	0.0850
Pre-school, primary and secondary education	0.0066	0.0068	0.0069	0.0974	0.1001	0.1015
Other education	0.0177	0.0178	0.0181	0.2283	0.2324	0.2347
Hospitals and nursing homes	0.0063	0.0065	0.0067	0.0871	0.0897	0.0912
Other health and community services	0.0163	0.0165	0.0167	0.2138	0.2176	0.2196
Personal and other community services	0.0151	0.0153	0.0155	0.1771	0.1801	0.1818
Average increase rate of output	0.0203	0.0204	0.0206	0.2183	0.2222	0.2243

Table 15 Output changes of the primary sectors (%)

The Primary Sectors	Coal (5%)			Oil (5%)		
	2025	2035	2050	2025	2035	2050
Horticulture and fruit growing	0.0039	0.0040	0.0040	0.0170	0.0172	0.0175
Livestock and cropping farming	0.0027	0.0027	0.0026	0.0118	0.0116	0.0114
Dairy cattle farming	0.0003	0.0003	0.0002	0.0012	0.0011	0.0007
Other farming	0.0023	0.0023	0.0022	0.0099	0.0099	0.0096
Forestry and logging	0.0077	0.0077	0.0077	0.0334	0.0335	0.0337
Fishing	0.0076	0.0075	0.0076	0.0331	0.0326	0.0330
Average increase rate of output	0.0041	0.0040	0.0040	0.0177	0.0177	0.0176

Table 16 Output changes of the primary sectors (%)

The Primary Sectors	Gas (5%)			Electricity (5%)		
	2025	2035	2050	2025	2035	2050
Horticulture and fruit growing	0.0110	0.0112	0.0113	0.0162	0.0168	0.0176
Livestock and cropping farming	0.0076	0.0075	0.0074	0.2017	0.2047	0.2049
Dairy cattle farming	0.0008	0.0007	0.0005	0.0720	0.0729	0.0715
Other farming	0.0064	0.0064	0.0062	0.0946	0.0961	0.0956
Forestry and logging	0.0217	0.0217	0.0218	0.2420	0.2464	0.2492
Fishing	0.0215	0.0211	0.0214	0.2264	0.2294	0.2315
Average increase rate of output	0.0115	0.0114	0.0114	0.1421	0.1444	0.1450

Table 17 Output changes of energy, manufacturing, transportation and other sectors (%)

Energy, Manufacturing, Transportation and other Sectors	Coal (5%)			Oil (5%)		
	2025	2035	2050	2025	2035	2050
Coal	1.5579	1.5708	1.5754	-0.2126	-0.2101	-0.2090
Oil	-0.0487	-0.0481	-0.0479	1.3894	1.4044	1.4097
Gas	-0.0487	-0.0481	-0.0479	-0.2126	-0.2101	-0.2090
Electricity generation and transmission and distribution	0.0030	0.0030	0.0031	0.0128	0.0131	0.0136
Other mining and quarrying	0.0877	0.0879	0.0882	0.3822	0.3830	0.3844
Meat manufacturing	0.0039	0.0039	0.0039	0.0168	0.0170	0.0171
Dairy manufacturing	-0.0037	-0.0038	-0.0039	-0.0162	-0.0165	-0.0171
Other food manufacturing	0.0009	0.0009	0.0010	0.0040	0.0040	0.0042
beverage, malt and tobacco manufacturing	0.0022	0.0021	0.0022	0.0095	0.0092	0.0094
Textiles and apparel manufacturing	-0.0016	-0.0016	-0.0015	-0.0068	-0.0068	-0.0065
Wood product manufacturing	0.0038	0.0038	0.0039	0.0165	0.0167	0.0171
Paper and paper product manufacturing	0.0001	0.0001	0.0002	0.0005	0.0004	0.0009
printing, publishing, and recorded media	0.0043	0.0043	0.0045	0.0189	0.0189	0.0195
Fertiliser and other industrial chemical manufacturing	-0.0025	-0.0026	-0.0025	-0.0107	-0.0111	-0.0109
Rubber, plastic, and other chemical product manufacturing	0.0038	0.0037	0.0038	0.0165	0.0161	0.0167
Non-metallic mineral product manufacturing	0.0111	0.0111	0.0112	0.0483	0.0485	0.0490
Basic metal manufacturing	0.0055	0.0054	0.0056	0.0242	0.0237	0.0243
Structural, sheet and fabricated metal product manufacturing	0.0025	0.0025	0.0026	0.0108	0.0109	0.0115
Machinery and other equipment manufacturing	-0.0037	-0.0037	-0.0036	-0.0161	-0.0162	-0.0158
Furniture and other manufacturing	0.0038	0.0039	0.0039	0.0167	0.0168	0.0172
Water supply	0.0132	0.0132	0.0133	0.0575	0.0576	0.0581
Sewerage, drainage, and waste disposal services	0.0140	0.0140	0.0142	0.0611	0.0612	0.0617
Construction	0.0100	0.0100	0.0101	0.0434	0.0437	0.0441
Wholesale and retail trade	0.0074	0.0074	0.0075	0.0321	0.0322	0.0325
Accommodation, restaurants, and bars	0.0044	0.0044	0.0045	0.0191	0.0193	0.0196
Road transport	0.0147	0.0147	0.0148	0.0639	0.0639	0.0647
Rail transport	0.0300	0.0300	0.0303	0.1306	0.1308	0.1319
Water transport	0.0323	0.0323	0.0325	0.1407	0.1407	0.1416
Average increase rate of output	0.0610	0.0615	0.0618	0.0729	0.0736	0.0743

Table 18 Output changes of energy, manufacturing, transportation and other sectors (%)

Energy, Manufacturing, Transportation and other Sectors	Gas (5%)			Electricity (5%)		
	2025	2035	2050	2025	2035	2050
Coal	-0.1377	-0.1360	-0.1354	-0.2406	-0.2388	-0.2354
Oil	-0.1377	-0.1360	-0.1354	-0.2406	-0.2388	-0.2354
Gas	1.4664	1.4805	1.4854	-0.2406	-0.2388	-0.2354
Electricity generation and transmission and distribution	0.0083	0.0085	0.0088	0.7748	0.7831	0.7889
Other mining and quarrying	0.2477	0.2482	0.2491	0.1949	0.2009	0.2046
Meat manufacturing	0.0109	0.0110	0.0111	0.2231	0.2268	0.2277
Dairy manufacturing	-0.0105	-0.0107	-0.0111	0.1331	0.1346	0.1330
Other food manufacturing	0.0026	0.0026	0.0027	0.2196	0.2233	0.2246
beverage, malt and tobacco manufacturing	0.0061	0.0060	0.0061	0.2058	0.2089	0.2107
Textiles and apparel manufacturing	-0.0044	-0.0044	-0.0042	0.2166	0.2200	0.2218
Wood product manufacturing	0.0107	0.0108	0.0111	0.3231	0.3282	0.3306
Paper and paper product manufacturing	0.0003	0.0003	0.0005	0.6555	0.6645	0.6676
Printing, publishing, and recorded media	0.0122	0.0123	0.0126	0.3263	0.3316	0.3348
Fertiliser and other industrial chemical manufacturing	-0.0070	-0.0072	-0.0071	0.2125	0.2156	0.2173
Rubber, plastic, and other chemical product manufacturing	0.0106	0.0104	0.0108	0.3275	0.3322	0.3354
Non-metallic mineral product manufacturing	0.0313	0.0314	0.0318	0.2875	0.2924	0.2953
Basic metal manufacturing	0.0157	0.0153	0.0157	1.3949	1.4127	1.4189
Structural, sheet and fabricated metal product manufacturing	0.0070	0.0070	0.0074	0.2955	0.3006	0.3040
Machinery and other equipment manufacturing	-0.0104	-0.0105	-0.0102	0.2228	0.2264	0.2294
Furniture and other manufacturing	0.0108	0.0109	0.0111	0.2198	0.2236	0.2261
Water supply	0.0373	0.0373	0.0376	0.5207	0.5277	0.5316
Sewerage, drainage, and waste disposal services	0.0396	0.0397	0.0400	0.3142	0.3194	0.3222
Construction	0.0281	0.0283	0.0286	0.2085	0.2123	0.2145
Wholesale and retail trade	0.0208	0.0209	0.0211	0.2429	0.2468	0.2489
Accommodation, restaurants, and bars	0.0124	0.0125	0.0127	0.1861	0.1896	0.1914
Road transport	0.0414	0.0414	0.0419	0.2529	0.2574	0.2601
Rail transport	0.0847	0.0848	0.0855	0.2464	0.2517	0.2546
Water transport	0.0912	0.0912	0.0918	0.3569	0.3633	0.3671
Average increase rate of output	0.0674	0.0681	0.0686	0.2800	0.2849	0.2877

Table 19 Macroeconomic impact of 3% energy efficiency improvement (%)

