Sectoral Electricity Demand and Direct Rebound Effects in New Zealand

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ABSTRACT

This paper is one of the limited studies to investigate rebound effects in sectoral electricity consumption and the specific case of New Zealand. New Zealand, like other OECD economies, has aimed for energy efficiency improvements and reduced electricity consumption from 9.2 MWh per capita in 2010 to 8.6 MWh per capita in 2015. However, following a significant decline since 2010, electricity consumption in the main New Zealand sectors is increasing. Energy conservation could play an important role in meeting the growing demand for electricity but rebound effects can affect the effectiveness of conservation policies. We decompose the sectoral electricity prices to capture the asymmetric demand response to electricity price changes and estimate electricity demand elasticity during 1980 and 2015 to estimate the sectoral rebound effects. We find partial rebound effects of 54% and 23% in the industrial and commercial sectors respectively while we find no rebound effect at the aggregate level. The rebound effect is insignificant in the residential sector. These findings lead to policy recommendations for sector specific energy conservation measures and policies.

Keywords: Electricity, Demand, Rebound, Heating, Time series analysis

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1. INTRODUCTION

Global electricity demand is growing faster than the increase in overall energy demand. In 2017, global electricity demand increased by 3.1% while energy demand grew by 2.1% (IEA, 2017a). The trend is set to continue and the share of electricity in total final energy consumption is expected to rise from 19% in 2015 to 24% in 2050 (EIA, 2016). The OECD economies have an average electricity consumption per capita of 7.9 MWh as compared to a per capita consumption of 2.1 MWh in 2017 in developing countries. The annual growth of electricity consumption in the OECD is expected to be about 1.2% (IEA, 2019).

However, due to the presence of rebound effects, attempts to measure energy savings by undertaking energy efficiency improvements in order to curb rising electricity consumption is complicated. The concept of rebound effects in electricity consumption implies that technical progress can makes energy less costly relative to other goods. As a result, improving energy efficiency may save less electricity than initially expected due to a rebound in electricity consumption (Gillingham, et al., 2016). Determining the magnitude of rebound effects is appealing from a policy point of view since energy saving programs can become less effective as a result (Hunt and Ryan, 2015).

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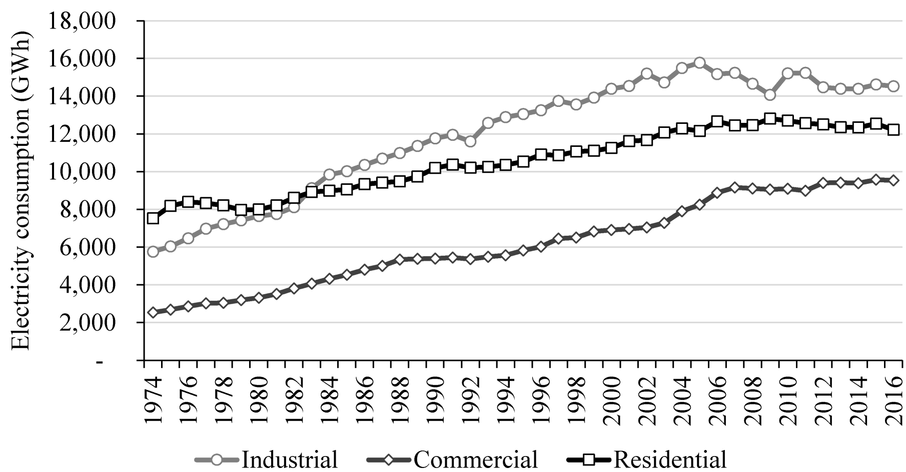
New Zealand is the 10th highest per capita electricity consuming country in the world (IEA, 2015, WB, 2017). The country has aimed to increase energy efficiency in all sectors in order to curb rising electricity consumption as stated in the energy policy statement of New Zealand under the New Zealand Energy Strategy 2011–2021 (MED, 2011). Per capita electricity consumption declined from 9.2 MWh in 2010 to 8.6 MWh in 2015 (MBIE, 2018, WB, 2019). However, the consumption trends in different sectors of the economy vary (see Figure 1). While electricity consumption in the commercial sector has increased continuously, consumption in the industrial and residential sectors declined between 2010 and 2013 and increased again thereafter. Demand for electricity is likely to more than double from approximately 40 TWh in 2018 to almost 90 TWh by 2050. Meanwhile, the share of electricity of total delivered energy demand is projected to increase from 25% in 2016 to 61% by 2050 (Tanspower, 2018).