	Scenario 1: Coal			Scenario 2: Oil			Scenario 3: Gas			Scenario 4: Electricity		
	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
GDP	0.0172	0.0175	0.0177	0.0751	0.0765	0.0770	0.0486	0.0496	0.0499	0.1826	0.1908	0.1929
CPI	0.0135	0.0137	0.0138	0.0588	0.0600	0.0603	0.0381	0.0388	0.0138	0.0432	0.0600	0.0603
Final consumption	0.0056	0.0057	0.0057	0.0246	0.0249	0.0251	0.0159	0.0162	0.0162	0.1761	0.1782	0.1791
household	0.5738	0.5825	0.5563	0.5957	0.6048	0.5788	0.5857	0.5946	0.5685	0.7915	0.8034	0.7785
NPISH	0.0043	0.0044	0.0044	0.0187	0.0191	0.0192	0.0121	0.0124	0.0124	0.0927	0.0961	0.0973
Government	0.0060	0.0060	0.0059	0.0184	0.0186	0.0186	0.0127	0.0129	0.0128	0.0701	0.0729	0.0737
Imports	0.0112	0.0116	0.0116	0.0488	0.0504	0.0508	0.0316	0.0327	0.0329	0.1929	0.2009	0.2029
Exports	0.0073	0.0072	0.0073	0.0318	0.0316	0.0321	0.0206	0.0205	0.0208	0.1304	0.1357	0.1377
Investment	0.0064	0.0065	0.0066	0.0279	0.0283	0.0289	0.0181	0.0184	0.0187	0.0854	0.0884	0.0907
Wage rate	0.0172	0.0175	0.0177	0.0751	0.0766	0.0772	0.0487	0.0496	0.0500	0.2161	0.2250	0.2275
Capital Price	0.0115	0.0116	0.0117	0.0500	0.0507	0.0509	0.0324	0.0328	0.0329	0.0556	0.0587	0.0583
Energy productivity of GDP	0.0097	0.0096	0.0095	0.0422	0.0419	0.0417	0.0273	0.0271	0.0270	0.0456	0.0481	0.0466

Table 20 Rebound effect on production and macroeconomy of 3% efficiency improvement (%)

x = coal, oil, gas, electricity	Scenario 1:Coal			Scenario 2: Oil			Scenario 3: Gas			Scenario 4: Electricity		
	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
Technical energy-efficiency imprivment (Υ)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Initial share (E_P/E_T)	0.58	0.59	0.59	0.58	0.59	0.59	0.58	0.59	0.59	0.74	0.75	0.75
Change in total energy $\boldsymbol{x}$ use (ΔE_T)	6.02	5.84	6.17	18.44	18.16	19.27	14.26	13.94	14.75	68.23	67.97	72.52
Production sectors (ΔE_P)	0.51	0.51	0.54	-4.27	-3.95	-4.10	-0.84	-0.73	-0.74	-59.83	-56.63	-58.88
Final demand (ΔE_C)	5.50	5.33	5.63	22.71	22.11	23.37	15.09	14.66	15.49	128.06	124.60	131.40
Rebound effect in production side (R_P)	101.49	101.50	101.51	97.16	97.35	97.39	99.14	99.24	99.27	84.48	85.12	85.36
Total economy-wide rebound effect (R_T)	117.47	117.16	117.15	112.25	112.21	112.25	114.64	114.47	114.49	117.70	117.86	118.03

Table 21 Macroeconomic impact of 2% energy efficiency improvement (%)

	Scenario 1: Coal			Scenario 2: Oil			Scenario 3: Gas			Scenario 4: Electricity		
	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
GDP	0.0116	0.0118	0.0119	0.0505	0.0514	0.0518	0.0327	0.0333	0.0335	0.1233	0.1288	0.1302
CPI	0.0090	0.0092	0.0092	0.0395	0.0403	0.0405	0.0256	0.0261	0.0262	0.0295	0.0403	0.0405
Final consumption	0.0038	0.0038	0.0039	0.0165	0.0168	0.0169	0.0107	0.0109	0.0109	0.1185	0.1199	0.1205
Household	0.5716	0.5803	0.5541	0.5863	0.5953	0.5692	0.5796	0.5885	0.5623	0.7180	0.7289	0.7035
NPISH	0.0029	0.0029	0.0030	0.0126	0.0128	0.0129	0.0081	0.0083	0.0084	0.0626	0.0648	0.0657
Government	0.0047	0.0047	0.0046	0.0131	0.0133	0.0132	0.0093	0.0094	0.0093	0.0480	0.0499	0.0504
Imports	0.0075	0.0078	0.0078	0.0328	0.0339	0.0342	0.0212	0.0220	0.0221	0.1302	0.1356	0.1369
Exports	0.0049	0.0049	0.0049	0.0213	0.0212	0.0215	0.0138	0.0138	0.0139	0.0880	0.0915	0.0929
Investment	0.0043	0.0044	0.0044	0.0187	0.0190	0.0194	0.0121	0.0123	0.0126	0.0576	0.0596	0.0612
Wage rate	0.0116	0.0118	0.0119	0.0505	0.0514	0.0519	0.0327	0.0333	0.0336	0.1458	0.1519	0.1535
Capital Price	0.0076	0.0078	0.0079	0.0337	0.0341	0.0341	0.0217	0.0221	0.0222	0.0377	0.0398	0.0395
Energy productivity of GDP	0.0065	0.0064	0.0064	0.0282	0.0280	0.0279	0.0183	0.0181	0.0180	0.0304	0.0321	0.0311

Table 22 Rebound effect on production and macroeconomy of 2% efficiency improvement (%)

x = coal, oil, gas, electricity	Scenario 1:Coal			Scenario 2: Oil			Scenario 3: Gas			Scenario 4: Electricity		
	2020	2030	2050	2020	2030	2050	2020	2030	2050	2020	2030	2050
Technical energy-efficiency imprivment (γ)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Initial share (E_P/E_T)	0.58	0.59	0.59	0.58	0.59	0.59	0.58	0.59	0.59	0.74	0.75	0.75
Change in total energy $\boldsymbol{x}$ use (ΔE_T)	4.04	3.92	4.15	12.41	12.22	12.97	9.58	9.37	9.92	46.05	45.87	48.94
Production sectors (ΔE_P)	0.35	0.34	0.37	-2.85	-2.63	-2.74	-0.55	-0.48	-0.49	-39.73	-37.58	-39.06
Final demand (ΔE_C)	3.69	3.58	3.78	15.26	14.86	15.70	10.14	9.85	10.40	85.78	83.45	88.01
Rebound effect in production side (R_P)	101.51	101.51	101.52	97.16	97.34	97.39	99.15	99.25	99.28	84.54	85.19	85.43
Total economy-wide rebound effect (R_T)	117.60	117.28	117.28	112.37	112.32	112.37	114.76	114.59	114.61	117.92	118.08	118.25

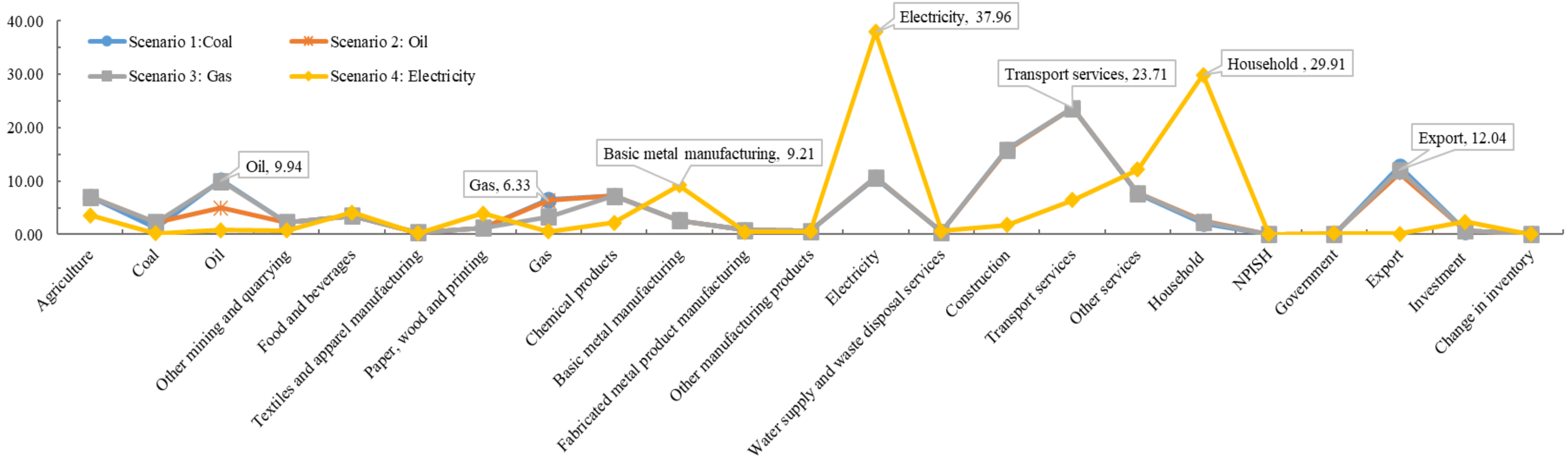


Figure 21 Decomposition of energy-specific rebound effect in 2050 (scenario 3%)

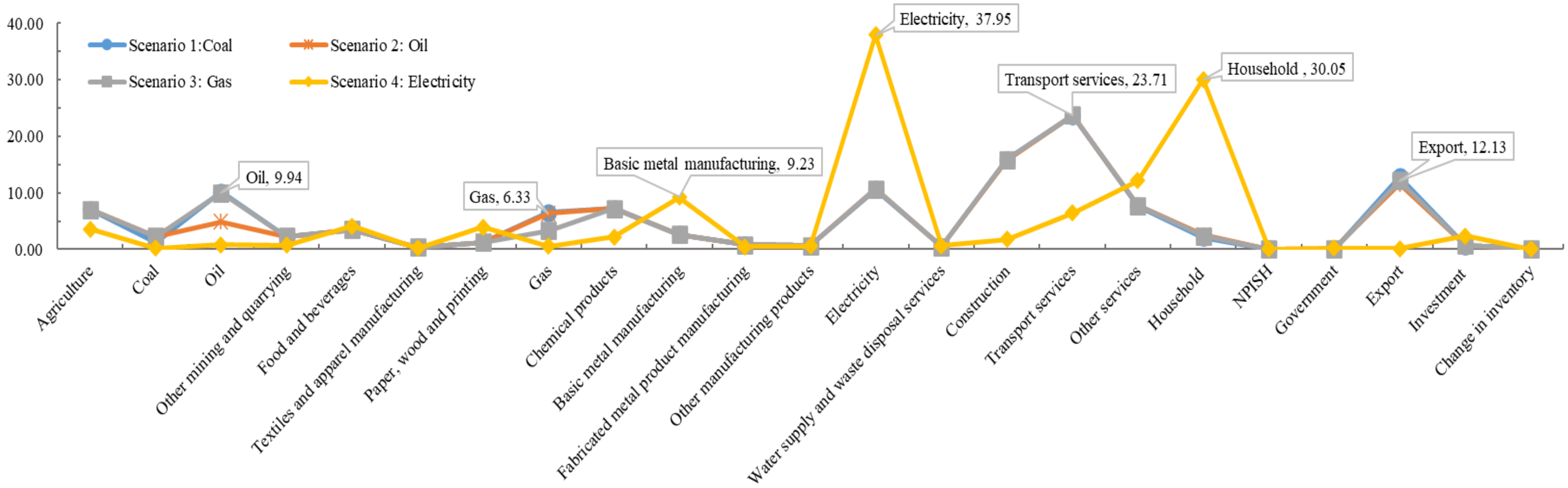


Figure 22 Decomposition of energy-specific rebound effect in 2050 (scenario 2%)

Appendix C2

New Zealand CGE Model equations

Production module

Production function for goods

$$QA_i = \lambda_a \left[\mu_a QVA^{\frac{\sigma_1-1}{\sigma_1}} + (1-\mu_a) QINTA^{\frac{\sigma_1-1}{\sigma_1}}\right]^{\frac{\sigma_1}{\sigma_1-1}} \quad (C.1)$$

Zero profit condition

$$PA_i * QA_i = QVA_i * PVA_i + QINTA_i * PINT_i \quad (C.2)$$

Production function for intermediate inputs

$$QINT_{ij} = \lambda_{int} * io_{ij} * QINTA_i \quad (C.3)$$

Zero profit condition

$$PINTA_{ij} = \sum io_{ij} * PQ_i \quad (C.4)$$

Energy aggregate function

$$QEN_a = \lambda_{qa} \cdot (\sum_{q \in Q} \delta_{qa} \cdot QN_{qa}{}^{-\rho_q})^{\frac{1}{\rho_q}} \quad (C.5)$$

Zero profit condition

$$PN_a = (1/\lambda_{qa}) \cdot (\sum_{q \in Q} \delta_{qa}{}^{\rho_q} \cdot PEN_{qa}{}^{1-\rho_q})^{\frac{1}{1-\rho_q}} \quad (C.6)$$

Value-added function

$$QVA_i = \lambda_{va} \left[\mu_{va} QLK^{\frac{\sigma_2-1}{\sigma_2}} + (1-\mu_{va}) QLAND^{\frac{\sigma_2-1}{\sigma_2}}\right]^{\frac{\sigma_2}{\sigma_2-1}} \quad (C.7)$$

Zero profit condition

$$PVA_i * QVA_i = QLK_i * PLK_i + QLAND_i * PLAND_i \quad (C.8)$$

Labor & Capital aggregate function

$$QKL_i = \lambda_{kl} * L_i^{\lambda^l} * K_i^{\lambda^k} \quad (C.9)$$

Zero profit condition

$$PLK_i * QLK_i = L_i * w_i + K_i * r_a \quad (C.10)$$

Trade Module

Armington function between imports and domestic goods

$$QQ_c = \alpha_c^q \left[\delta_c^q QD_c^{\rho_c^q} + (1-\delta_c^q) QM_c^{\rho_c^q}\right]^{\frac{1}{\rho_c^q}} \quad (C.11)$$

CET function between exports and domestic goods

$$QA_a = \alpha_a^t \left[\delta_a^t QDA_a^{\rho_a^t} + (1-\delta_a^t) QE_a^{\rho_a^t}\right]^{\frac{1}{\rho_a^t}} \quad (C.12)$$

Wage curve:

$$PQ_c \cdot QQ_c = PD_c \cdot QD_c + PM_c \cdot QM_c \quad (C.13)$$
$$PA_a \cdot QA_a = PDA_a \cdot QDA_a + PE_a \cdot QE_a \quad (C.14)$$
$$PM_c = pwm_c \cdot (1 + tm_c) \cdot EXR \quad (C.15)$$
$$PE_a = pwe_a \cdot EXR \quad (C.16)$$

Closure rule:

$$\sum_c pwe_c \cdot QE_c = \sum_c pwm_c \cdot QM_c + FINV \quad (C.17)$$

Income and expenditure module

Household

Household income

$$YH = PL * QLS + PK * QKS * shif_{hk} + PLAND * LANDS * shif_{hland} + transf_{gov_h}$$
(C.18)

Household expenditure

$$EH = shrh_c * mpc_h * (1 - t_h) * YH \quad (C.19)$$

Household saving:

$$HS = (1 - mpc_h) * (1 - t_h) * YH \quad (C.20)$$

Enterprise

Enterprise pre-tax income:

$$YENT = shif_{ent_k} * PK * KS \quad (C.21)$$

Enterprise savings:

$$ENTS = (1 - t_{ent}) YENT - transf_{ent_g} \quad (C.22)$$

Enterprise investment:

$$ENTS = \sum_c PQ_c * \overline{QINV_c} \quad (C.23)$$

NPISH

NPISH income

$$YN = \ transfr_{g_{np}} \quad (C.24)$$

NPISH consumption

$$EN = shrn_c * mpc_n * YN \quad (C.25)$$

Government

Government revenue:

$$YG = \sum_i t_p * PA_i * QA_i + t_h * YH + t_{ent} * YENT + \sum_C tm_c * pwm_c * QM_c * EXR \quad (C.26)$$

Government expenditure for commodities demand:

$$PQ_c * QG_c = shrg_c * mpc_g * \left(YG - transfr_{g_h} - transfr_{g_n}\right) \quad (C.27)$$

Government saving:

$$GS = (1 - mpc_g) * \left(YG - transfr_{g_h} - transfr_{g_n}\right) \quad (C.28)$$

Carbon module

$$EnCO2_a = QXEN_a \cdot emf_q \quad (C.29)$$

Dynamic equations

Capital stock growth

$$KST_{t+1} = (1 + g_k) * (1 - dep) * KST_t + INVPS_t \quad (C.30)$$

Labor supply growth

$$LST_{t+1} = (1 + gpop_t) * LST_t \quad (C.31)$$

Market balance

Goods and services market balance

$$QQ_c = \sum_a QINT_{ca} + QH_c + QG_c + QINV_c \quad (C.32)$$

Saving/investment balance

$$EINV = \sum_c PQ_c \cdot QINV_c + EXR \cdot FINV \quad (C.33)$$

$$EINV = HSAV + GSAV \quad (C.34)$$

Technological change

Energy production function

$$QEN_a = \lambda_{qa}\left(\sum_{q \in Q} \delta_{qa}(\alpha_q QN_{qa})^{-\rho_q}\right)^{\frac{1}{\rho_q}} \quad (C.35)$$

Energy price function

$$PN_a = (1/\lambda_{qa}) \cdot \left(\sum_{q \in Q} \delta_{qa}{}^{\rho_q} \cdot \alpha_q{}^{1-\frac{1}{\rho_q}} \cdot PEN_{qa}{}^{1-\rho_q}\right)^{\frac{1}{1-\rho_q}} \quad (C.36)$$