Figure 1: Sectoral electricity demand



Source: MBIE (2018)

Therefore, improvements in energy efficiency in the residential, industrial and commercial sectors are a priority under the New Zealand energy strategy to support economic growth, reduce greenhouse gas and improve energy security. The government also established a companion Energy Efficiency and Conservation Act in 2000 in order to back the energy strategy and launched the New Zealand Energy Efficiency and Conservation Strategy 2017–2022 in order to deliver an energy productive and low emissions economy. Nonetheless, the electricity demand projections in New Zealand do not consider rebound effects from energy efficiency improvements to electricity consumption. Ignoring the rebound effect may hamper the development of effective energy policies (Vivanco, et al., 2016), especially in generation and network investment planning as well as the operation of the power sector. Disregarding rebound effects leads to underestimation of demand projection, supply shortages, forced power outages, while overestimation of the demand may result in overinvestments, and ultimately in higher electricity prices (Steinbuks, 2017).

This paper aims to analyze rebound effects as a potential cause of increase in electricity consumption by the residential, industrial, and commercial sectors in New Zealand between 1980 and 2015. We use structural time-series econometrics to separate the influences of rebound effects and income on sectoral electricity consumptions. The possibility of income affecting energy consumption in New Zealand has been dismissed in several studies. Isaacs, et al. (2010) found that under-heating in households is common, regardless of the income of the households. This paper is one of the few to analyze the consumption patterns and the rebound effect in the residential, industrial and commercial sector. The findings are also relevant for other countries aiming to implement efficiency policies to slow down the increase in electricity demand.

Previous studies did not find causality between total electricity consumption and real gross domestic product (GDP) in New Zealand (Fatai, et al., 2004, Narayan and Prasad, 2008). Fatai, et al. (2003) found a long run cointegrated relationship between electricity demand, real GDP, electricity price and consumer price index (CPI) representing other energy prices. However, they did not find cointegration for consumptions in industrial, commercial and residential sectors. The findings of previous studies are inconclusive, partly owing to the omission of the rebound effect in estimations of electricity consumption.

More than 15 years have passed since the original study by Fatai, et al. (2003) in estimating the New Zealand sectoral electricity demand was conducted. Within these years, economic development and technological transformation has influenced the sectoral electricity consumption patterns in New Zealand. Hence, we revisit and extend the previous studies and approaches in a number of ways. First, we update the data to capture the current consumption patterns in New Zealand. Second, instead of using data in total values, we use data in per capita unit following the majority of studies on estimating electricity demand (Dergiades and Tsoulfidis, 2008, Narayan and Smyth, 2005, Okajima and Okajima, 2013, Saunoris and Sheridan, 2013). Third, we use the actual natural gas price data instead of a price index as in Fatai, et al. (2003) as a proxy for price of a close energy substitute for the residential and the commercial sectors. Fourth, we estimate the magnitude of the rebound effect that may reduce the effectiveness of energy conservation policies. Fifth, a better understanding of the factors determining demand for electricity at sectoral level, as in the present study in the case of New Zealand, is needed given the gap in the literature. These factors include supply bottlenecks such as being an isolated electricity system, adverse effects of electricity shortage arising from heavy reliance on hydroelectricity and costly investments in new capacity with long gestation periods (Bhatia, 1987).

The remainder of the paper is structured as follows. Section 2 provides a brief overview of the energy conservation policy in New Zealand and discusses the relevant literature. Section 3 explains the estimations methodology including the empirical framework of our analysis based on asymmetric demand responses to electricity price change and the data. Section 4 presents the estimation results. Section 5 concludes the study with relevant policy implications.

2. THE NEW ZEALAND ELECTRICITY SECTOR AND THE LITERATURE

The rebound effect is well conceptualized in the energy economics literature as a phenomenon where energy conservation measures potentially reduce energy costs and, consequently, encourage people to consume more energy (Gillingham, et al., 2013, Gillingham, et al., 2016, Greening, et al., 2000, Khazzoom, 1980, Orea, et al., 2015, Turner, 2013). The sub-sections below discusses the status of energy conservation policies in New Zealand and also reviews the relevant literature around rebound estimates respectively.