Chapter 5 Conclusion

5.1 Research objective

Climate change resulting from greenhouse gas emissions has large-scale, comprehensive, and multi-level impact on nature, ecology and the environment, and even the survival and development of human society. There is a growing international consensus on the need to reduce global carbon emissions (Schleussner et al., 2016). Many governments have implements emission reduction measures to deal with climate change and achieve carbon emission reduction targets. The NZ ETS was designed as a mechanism to price CO_2-e emissions that contribute to climate change The NZ ETS includes forestry sequestration for generating carbon credits, allowing carbon emitters to offset their emissions (Manley & Maclaren, 2012; van Kooten, 2017). However, the price of carbon determined by ETS has been controversial because of its design features. The effectiveness of NZ ETS has been challenged since the carbon price collapsed in 2011 and bottomed out till mid-2013 (Diaz-Rainey & Tulloch, 2018). What are the endogenous carbon prices of NZ ETS included forestry sequestration in the context of different emission-reduction target and free allocation to agricultural sector? Chapter 2 modelled forestry carbon sequestration and evaluated the effects of CO_2-e emissions reduction targets (as an external shock) using a recursive dynamic mechanism. Specifically, chapter 2 includes forestry carbon sequestration linked to timber growth characteristics in a recursive dynamic CGE model, where forest carbon sinks react dynamically to capture the effects of forest growth on carbon removal and carbon prices endogenously. In addition, a carbon trading module is introduced in the dynamic CGE model. The essential features of the NZ ETS are included in the model, such as carbon cap and free allocation, to simulate the impact of an external reduction target on carbon prices, land use and land use changes, and macroeconomic variables.

New Zealand's agriculture sector is the largest contributor to CO_2-e emissions, accounting for half of New Zealand's total carbon emissions. Reducing emissions from agriculture would make a massive contribution to achieving the Government's emission reduction targets. However, agriculture remains outside the ETS, because of the impact a carbon price would have on Zealand's agricultural international competitiveness. The government is considering the best way to include agricultural emissions into NZ ETS (MPI, 2020). Leining et al. (2020) suggested that agricultural bio-emissions should be priced from 2025. As an alternative carbon pricing tool a carbon tax could be less costly than cap-and-trade systems, although there is uncertainty about environmental benefits, cost-effectiveness and distributional impacts (Aldy et al., 2008). What is the impact of agricultural carbon tax combined with agricultural technology progress on the transition to the low-carbon economy? Chapter 3 reports on the design and application of d a land based dynamic CGE model to comprehensively analyze the combined effects of an agricultural carbon tax and agricultural technological progress on the macroeconomy and land use-related emissions reduction, land use and land use changes in New Zealand from macro level. In particular, agricultural technological progress is characterised as labour-augmenting, and capital-augmenting, and land-augmenting. The agricultural carbon tax is combined with technological progress, enabling us to explore the differential impacts of technological progress, given an emissions tax, on the economy and agricultural GHG emissions reduction.

New Zealand energy sector emissions have increased over the last few decades from 24 Mt CO_2-e in 1990 to 33 Mt CO_2-e today, representing 41 per cent of New Zealand's gross emissions. This suggests that energy efficiency increases in fossil energy and electricity can contribute to New Zealand's carbon reduction targets. However, energy savings brought by increased energy efficiency can be offset by increased energy demand. This is the so-called "rebound effect" (Bentzen, 2004). What is the rebound effect derived from the energy efficiency improvement and its effect on energy related emissions reduction in New Zealand? in Chapter 4, the dynamic CGE model was used to analyse the rebound effect of New Zealand's energy efficiency on macro-economy, energy consumption and energy-related emission reduction. First, the rebound effect of energy efficiency in production and economy-wide is dynamically estimated in the medium and long term. Second, four energy sources (coal, oil, gas and electricity) are identified so as to track each sector's energy-specific rebound effect.

To sum up, according to the New Zealand government's target to transition to a low-carbon economy, this dissertation examines whether three emission-reduction policies can achieve the transition to a low-carbon economy.

5.2 Results summary

5.2.1 Impact of the NZ ETS with free allocation to agriculture

Chapter 2 compiles a SAM table containing 49 sectors to data support the dynamic CGE model. The price of carbon emissions increases as carbon reduction targets become more ambitious. A small emission reduction rate may bring a greater carbon price and the carbon price changes in the same direction as the emission reduction rate changes. When the net emissions less than 25Mt, the greater of free emissions payment to the agricultural sector could not lower the carbon price. The corresponding price is up to NZ$325.74 per ton. Carbon prices in this study keep within a reasonable range and work for carbon emissions reduction. To achieve New Zealand’s carbon emissions targets in 2050, the carbon price ranges from NZ$136.37 per ton to NZ$325.74 per ton. In the long run, carbon prices have a negative impact on GDP.

Another result is that New Zealand’s net emissions in 2050 achieved through forest carbon sinks have a critical point. Carbon prices will increase rapidly by less than 25 Mt net emissions cap, and marginal emission reduction costs will increase.

5.2.2 The impact of agricultural carbon tax and agricultural technological progress

Chapter 3 analyses the impact of agricultural carbon tax (From $20 to $100 per ton) and technological progress on the macroeconomy using the land based CGE model. It finds that agricultural carbon tax does not cause substantial emission reductions, $100 per ton in Scenario SAE2, the emission reduction is 2.45% in 2030 and 5.66% in 2050. The result is consistent with Madronas and Lipski (2020) who estimated that the impact of carbon taxes (from US$5 to US$131 per ton) on CO_2-e emissions from agriculture would not substantially reduce emissions and reduce GDP. The higher the carbon tax rate, the greater the negative impact on New Zealand’s GDP growth rate, which is consistent with Fan et al. (2018). Our conclusion is similar to that of Ntombela et al. (2019), who found that a carbon tax is a useful policy tool to reduce emissions but would lead to a welfare loss, reducing the GDP by 0.91%

There is an interesting, and relevant finding in this study that although different types of technological progress can dampen the adverse impact of an agricultural carbon tax on GDP and other macroeconomic variables, the advancement of agricultural technological progress works to increase carbon emissions. Particularly, land-augmenting technological improvement contributes the most to the macro economy.

5.2.3 The rebound effect of energy efficiency

In Chapter 4, the dynamic CGE model with 49 sectors is used to analyze the economy-wide rebound effect of specific energy caused by the energy efficiency improvements of 2%, 3% and 5%.

The simulation results show that the improvement in energy efficiency results in a slight decrease in energy use, indicating that there is a considerable energy rebound effect. The energy-saving effect of improved coal efficiency results in rebound effect in production of 101.4%, and when the final consumption is taken into account, the economy-wide energy rebound effect is about 117%. It is the phenomenon of “backfire”, as Turner (2009) found with a rebound effect that was greater than 100% in the UK. Improvements in electricity efficiency cause a partial rebound effect on production, and the rebound effect is the smallest, which is very close to the rebound effect of electricity efficiency in China, 83.4%, found by Du et al. (2019). The rebound effects on production of the other two energies (oil and gas) are close to 100%.

It is necessary for government to account for the rebound effect when formulating energy conservation and emission reduction policies. Compared with other developed countries, New Zealand’s energy rebound effect is relatively high, Scotland’s 5% energy efficiency improvement brings about an oil rebound effect of less than 40% (Anson & Turner, 2009). When Spain's energy efficiency increases by 5%, the economy-wide rebound effect is 82.82% (Freire-González, 2020), which is close to that of New Zealand’s on the production side.

5.3 Limitations and suggestions for further research

In Chapter 2, some uncertainties exist both in forest biomass and land-use changes. It is not straight forward to include forest carbon sequestration in a CGE model that captures dynamic forest growth. As a result, assumptions were necessary to simplify model design. The sequestration modelled is essentially a “step change” removal when land is converted from agriculture to forestry. This approach may gloss over important transitional dynamics, depending on how the NZ ETS actually operates and how forest owners/managers respond. A more detailed simulation of the growth stages of trees would be a good research project for the future.

Chapter 3 modelled the impact of technological progress (factor-saving productivity) on agricultural emissions reduction. However, specific technological practices, such as methane inhibitors and methane vaccines, were not modelled. The focus of this chapter simulated a production process and its effects on macroeconomy and carbon emissions in response to factor augmenting-technological progress. Clearly, exogenous technological progress is a simplification. Endogenous technical changes would be a good topic for future research.

In Chapter 4, as to future studies about energy use in New Zealand, reducing energy consumption and emissions is a challenge for New Zealand achieving a low-carbon economy. From the simulation results, there may be some discrepancies in the expected effects of improved energy efficiency because the complexity of the economy makes it difficult for the CGE model to describe the entire national economy, particularly as there is no detailed analysis of renewable energy’s role in reducing emissions. Studies about the use of renewable energy and the development of low-carbon technologies would further contribute to our understanding of New Zealand’s transition to the low-carbon economy.

Finally, the data used in this thesis were based on the New Zealand input-output table for 2013. The model can be updated when the latest table is available.

Reference

Aatola, P., Ollikainen, M., & Toppinen, A. (2013). Price determination in the EU ETS market: Theory and econometric analysis with market fundamentals. *Energy Economics, 36*, 380-395.

Acemoglu, D. (2002). Directed technical change. *The review of economic studies, 69*(4), 781-809.