2.1. Energy Conservation Policy in New Zealand

Electricity is the main source of energy in the New Zealand residential sector. Electricity alone meets 69% of household energy demand while 34% of the total energy is used for space heating (Isaacs, et al., 2010). Traditionally, households in New Zealand have encountered under-heating problems since their average indoor temperature is below the standard temperature recommended by the World Health Organization (WHO), i.e., 21 degrees Celsius (Howden-Chapman, et al., 2009, Isaacs, et al., 2010, Lloyd, et al., 2008, O'Sullivan, et al., 2016). Factors explaining the poor heating conditions include the relatively old-age of the houses and inferior thermal insulation (Howden-Chapman, et al., 2009, Isaacs, et al., 2010, O'Sullivan, et al., 2015). For that, MED (2011) aimed to improve the house insulation that will not only increase the temperature but also gain significant energy and electricity savings (Grimes, et al., 2011).

The Energy Efficiency and Conservation Strategy 2017–2022 recognizes the need for improving energy efficiency and productivity in the industrial and commercial use of electricity (MBIE, 2017). The strategy perceives that cost-effective energy efficiency improvements could reduce New Zealand's energy use and carbon emissions. Focusing on energy saving in the industrial and commercial sector will further leverage the renewable energy generation advantage for New Zealand as these sectors provide huge opportunities to reduce carbon emissions. Therefore, improvements in energy efficiency also imply improvements in carbon emission efficiency for New Zealand's economy as the electricity sector has 80% renewable generation (Khan, et al. 2018).

In New Zealand, any energy efficiency improvements policy in order to promote energy savings needs to be implemented against the backdrop of a unique electricity system. No other country generates electricity from the same generation mix, low levels of energy storage and without a grid connection to another country (Transpower, 2018). A rapid electrification of the industrial and transport sectors in the push towards decarbonization is expected to pose energy security risks to New Zealand's electricity sector. For instance, electric vehicles (EVs) are expected to reach 40% market share by 2030 and 85% by 2050. Globally, the share of electricity in transportation is expected to double between 2015 and 2040 as more plug-in electric vehicles enter the fleet (IEA, 2017b).

The Energy Efficiency and Conservation Strategy 2017–2022 promotes the residential, commercial and industrial sectors to conduct energy audits as well as energy efficiency practices, including the building code stating the minimum energy performance standards (MEPS) for heating, ventilation, cooling, and lighting systems. Nonetheless, energy conservation could cause a rebound effect, which is ignored by the existing New Zealand energy policy. Therefore, understanding the rebound effects provides insight for New Zealand's energy policymakers in aligning energy security policies with environmental sustainability while maintaining healthy living standards and sustaining economic growth. However, the empirical evidence of rebound effects is limited for sectoral electricity consumptions in New Zealand. This gap is covered by our study.

2.2 Relevant Literature on the Estimations of Rebound Effects

Energy policy concerns around rebound effects have attracted global attention as evident from Table 1. However, none of the previous studies has examined rebound effects in electricity demand at all different sectoral levels within an economy. Some studies have estimated the rebound effects in residential and industrial sectors in China but do not include the commercial sector. The most common econometric methods of estimating rebound effects are indirect estimations from own-price elasticity of energy (Bentzen, 2004, Dahlqvist, et al., 2021, Lin and Liu, 2015, Lin and Tian, 2016, Nurse, et al., 2014, Yang and Li, 2017) and direct estimates from the elasticity of non-positive and non-increasing components of the energy price to consider asymmetric effects of changes in energy prices (Bentzen, 2004, Haas and Biermayr, 2000, Lin and Tian, 2016, Nurse, et al., 2014, Wang, et al., 2014, Yang and Li, 2017).

Recently, several new methods have been introduced, but their applications are still limited for cross-country comparisons, such as methodologies based on the time-varying coefficient state space model (Shao, et al., 2014), the energy demand frontier model (Orea, et al., 2015), and the panel threshold model (Zhang and Peng, 2017). The results from most existing studies confirmed the presence of partial rebound effects except studies by Lin and Liu (2015) and Dahlqvist, et al. (2017) which report a backfire case in the rural residential sector in China and in heavy industries in Sweden, respectively.

Prior studies of electricity consumption in other OECD countries have produced some conflicting results. Most countries have shown an inelastic income elasticity of demand for electricity except for Greece and South Korea (Hondroyiannis, 2004, Saunoris and Sheridan, 2013). Meanwhile, countries such as Switzerland, the United States, and South Korea show an elastic price elasticity of demand for electricity (Dergiades and Tsoulfidis, 2008, Filippini, 2011, Lim, et al., 2014, Saunoris and Sheridan, 2013).

Previous studies of rebound effects in New Zealand's residential sector have produced inconclusive results. Lloyd, et al. (2008) indicated that the rebound effect phenomenon is not significant in New Zealand houses after evaluating the government-sponsored thermal insulation projects in 100 houses. In the winter season, the project only increased the temperature for 0.6 degrees Celsius on average since the house-owners still used less energy for space heating. In contrast, Howden-Chapman, et al. (2009) observed the effects of energy saving among 1,110 households and concluded that most households convert the energy efficiency gain into higher room temperature, which means a partial rebound effect.

The existing studies of New Zealand do not find evidence of long-run relationships between electricity consumption, income, and energy prices (Fatai, et al., 2004, Narayan and Prasad, 2008). Fatai, et al. (2003) advanced the electricity demand analysis by comparing different cointegration approaches and disaggregating electricity consumption into sectoral consumers. The results showed a cointegrating relationship between total electricity consumption, real GDP, electricity price and consumer price index (CPI), as a measure for price of a substitute for energy, between 1960 and 1999. The estimated income and price elasticities were 0.81 and –0.59 respectively. However, Fatai, et al. (2003) did not find any cointegrating relationships for electricity consumption in the residential, industrial, and commercial sectors between 1960 and 1999. The findings of Fatai, et al. (2003) supported the hypothesis by Howden-Chapman, et al. (2009) that high electricity price is the cause of the under-heating problem in New Zealand.

3. EMPIRICAL FRAMEWORK, ESTIMATION METHODOLOGY AND DATA

The underlying concept of the rebound effect based on the literature is that demand for energy or fuel changes when the cost of energy declines due to a reduction in energy prices or higher efficiency (Turner, 2013; Chitnis et al. 2020; Schmitz and Madlener, 2020). Improvement in energy efficiency causes a decline in effective price of energy and leads to an increase in energy consumption. The rising energy consumption may offset the resulting energy savings (i.e., partial or full rebound effect case) or even cause higher energy consumptions (i.e., backfire case). There is also the possibility for a zero rebound effect when actual energy saving is as expected or super conservation when actual energy saving is beyond expectation (Jamasb and Llorca, 2021).

Table 1: Previous studies of rebound effects

Sector	Country	Analysis period	Commodity	Rebound Effect (%)	Sources
Residential	China–Beijing	1989–2012	Electricity	40.2	Wang, et al. (2016)
Residential	China–urban area	1994–2011	Electricity	65.5–88.5	Lin and Liu (2015)
Residential	China–rural area	1994–2011	Electricity	127.0–236.3	Lin and Liu (2015)
Residential	China–30 urban area	1996–2010	Electricity	74.1	Wang, et al. (2014)
Residential	China–29 provinces	2000–2013	Electricity	71.5	Zhang and Peng (2017)
Residential	Austria	1970–1995	Energy	20.0	Haas and Biermayr (2000)
Residential	United States–48 states	1995–2011	Energy	56–80	Orea, et al. (2015)
Industrial	China–Heavy industry sector	1980–2011	Energy	74.3	Nurse, et al. (2014)
Industrial	China–Light industry	1980–2012	Energy	37.7	Lin and Tian (2016)
Industrial	China–Electricity sector	1985–2010	Energy	11.6	Yang and Li (2017)
Industrial	China–36 industrial sectors	1995–2012	Energy	38.9	Zhang, et al. (2017)
Industrial	China–Manufacturing sector	1995–2012	Energy	27.9	Zhang, et al. (2017)
Industrial	Swedish–4 heavy industry sectors	2001–2012	Fuel and electricity	132–162	Dahlqvist, et al. (2017)
Industrial	US–Manufacturing sector	1949–1999	Energy	24.0	Bentzen (2004)
National	China	1954–2010	Energy	39.73	Shao, et al. (2014)