Acemoglu, D. (2003). Labor-and capital-augmenting technical change. *Journal of the European Economic Association, 1*(1), 1-37.

Acemoglu, D. (2007). Equilibrium bias of technology. *Econometrica, 75*(5), 1371-1409.

Acemoglu, D., Akcigit, U., Hanley, D., & Kerr, W. (2016). Transition to clean technology. *Journal of Political Economy, 124*(1), 52-104.

Acosta, S. C., Grimes, A. L., & Leining, C. (2020). Decision trees: Forestry in the New Zealand Emissions Trading Scheme post-2020.

Adams, T., & Turner, J. A. (2012). An investigation into the effects of an emissions trading scheme on forest management and land use in New Zealand. *Forest Policy and Economics, 15*(Supplement C), 78-90.

Aldy, J., Ley, E., & Parry, I. (2008). What is the Role of Carbon Taxes in Climate Change Mitigation?

Amri, F., Zaied, Y. B., & Lahouel, B. B. (2019). ICT, total factor productivity, and carbon dioxide emissions in Tunisia. *Technological Forecasting Social Change, 146*, 212-217.

Ang, B. W., Mu, A., & Zhou, P. (2010). Accounting frameworks for tracking energy efficiency trends. *Energy Economics, 32*(5), 1209-1219.

Anson, S., & Turner, K. (2009). Rebound and disinvestment effects in refined oil consumption and supply resulting from an increase in energy efficiency in the Scottish commercial transport sector. *Energy Policy, 37*(9), 3608-3620.

Atkins, M. J., Morrison, A. S., & Walmsley, M. R. (2010). Carbon emissions pinch analysis (CEPA) for emissions reduction in the New Zealand electricity sector. *Applied Energy, 87*(3), 982-987.

Balietti, A. C. (2016). Trader types and volatility of emission allowance prices. Evidence from EU ETS Phase I. *Energy policy, 98*, 607-620.

Ballingall, J., Pambudi, D., & Corong, E. (2018). Economic impact analysis of 2050 emissions targets: a dynamic computable general equilibrium analysis.

Banerjee, O., & Alavalapati, J. (2009). A computable general equilibrium analysis of forest concessions in Brazil. *Forest Policy and Economics, 11*(4), 244-252.

Beauchemin, K., Kreuzer, M., O'mara, F., & McAllister, T. (2008). Nutritional management for enteric methane abatement: a review. *Australian Journal of Experimental Agriculture, 48*(2), 21-27.

Belaïd, F., Bakaloglou, S., & Roubaud, D. (2018). Direct rebound effect of residential gas demand: Empirical evidence from France. *Energy policy, 115*, 23-31.

Benavente, J. M. G. (2016). Impact of a carbon tax on the Chilean economy: A computable general equilibrium analysis. *Energy Economics, 57*, 106-127.

Bentzen, J. (2004). Estimating the rebound effect in US manufacturing energy consumption. *Energy Economics, 26*(1), 123-134.

Benz, E., & Trück, S. (2009). Modeling the price dynamics of CO_2 emission allowances. *Energy Economics, 31*(1), 4-15.

Bergman, L. (1988). Energy policy modeling: a survey of general equilibrium approaches. *Journal of Policy Modeling, 10*(3), 377-399.

Berkhout, P. H., Muskens, J. C., & Velthuijsen, J. W. (2000). Defining the rebound effect. *Energy policy, 28*(6-7), 425-432.

Blyth, W., Bradley, R., Bunn, D., Clarke, C., Wilson, T., & Yang, M. (2007). Investment risks under uncertain climate change policy. *Energy policy, 35*(11), 5766-5773.

Böhringer, C., & Lange, A. (2005). On the design of optimal grandfathering schemes for emission allowances. *European Economic Review, 49*(8), 2041-2055.

Boston, J. (2008). Developing a long-term climate change mitigation strategy. *Political Science, 60*(1), 99-115.

Brännlund, R., Ghalwash, T., & Nordström, J. (2007). Increased energy efficiency and the rebound effect: Effects on consumption and emissions. *Energy Economics, 29*(1), 1-17.

Broberg, T., Berg, C., & Samakovlis, E. (2015). The economy-wide rebound effect from improved energy efficiency in Swedish industries–A general equilibrium analysis. *Energy policy, 83*, 26-37.

Brookes, L. (1978). Energy policy, the energy price fallacy and the role of nuclear energy in the UK. *Energy policy, 6*(2), 94-106.

Bruns, S. B., Moneta, A., & Stern, D. I. (2021). Estimating the economy-wide rebound effect using empirically identified structural vector autoregressions. *Energy Economics, 97*, 105158.

Bullock, D. (2012). Emissions trading in New Zealand: development, challenges and design.

Environmental Politics, 21(4), 657-675.

Burfisher, M. E. (2017). *Introduction to computable general equilibrium models*: Cambridge University Press.

Burtraw, D., & McCormack, K. (2017). Consignment auctions of free emissions allowances. *Energy policy, 107,* 337-344.

Carroll, J. L., & Daigneault, A. J. (2019). Achieving ambitious climate targets: is it economical for New Zealand to invest in agricultural GHG mitigation? *Environmental Research Letters, 14*(12), 124064.

Carver, T., Dawson, P., & Kerr, S. (2017). Including forestry in an emissions trading scheme: Lessons from New Zealand. *Available at SSRN 3015082*

Caselli, F., & Coleman II, W. J. (2006). The world technology frontier. *American Economic Review, 96*(3), 499-522.

Chen, S., Oxley, L., Xu, Z., Wang, Y., & Ma, H. (2013). The dynamic adjustment of factor inputs and its policy implications for major wheat producing areas in China. *Economic Modelling, 33*, 450-457.

Choi, Y., Liu, Y., & Lee, H. (2017). The economy impacts of Korean ETS with an emphasis on sectoral coverage based on a CGE approach. *Energy policy, 109*, 835-844.

Ciaschini, M., Pretaroli, R., Severini, F., & Socci, C. (2012). Regional double dividend from environmental tax reform: An application for the Italian economy. *Research in Economics, 66*(3), 273-283.

Cifci, E., & Oliver, M. (2018). Reassessing the Links between GHG Emissions, Economic Growth, and the UNFCCC: A Difference-in-Differences Approach. *Sustainability, 10*(2), 334.

Clark, H., Kelliher, F., & Pinares-Patino, C. (2011). Reducing CH_4 emissions from grazing ruminants in New Zealand: challenges and opportunities. *Asian-Australasian Journal of Animal Sciences, 24*(2), 295-302.

Conrad, J. M. (1999). *Resource economics*: Cambridge University Press.

Daigneault, A. (2015). Modelling the economic impact of New Zealand’s post-2020 climate change contribution. *Auckland: Prepared for the Ministry for Primary Industries and the Ministry for the Environment by Landcare Research. https://mfe. govt. nz/sites/default/files/media/Extra% 20downloads/Source% 20file/econom ic% 20impact% 20of% 20NZ% 20post-2020% 20climate% 20change% 20contribution. docx*

De Klein, C., & Eckard, R. (2008). Targeted technologies for nitrous oxide abatement from animal agriculture. *Australian Journal of Experimental Agriculture, 48*(2), 14-20.

Defourny, J., & Thorbecke, E. (1984). Structural path analysis and multiplier decomposition within a social accounting matrix framework. *The Economic Journal, 94*(373), 111-136.

Diaz-Rainey, I., & Tulloch, D. J. (2018). Carbon pricing and system linking: Lessons from the New Zealand Emissions Trading Scheme. *Energy Economics, 73*, 66-79.

Du, H., Chen, Z., Zhang, Z., & Southworth, F. (2020). The rebound effect on energy efficiency improvements in China's transportation sector: A CGE analysis. *Journal of Management Science Engineering, 5*(4), 249-263.

Du, Q., Li, Z., Li, Y., Bai, L., Li, J., & Han, X. (2019). Rebound effect of energy efficiency in China's construction industry: a general equilibrium analysis. *Environmental Science Pollution Research, 26*(12), 12217-12226.

Duarte, R., Sánchez-Chóliz, J., & Sarasa, C. (2018). Consumer-side actions in a low-carbon economy: A dynamic CGE analysis for Spain. *Energy policy, 118*, 199-210.

EECA. (2018). EECA's submission on Productivity Commission's report. *Retrieved from https://www.eeca.govt.nz/assets/Resources-Main/EECA-submission-to-the-Productivity-Commission-report-8-June-2018.pdf*

Evison, D. (2017). The New Zealand forestry sector's experience in providing carbon sequestration services under the New Zealand Emissions Trading Scheme, 2008 to 2012. *Forest Policy Economics, 75*, 89-94.

Fan, W., Gao, Z., Chen, N., Wei, H., Xu, Z., Lu, N., . . . Ulgiati, S. (2018). It is Worth Pondering Whether a Carbon Tax is Suitable for China's Agricultural-Related Sectors. *Energies, 11*(9), 2296.