3.1. Empirical Framework

Price elasticity of energy demand captures the direct rebound effects in the absence of data on energy efficiency or on the energy services (such as heating or lighting) provided by the energy that is used to produce them (Dahlqvist, et al., 2017, Hunt and Ryan, 2015). However, there are asymmetric energy demand responses when energy prices rise and fall as captured by the varying price elasticities of demand. If energy prices increase, consumers try to improve energy efficiency in order to save. If energy prices fall, consumers cannot directly remove the cost savings derived from energy efficiency improvements (Gately and Huntington, 2002). Therefore, it is more accurate to estimate the direct rebound effect with the price elasticity of energy demand in periods of falling energy prices. Increases in energy efficiency translate into decreasing energy prices, implying that the energy efficiency relevant price elasticities for estimating rebound effects would be those obtained when energy prices fall (Sorrell and Dimitropoulos, 2008).

However, actual energy prices are volatile and changing. Therefore, energy prices (PE_t) can be decomposed into three components to overcome the price volatility problem, including: the maximum price component ($PE_{max,t}$) which represents the maximum historical values of energy prices; the non-positive and non-increasing price component ($PE_{cut,t}$) which captures the cumulative decreases or cuts in energy prices and, the energy price recovery component ($PE_{rec,t}$) which represents the cumulative sub-maximum recoveries in energy prices (Bentzen, 2004, Gately, 1993, Haas and Biermayr, 2000, Lin and Tian, 2016, Nurse, et al., 2014, Wang, et al., 2016, Yang and Li, 2017).1 The price decomposition is undertaken as follows:

$$PE_t = PE_{max,t} * PE_{cut,t} * PE_{rec,t} \quad (1)$$

Equation 2 is a logarithmic transformation of equation 1 by taking logarithm on both sides:

$$LPE_t = LPE_{max,t} + LPE_{cut,t} + LPE_{rec,t} \quad (2)$$

1. Our analysis allows for competitive pricing where the effects of exogenous changes such as those imposed through legislation or minimum efficiency performance standards are taken into account as discussed in Hunt and Ryan (2015).

where:

$$LPE_{max,t} \equiv \max(LPE_0, \ldots, LPE_t)$$

$$LPE_{cut,t} \equiv \sum_{i=0}^{t} \min\left(0, \left(LPE_{max,i-1} - LPE_{i-1}\right) - \left(LPE_{max,i} - LPE_i\right)\right)$$

$$LPE_{rec,t} \equiv \sum_{i=0}^{t} \max\left(0, \left(LPE_{max,i-1} - LPE_{i-1}\right) - \left(LPE_{max,i} - LPE_i\right)\right)$$

The magnitude of the direct rebound effect is represented by the estimated coefficient of $LPE_{cut,t}$. The rebound effect can be classified into different types (as stated below) based on Saunders (1992, 2005, 2008) hence, if the estimated coefficient of:

- $LPE_{cut,t} < -1$, the rebound effect is called backfire effect.
- $LPE_{cut,t} = -1$, the rebound effect is called full rebound effects.
- $0 > LPE_{cut,t} > -1$, this is partial rebound effect.
- $LPE_{cut,t} = 0$ is a case of zero rebound effect.
- $LPE_{cut,t} > 0$ is a called super conservation effect.

The estimation of direct rebound effects in electricity demands of residential, industrial and commercial sectors in New Zealand including the econometric methodology applied and data is described in the following sub-section.

3.2. Estimation Methodology

Our specification of electricity demand follows the Cobb-Douglas demand function with the following representation:

$$EC_t = AY_t^{\alpha_1} PE_t^{\alpha_2} PG_t^{\alpha_3} T_t^{\alpha_4} e_t^{\varepsilon_t} \quad (3)$$

where EC_t is electricity consumption defined as kilowatt-hour per capita(kWh/capita), A is the drift term, Y_t is the real GDP in New Zealand Dollar (NZD)/capita, PE_t is the real electricity price in cents NZD/kWh, PG_t is the real price of gas in cents NZD/kWh, T is the average temperature in degrees Celsius, e is the Euler's constant, and ε is the error term. The natural gas price is used as a proxy for the substitute energy price since natural gas consumption is closely related to electricity consumptions in all sectors as shown in Figure 2.

Equation 4 is obtained by taking the natural logarithms on both sides of Equation 3 where 'L' indicates that all series are in their natural logarithm form:

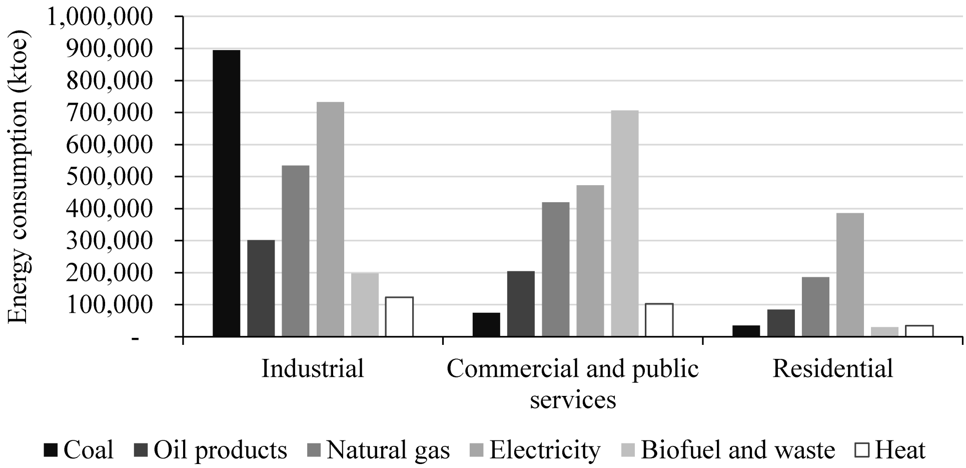
$$LEC_t = \alpha_0 + \alpha_1 LY_t + \alpha_2 LPE_t + \alpha_3 LPG_t + \alpha_4 LT_t + e_t \quad (4)$$

Equation 5 accounts for electricity price decomposition and is expressed as below:

$$LEC_t = \gamma_0 + \gamma_1 LY_t + \gamma_2 LPE_{max,t} + \gamma_3 LPE_{cut,t} + \gamma_4 LPE_{rec,t} + \gamma_5 LPG_t + \gamma_6 LT_t + e_t \quad (5)$$

The first step of the estimation is to check the possibility of a multicollinearity problem in the series by using the correlation test. Second, the order of the integration of the series is assessed by using the Augmented Dickey-Fuller (ADF) unit root test (Dickey and Fuller, 1981) to examine the maximum order of integration of the series. Third, we estimate Equation 5 using an autoregressive distributed lag (ARDL) model, which is superior to other approaches (Fatai, et al., 2003) and ignores the uncertainty of order of integration identified from the ADF test (Pesaran and Shin, 1998,

Figure 2: Energy consumption in 2015



Source: IEA (2018)

Pesaran, et al., 2001). The ARDL model includes a bound test for cointegration in order to confirm the presence or absence of long-run equilibrium relationships by testing the coefficients of the unrestricted error correction model (ECM) as specified in Equation 6. The bounds testing approach has more precision and reliability than other cointegration tests (Pesaran, et al., 2001).

$$\begin{aligned}\Delta LEC_t &= a_0 + \sum_{i=1}^{n} a_{1i}\Delta LEC_{t-i} + \sum_{i=1}^{n} a_{2i}\Delta LY_{t-i} + \sum_{i=1}^{n} a_{3i}\Delta LPE_{max,t-i} + \sum_{i=1}^{n} a_{4i}\Delta LPE_{cut,t-i}\\ &+\sum_{i=1}^{n} a_{5i}\Delta LPE_{rec,t-i} + \sum_{i=1}^{n} a_{6i}\Delta LPG_{t-i} + \sum_{i=1}^{n} a_{7i}\Delta LT_{t-i} + a_8 LEC_{t-1} + a_9 LY_{t-1}\\ &+a_{10} LPE_{max,t-1} + a_{11} LPE_{cut,t-1} + a_{12} LPE_{rec,t-1} + a_{13} LPG_{t-1} + a_{14} LT_{t-1} + \varepsilon_{1t}\end{aligned} \tag{6}$$

We estimate the following ARDL $(p_1, q_1, q_2, q_3, q_4, q_5, q_6)$ specification once the long-run equilibrium relationship is confirmed through the existence of cointegration relationships:

$$\begin{aligned}LEC_t &= b_0 + \sum_{i=1}^{p_1} b_{1i} LEC_{t-i} + \sum_{i=0}^{q1} b_{2i} LY_{t-i} + \sum_{i=0}^{q2} b_{3i} LPE_{max,t-i} + \sum_{i=0}^{q3} b_{4i} LPE_{cut,t-i} + \sum_{i=0}^{q4} b_{5i} LPE_{rec,t-i}\\ &+\sum_{i=0}^{q5} b_{6i} LPG_{t-i} + \sum_{i=0}^{q6} b_{7i} LT_{t-i} + u_t\end{aligned} \tag{7}$$