Fan, Y., Jia, J.-J., Wang, X., & Xu, J.-H. (2017). What policy adjustments in the EU ETS truly affected the carbon prices? *Energy policy, 103*, 145-164.

Fernandez, M., & Daigneault, A. (2015). The climate mitigation, adaptation and trade in dynamic general equilibrium (CliMAT-DGE) model. *Landcare Research Contract Report, 2156 prepared for the Ministry for the Environment.*

Forest Owners Association (2014). Carbon sequestration and emissions trading. *Retrieved from https://www.nzfoa.org.nz/plantation-forestry/carbon-sequestration*

Frank, S., Havlík, P., Valin, H., Wollenberg, E. K., Hasegawa, T., & Obersteiner, M. (2017). Carbon prices, climate change mitigation & food security: How to avoid trade-offs?

Freire-González, J. (2020). Energy taxation policies can counteract the rebound effect: analysis within a general equilibrium framework. *Energy Efficiency, 13*(1), 69-78.

Frondel, M., & Vance, C. (2013). Re-identifying the rebound: what about asymmetry? *The energy journal, 34*(4)

Gangadharan, A., & Saadeh, A. (2018). The extent to which businesses in New Zealand are willing to pay carbon tax and other related mechanisms of carbon pricing.

George, D. A., Clewett, J. F., Lloyd, D., McKellar, R., Tan, P.-L., Howden, M., . . . Barlow, S. (2019). Research priorities and best practices for managing climate risk and climate change adaptation in Australian agriculture. *Australasian Journal of Environmental Management, 26*(1), 6-24.

Geylani, P. C., & Stefanou, S. E. (2011). Productivity growth patterns in US dairy products manufacturing plants. *Applied Economics, 43*(24), 3415-3432.

Gillingham, K., Kotchen, M. J., Rapson, D. S., & Wagner, G. (2013). The rebound effect is overplayed. *Nature, 493*(7433), 475-476.

Golub, A., Hertel, T., & Sohngen, B. (2007). *Projecting land use change in the dynamic GTAP framework.* Paper presented at the tenth Annual Conference on Global Economic Analysis, Purdue University, West Lafayette, IN., USA.

Golub, A., & Hertel, T. W. (2008). Global economic integration and land use change. *Journal of Economic integration*, 463-488.

Goulder, L. H., & Schein, A. R. (2013). Carbon taxes versus cap and trade: a critical review. *Climate Change Economics, 4*(03), 1350010.

Greening, L. A., Greene, D. L., & Difiglio, C. (2000). Energy efficiency and consumption—the rebound effect—a survey. *Energy policy, 28*(6-7), 389-401.

Haas, R., & Biermayr, P. (2000). The rebound effect for space heating Empirical evidence from Austria. *Energy Policy, 28*(6-7), 403-410.

Haites, E. (2018). Carbon taxes and greenhouse gas emissions trading systems: what have we learned? *Climate Policy, 18*(8), 955-966.

Hanley, N., McGregor, P. G., Swales, J. K., & Turner, K. (2009). Do increases in energy efficiency improve environmental quality and sustainability? *Ecological Economics, 68*(3), 692-709.

Hasan, M. A., Frame, D. J., Chapman, R., & Archie, K. M. (2020). Curbing the car: the mitigation potential of a higher carbon price in the New Zealand transport sector. *Climate Policy, 20*(5), 563-576.

Hazilla, M., & Kopp, R. (1990). Social cost of environmental quality regulations: A general equilibrium analysis. *Journal of Political Economy, 98*(4), 853-873.

Hicks, J. (1963). *The theory of wages*: Springer.

Hong, S. H., Oreszczyn, T., Ridley, I., & Group, W. F. S. (2006). The impact of energy efficient refurbishment on the space heating fuel consumption in English dwellings. *Energy and Buildings, 38*(10), 1171-1181.

Hübler, M., Voigt, S., & Löschel, A. (2014). Designing an emissions trading scheme for China—An up-to-date climate policy assessment. *Energy policy, 75*, 57-72.

Ianchovichina, E., Darwin, R., & Shoemaker, R. (2001). Resource use and technological progress in agriculture: a dynamic general equilibrium analysis. *Ecological Economics, 38*(2), 275-291.

IEA, I. (2018). World energy statistics and balances: OECD iLibrary, eISSN.

IEA. (2014). *Energy Efficiency Market Report 2014*.

Jevons, W. S. (1866). The Coal Question; An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of our Coal-Mines. *Fortnightly, 6*(34), 505-507.

Jiang, M., Zhu, B., Chevallier, J., & Xie, R. (2018). Allocating provincial CO_2 quotas for the Chinese national carbon program. *Australian Journal of Agricultural Resource Economics, 62*(3), 457-479.

Jiang, M. X., Yang, D. X., Chen, Z. Y., & Nie, P. Y. (2016). Market power in auction and efficiency in emission permits allocation. *Journal of environmental management, 183*, 576-584.

Johansen, L. (1960). Multi-sectoral study of economic growth.

Jones, K. (2015). Energy Efficiency in New Zealand's Light Transport Fleet: Is It Time for a CO_2/Fuel Efficiency Standard. *NZJ Envtl. L., 19*, 139.

Jorgenson, D. W., & Wilcoxen, P. (1990). Intertemporal general equilibrium modeling of US environmental regulation. *Journal of Policy Modeling, 12*(4), 715-744.

Jotzo, F. (2012). Australia's carbon price. *Nature Climate Change, 2*(7), 475-476.

Kerr, S., Anastasiadis, S., Olssen, A., Power, W., Timar, L., & Zhang, W. (2012). Spatial and temporal responses to an emissions trading scheme covering agriculture and forestry: simulation results from new zealand. *Forests, 3*(4), 1133-1156.

Kerr, S., & Zhang, W. (2009). Allocation of New Zealand units within agriculture in the New Zealand emissions trading system. *Motu Economic Public Policy Research Working Paper*(09-16)

Key, N. (2019). Farm size and productivity growth in the United States Corn Belt. *Food Policy, 84*, 186-195.

Khazzoom, J. D. (1980). Economic implications of mandated efficiency in standards for household appliances. *The energy journal, 1*(4)

Khosroshahi, M. K., & Sayadi, M. (2020). Tracking the sources of rebound effect resulting from the efficiency improvement in petrol, diesel, natural gas and electricity consumption; A CGE analysis for Iran. *Energy*, 117134.

Kirschbaum, M. U., Rutledge, S., Mudge, P. L., Puche, N., Schipper, L. A., & Campbell, D. I. (2015). *Changes in soil carbon stocks of New Zealand's grazed pasture in response to variations in management and environmental factors.* Paper presented at the 28th Annual FLRC Workshop.

Koch, N., Fuss, S., Grosjean, G., & Edenhofer, O. (2014). Causes of the EU ETS price drop: Recession, CDM, renewable policies or a bit of everything?—New evidence. *Energy policy, 73*, 676-685.

Koesler, S., Swales, J. K., & Turner, K. (2014). Beyond National Economy-Wide Rebound Effects. An Applied General Equilibrium Analysis Incorporating International Spillover Effects. *An Applied General Equilibrium Analysis Incorporating International Spillover Effects. ZEW-Centre for European Economic Research Discussion Paper*(14-025)

Koesler, S., Swales, K., & Turner, K. (2016). International spillover and rebound effects from increased energy efficiency in Germany. *Energy Economics, 54*, 444-452.

Kuik, O., & Mulder, M. (2004). Emissions trading and competitiveness: pros and cons of relative and absolute schemes. *Energy policy, 32*(6), 737-745.

Lawson, K., Burns, K., Low, K., Heyhoe, E., & Ahammad, H. (2008). Analysing the economic potential of forestry for carbon sequestration under alternative carbon price paths. *Australian Bureau of Agricultural Resource Economics, Canberra*

Lecca, P., McGregor, P. G., Swales, J. K., & Turner, K. (2014). The added value from a general equilibrium analysis of increased efficiency in household energy use. *Ecological Economics, 100*, 51-62.

Lecca, P., Swales, K., & Turner, K. (2011). An investigation of issues relating to where energy should enter the production function. *Economic Modelling, 28*(6), 2832-2841.

Lee, H.-L. (2005). *Incorporating agro-ecologically zoned land use data and land-based greenhouse gases emissions into the GTAP framework.* Paper presented at the 8th annual conference on Global Economic Analysis, Lübeck, Germany.

Leining, C., Allan, C., & Kerr, S. (2017). *Evolution of the New Zealand Emissions Trading Scheme: sectoral coverage and point of obligation*.

Leining, C., Kerr, S., & Bruce-Brand, B. (2020). The New Zealand Emissions Trading Scheme: critical review and future outlook for three design innovations. *Climate Policy, 20*(2), 246-264.

Lennox, J., & van Nieuwkoop, R. (2009). *Affordable and effective climate change mitigation policies for New Zealand.* Paper presented at the 15th Annual International Sustainable Development Research Conference, Utrecht, The Netherlands.

Lennox, J. A., & Van Nieuwkoop, R. (2010). Output-based allocations and revenue recycling: Implications for the New Zealand Emissions Trading Scheme. *38*(12), 7861-7872.

Li, D., Gao, M., Hou, W., Song, M., & Chen, J. (2020). A modified and improved method to measure economy-wide carbon rebound effects based on the PDA-MMI approach. *Energy policy, 147*, 111862.

Li, G., Yang, J., Chen, D., & Hu, S. (2017). Impacts of the coming emission trading scheme on China's coal-to-materials industry in 2020. *Applied Energy, 195*, 837-849.

Li, W., & Jia, Z. (2016). The impact of emission trading scheme and the ratio of free quota: A dynamic recursive CGE model in China. *Applied Energy, 174*, 1-14.

Lin, B., & Jia, Z. (2017). The impact of Emission Trading Scheme (ETS) and the choice of coverage industry in ETS: A case study in China. *Applied Energy, 205*, 1512-1527.

Lin, B., & Jia, Z. (2019). Impacts of carbon price level in carbon emission trading market. *Applied Energy, 239*, 157-170.

Liu, Y., Tan, X.-J., Yu, Y., & Qi, S.-Z. (2017). Assessment of impacts of Hubei Pilot emission trading schemes in China–A CGE-analysis using TermCO_2 model. *Applied Energy, 189*, 762-769.

Lofgren, H., Harris, R. L., & Robinson, S. (2002). *A standard computable general equilibrium (CGE) model in GAMS* (Vol. 5): Intl Food Policy Res Inst.

Lu, C., Tong, Q., & Liu, X. (2010). The impacts of carbon tax and complementary policies on Chinese economy. *Energy policy, 38*(11), 7278-7285.

Lu, Y., Liu, Y., & Zhou, M. (2017). Rebound effect of improved energy efficiency for different energy types: A general equilibrium analysis for China. *Energy Economics, 62*, 248-256.

Mahmood, A., & Marpaung, C. O. (2014). Carbon pricing and energy efficiency improvement--why to miss the interaction for developing economies? An illustrative CGE based application to the Pakistan case. *Energy policy, 67*, 87-103.

Manley, B., & Maclaren, P. (2012). Potential impact of carbon trading on forest management in New Zealand. *Forest Policy Economics, 24*, 35-40.

Mardones, C., & Lipski, M. (2020). A carbon tax on agriculture? A CGE analysis for Chile. *Economic Systems Research, 32*(2), 262-277.

Mardones, C., & Muñoz, T. (2018). Environmental taxation for reducing greenhouse gases emissions in Chile: an input–output analysis. *Environment, Development Sustainability, 20*(6), 2545-2563.

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., . . . Pidcock, R. (2018). Global warming of 1.5 C. *An IPCC Special Report on the impacts of global warming of 2018, 1*(5)

Matos, F. J., & Silva, F. J. (2011). The rebound effect on road freight transport: Empirical evidence from Portugal. *Energy Policy, 39*(5), 2833-2841.

MBIE. (2019). New Zealand energy sector greenhouse gas emissions. *Ministry of Business, Innovation and Employmentt, Wellington.*

McNally, S. R., Beare, M. H., Curtin, D., Meenken, E. D., Kelliher, F. M., Calvelo Pereira, R., . . . Baldock, J. (2017). Soil carbon sequestration potential of permanent pasture and continuous cropping soils in New Zealand. *Global change biology, 23*(11), 4544-4555.

Meng, S. (2015). Is the agricultural industry spared from the influence of the Australian carbon tax? *Agricultural economics, 46*(1), 125-137.

Meng, S., Siriwardana, M., & McNeill, J. (2013). The environmental and economic impact of the carbon tax in Australia. *Environmental and Resource Economics, 54*(3), 313-332.

MfE. (2017). New Zealand's Greenhouse Gas Inventory 1990–2015. *Ministry for the Environment, Wellington*

MfE. (2019a). About New Zealand's emissions reduction targets. *Retrieved from https://www.mfe.govt.nz/climate-change/climate-change-and-government/emissions-reduction-targets/about-our-emissions*

MfE. (2019b). Agriculture emissions and climate change. *Retrieved from https://www.mfe.govt.nz/climate-change/climate-change-and-government/emissions-reduction-targets/about-our-emissions*

MfE. (2019c). Measuring Emissions: A Guide for Organisations. *Retrieved from https://www.mfe.govt.nz/sites/default/files/media/Climate%20Change/2019-detailed-guide.pdf*

MfE. (2020a). New Zealand's Greenhouse Gas Inventory. *Retrieved from https://www.mfe.govt.nz/climate-change/state-of-our-atmosphere-and-climate/new-zealands-greenhouse-gas-inventory*

MfE. (2020b). Price controls in the New Zealand Emissions Trading Scheme. *Retrieved from https://www.mfe.govt.nz/reforming-nzets-price-controls*

MfE. (2021). Projections of greenhouse gas emissions as published on 29 January 2021.

Retrieved from https://environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/emissions-reduction-targets/new-zealands-projected-greenhouse-gas-emissions-to-2050/

Michetti, M., & Rosa, R. (2012). Afforestation and timber management compliance strategies in climate policy. A computable general equilibrium analysis. *Ecological Economics, 77*, 139-148.

Mizobuchi, K. (2008). An empirical study on the rebound effect considering capital costs. *Energy Economics, 30*(5), 2486-2516.

Monge, J. J., Bryant, H. L., Gan, J., & Richardson, J. W. (2016). Land use and general equilibrium implications of a forest-based carbon sequestration policy in the United States. *Ecological Economics, 127*, 102-120.

Mosnier, C., Britz, W., Julliere, T., De Cara, S., Jayet, P.-A., Havlík, P., . . . Mosnier, A. (2019). Greenhouse gas abatement strategies and costs in French dairy production. *Journal of Cleaner Production, 236*, 117589.

Moyes, T. E. (2008). Greenhouse gas emissions trading in New Zealand: trailblazing comprehensive cap and trade. *Ecology LQ, 35*, 911.

MPI. (2020). Emissions Trading Scheme. *Retrieved from https://www.mpi.govt.nz/protection-and-response/environment-and-natural-resources/emissions-trading-scheme/*

Mu, Y., Evans, S., Wang, C., & Cai, W. (2018). How will sectoral coverage affect the efficiency of an emissions trading system? A CGE-based case study of China. *Applied Energy, 227*, 403-414.

Nong, D., Meng, S., & Siriwardana, M. (2017). An assessment of a proposed ETS in Australia by using the MONASH-Green model. *Energy policy, 108*, 281-291.

Nong, D., Nguyen, T. H., Wang, C., & Van Khuc, Q. (2020). The environmental and economic impact of the emissions trading scheme (ETS) in Vietnam. *Energy policy, 140*, 111362.

Ntombela, S. M., Bohlmann, H. R., & Kalaba, M. W. (2019). Greening the South Africa's economy could benefit the food sector: evidence from a carbon tax policy assessment. *Environmental Resource Economics, 74*(2), 891-910.

NZ Forestry. (2020). Carbon Forestry. *Retrieved from https://nzforestry.co.nz/services/carbon-forestry/*

NZIER. (2008). The Impact of the Proposed Emissions Trading Scheme on New Zealand's Economy. *New Zealand Institute for Economic Research, Wellington,New Zealand.*

NZIER. (2009). Macroeconomic impacts of climate change policy: Impact of Assigned Amount Units and international trading. *Retrieved from* *https://www.mfe.govt.nz/publications/climate-change/macroeconomic-impacts-climate-change-policy-impact-assigned-amount-units*

OECD. (2013). *Taxing Energy Use: A Graphical Analysis*: OECD Publishing.

Oh, D., Heshmati, A., & Lööf, H. (2012). Technical change and total factor productivity growth for Swedish manufacturing and service industries. *Applied Economics, 44*(18), 2373-2391.

Orlov, A., & Grethe, H. (2012). Carbon taxation and market structure: A CGE analysis for Russia. *Energy Policy, 51*, 696-707.

Paltsev, S., Reilly, J. M., Jacoby, H. D., Eckaus, R. S., McFarland, J. R., Sarofim, M. C., . . . Babiker, M. H. (2005). *The MIT emissions prediction and policy analysis (EPPA) model: version 4*. MIT Joint Program on the Science and Policy of Global Change.

Pant, H. M. (2010). *An analytical framework for incorporating land use change and forestry in a dynamic CGE model*.

Parliament, N. Z. (2008). *Terms of Reference Emissions Trading Scheme Review*. Wellington, New Zealand

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I.-C., . . . Evengård, B. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science, 355*(6332)

Pezzey, J. C., & Jotzo, F. (2013). Carbon tax needs thresholds to reach its full potential. *Nature Climate Change, 3*(12), 1008-1011.

Pigou, A. C. (1924). The economics of welfare 2 nd edition. *Appendix IIPigou2The Economics of Welfare*

Pradhan, B. B., Shrestha, R. M., Hoa, N. T., & Matsuoka, Y. (2017). Carbon prices and greenhouse gases abatement from agriculture, forestry and land use in Nepal. *Global Environmental Change, 43*, 26-36.

Rae, A., Strutt, A., & Cassells, S. (2008). Towards analysis of sustainable export-oriented agriculture: Exploring land-use data and cge modelling in New Zealand.

Rausch, S., & Schwerin, H. (2018). Does higher energy efficiency lower economy-wide energy use? *CER-ETH Working Paper, 18*, 299.

Reisinger, A., & Ledgard, S. (2013). Impact of greenhouse gas metrics on the quantification of agricultural emissions and farm-scale mitigation strategies: a New Zealand case study. *Environmental Research Letters, 8*(2), 025019.

Richter, J. L., & Mundaca, L. (2013). Market behavior under the New Zealand ETS. *Carbon Management, 4*(4), 423-438.

Sancho, F. (2010). Double dividend effectiveness of energy tax policies and the elasticity of substitution: A CGE appraisal. *Energy Policy, 38*(6), 2927-2933.

Saunders, H. D. (2000). A view from the macro side: rebound, backfire, and Khazzoom–Brookes. *Energy policy, 28*(6-7), 439-449.

Saunders, H. D. (2008). Fuel conserving (and using) production functions. *Energy Economics, 30*(5), 2184-2235.

Schleussner, C.-F., Rogelj, J., Schaeffer, M., Lissner, T., Licker, R., Fischer, E. M., . . . Hare, W. (2016). Science and policy characteristics of the Paris Agreement temperature goal. *Nature Climate Change, 6*(9), 827-835.

Schusser, S., & Jaraite, J. (2016). Explaining the interplay of three markets: Green certificates, carbon emissions and electricity.

Scrimgeour, F., Oxley, L., & Fatai, K. (2005). Reducing carbon emissions? The relative effectiveness of different types of environmental tax: The case of New Zealand. *Environmental Modelling Software*, *20*(11), 1439-1448.

Shahbaz, M., Loganathan, N., Muzaffar, A. T., Ahmed, K., & Jabran, M. A. (2016). How urbanization affects CO2 emissions in Malaysia? The application of STIRPAT model. *Renewable Sustainable Energy Reviews, 57*, 83-93.

Solaymani, S., & Kari, F. (2014). Impacts of energy subsidy reform on the Malaysian economy and transportation sector. *Energy Policy, 70*, 115-125.

Solow, R. M. (1957). Technical change and the aggregate production function. *The review of economics statistics*, 312-320.

Song, Y., Liang, D., Liu, T., & Song, X. (2018). How China’s current carbon trading policy affects carbon price? An investigation of the Shanghai Emission Trading Scheme pilot. *Journal of Cleaner Production, 181*, 374-384.

Sorrell, S. (2007). The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency: UK Energy Research Centre London.

Sorrell, S. (2014). Energy substitution, technical change and rebound effects. *Energies, 7*(5), 2850-2873.

Sorrell, S., & Sijm, J. (2003). Carbon trading in the policy mix. *Oxford review of economic policy, 19*(3), 420-437.

Stainback, G. A., & Alavalapati, J. R. (2002). Economic analysis of slash pine forest carbon sequestration in the southern US. *Journal of Forest Economics*, *8*(2), 105-117.

Stavins, R. N., & Richards, K. R. (2005). The cost of U. S. forest-based carbon sequestration. *Pew Center on Global Climate Change*, 52.

Stern, D. I. (2020). How large is the economy-wide rebound effect? *Energy policy, 147*, 111870.

Stevanovic, M., Popp, A., Bodirsky, B. L., Humpenöder, F., Müller, C., Weindl, I., . . . Rolinski, S. (2017). Mitigation strategies for greenhouse gas emissions from agriculture and land-use change: consequences for food prices. *Environmental Science, 51*(1), 365-374.

Stroombergen, A. (2007). General Equilibrium Analysis of Options for Meeting New Zealand's International Emissions Obligations. *Infometrics, Wellington, http://www. mfe. govt. nz/publications/climate/general-equilibrium-analysis-oct07/generalequilibrium-analysis. pdf [17 March 2008]*

Sue Wing, I. (2011). Computable General Equilibrium Models for the Analysis of Economy-Environment Interactions. *Research Tools in Natural Resource and Environmental Economics*, 255.

Sue Wing, I., & Balistreri, E. (2018). Computable general equilibrium models for economic policy evaluation and economic consequence analysis. *Oxford University Press Handbook on Computational Economics Finance.*

Tee, J., Scarpa, R., Marsh, D., & Guthrie, G. (2014). Forest valuation under the New Zealand emissions trading scheme: a real options binomial tree with stochastic carbon and timber prices. *Land Economics*, *90*(1), 44-60.

Timar, L., & Kerr, S. (2014). Land-use intensity and greenhouse gas emissions in the LURNZ model.

Tokunaga, S., Okiyama, M., & Ikegawa, M. (2020). Spatial analysis of climate change impacts on regional economies through Japan's rice production changes and innovative food industry cluster: Using the nine interregional CGE model *Environmental Economics and Computable General Equilibrium Analysis* (pp. 301-332): Springer.

Turner, K. (2009). Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK economy. *Energy Economics, 31*(5), 648-666.

Turner, K., & Hanley, N. (2011). Energy efficiency, rebound effects and the environmental Kuznets Curve. *Energy Economics, 33*(5), 709-720.

van Kooten, G. C. (2017). Forest carbon offsets and carbon emissions trading: Problems of contracting: Elsevier.

van Kooten, G. C., & Sohngen, B. (2007). Economics of forest ecosystem carbon sinks: a review.

Verma, P., Patel, N., Nair, N.-K. C., & Brent, A. C. (2018). Improving the energy efficiency of the New Zealand economy: A policy comparison with other renewable-rich countries. *Energy Policy, 122*, 506-517.

Walras, L. (1954). *Elements of Pure Economics Or The Theory of Social Wealth:(A Transl. of the Éd. Définitive, 1926, of the Eléments D'économie Politique Pure, Annotated and Collated with the Previous Editions)*: George Allen & Unwin Limited.

Wang, X., & Teng, F. (2015). Research on free quota allocation scheme's influence on major industrial sectors in China's carbon market. *China Population, Resources and Environment, 25*, 129-134.

Wang, Y., Sharp, B., Poletti, S., & Nam, K.-M. (2021). Economic and land use impacts of net zero-emission target in New Zealand. *International Journal of Urban Sciences*, 1-18.

Wang, Z., & Lu, M. (2014). An empirical study of direct rebound effect for road freight transport in China. *Applied Energy, 133*, 274-281.

Wei, T., & Liu, Y. (2017). Estimation of global rebound effect caused by energy efficiency improvement. *Energy Economics, 66*, 27-34.

Wei, T., Zhou, J., & Zhang, H. (2019). Rebound effect of energy intensity reduction on energy consumption. *Resources, Conservation Recycling, 144*, 233-239.

Weizsäcker, E. U., Lovins, A. B., & Lovins, L. H. (1998). *Factor four: doubling wealth-halving resource use: the new report to the Club of Rome*: Earthscan.

Wollenberg, E., Richards, M., Smith, P., Havlík, P., Obersteiner, M., Tubiello, F. N., . . . Reisinger, A. (2016). Reducing emissions from agriculture to meet the 2 C target. *Global change biology, 22*(12), 3859-3864.

Wu, Q., & Li, C. (2020). How quota allocation affects the unified ETS of China: a simulation with dynamic CGE model. *Environmental Science and Pollution Research, 27*(2), 1835-1851.

Yang, L., & Li, Z. (2017). Technology advance and the carbon dioxide emission in China–Empirical research based on the rebound effect. *Energy policy, 101*, 150-161.

Ye, S., Dai, P.-F., Nguyen, H. T., & Huynh, N. Q. A. (2021). Is the cross-correlation of EU carbon market price with policy uncertainty really being? A multiscale multifractal perspective. *Journal of environmental management, 298*, 113490.

Yu, Z., Geng, Y., Dai, H., Wu, R., Liu, Z., Tian, X., & Bleischwitz, R. (2018). A general equilibrium analysis on the impacts of regional and sectoral emission allowance allocation at carbon trading market. *Journal of Cleaner Production, 192*, 421-432.

Zhang, L., Li, Y., & Jia, Z. (2018). Impact of carbon allowance allocation on power industry in China's carbon trading market: Computable general equilibrium based analysis.

Applied Energy, 229, 814-827.

Zhang, Q., Sun, Z., Wu, F., & Deng, X. (2016). Understanding rural restructuring in China: The impact of changes in labor and capital productivity on domestic agricultural production and trade. *Journal of Rural Studies, 47*, 552-562.

Zhou, M., Liu, Y., Feng, S., Liu, Y., & Lu, Y. (2018). Decomposition of rebound effect: An energy-specific, general equilibrium analysis in the context of China. *Applied Energy, 221*, 280-298.

Zhu, L., Zhang, X.-B., Li, Y., Wang, X., & Guo, J. (2017). Can an emission trading scheme promote the withdrawal of outdated capacity in energy-intensive sectors? A case study on China's iron and steel industry. *Energy Economics, 63*, 332-347.