The long-run coefficients in Equation 5 are obtained as specified in equations 8 and 9, where $j = 1,\ldots,6$ and $m = 2,\ldots,7$:

$$\gamma_0 = \frac{b_0}{1-\sum_{i=1}^{p_i} b_{1,i}} \tag{8}$$

$$\gamma_j = \frac{b_m}{1-\sum_{i=1}^{p_i} b_{1,i}} \tag{9}$$

The last step of the estimation strategy involves estimating a short-run relationship model to measure the adjustment speed (ECT) for a deviation in the short-run:

$$\Delta LEC_t = c_0 + \sum_{i=1}^{n} c_{1i}\Delta LEC_{t-i} + \sum_{i=0}^{n} c_{2i}\Delta LY_{t-i} + \sum_{i=0}^{n} c_{3i}\Delta LPE_{max,t-i} + \sum_{i=0}^{n} c_{4i}\Delta LPE_{cut,t-i} + \sum_{i=0}^{n} c_{5i}\Delta LPE_{rec,t-i} + \sum_{i=0}^{n} c_{6i}\Delta LPG_{t-i} + \sum_{i=0}^{n} c_{7i}\Delta LT_{t-i} + c_8 ECT_{t-1} + e_t \quad (10)$$

The robustness of the estimated models is checked by undertaking standard residual diagnostic tests, which are serial LM correlation test, normality test, Autoregressive conditional heteroskedasticity (ARCH) test, misspecification test, Ramsey Regression Equation Specification Error Test (RESET) and stability tests (i.e. CUSUM and CUSUMQ). We interpret the actual energy saving based on the size of the rebound effect as in Wang, et al. (2014) by using the following formula:

$$Actual\ energy\ saving = (1+\gamma_3) * Energy\ saving\ target \quad (11)$$

3.3. Data

We use historical data for the period from 1980 to 2015. Data for electricity consumption (GWh), real electricity and gas prices (constant cent NZD/ kWh) is obtained from the Ministry of Business, Innovation and Employment (MBIE) (MBIE, 2018). Data for real income (in constant NZD) and population is obtained from the World Development Indicator (WDI) (WB, 2017). Income for the residential sector is proxied by real final expenditure while income for other sectors is represented by real value added. We use population data to convert electricity demand and income to per capita units to capture varying sectoral income elasticities of electricity demand in New Zealand. No prior study has used per capita data to model electricity demand in New Zealand considering that the per capita income measure is also correlated with other aspects of quality of life such as health, life expectancy and education (Jones and Vollrath, 2013). Temperature data is obtained from the Ministry for the Environment (MFE, 2017) and stated in Celsius degree. A detailed description of the data used in this study is provided in the Appendix.

4. RESULTS

We report the results from price decomposition, correlation tests, ADF unit root tests, bounds test for cointegration and error correction modelling in this section. Figures 3, 4, 5, and 6 show the results of electricity price decomposition. $LPE_{max,t}$ has a stable trend that may not be correlated to $LPE_{cut,t}$ and $LPE_{rec,t}$ price series.

Correlation test results in Table 2 support the fact that $LPE_{max,t}$ in industrial and commercial sectors are constant, producing no correlation with other series. Therefore, we omit $LPE_{max,t}$ in all estimations. Table 2 also shows that residential electricity demand is positively correlated to the electricity price and negatively correlated to the natural gas price. Commercial electricity consumption also shows that the electricity price is negatively correlated to the natural gas price.

Table 3 shows mixed unit test results for series LEC, LPE and LPG at different assumptions used in the test. However, all assumptions of the unit root test conclude that all series are stationary at their first difference. Table 3 also shows that no series are integrated of order 2 and hence, allowing us to proceed with the ARDL estimation. The first step of the estimation is the bound test for cointegration with the results reported in Table 4. Models estimated without a rebound effect are models 1, 2 and 3 while models 4, 5 and 6 are estimated in the presence of a rebound effect. We find

Figure 3: Natural log of decomposition of residential electricity price

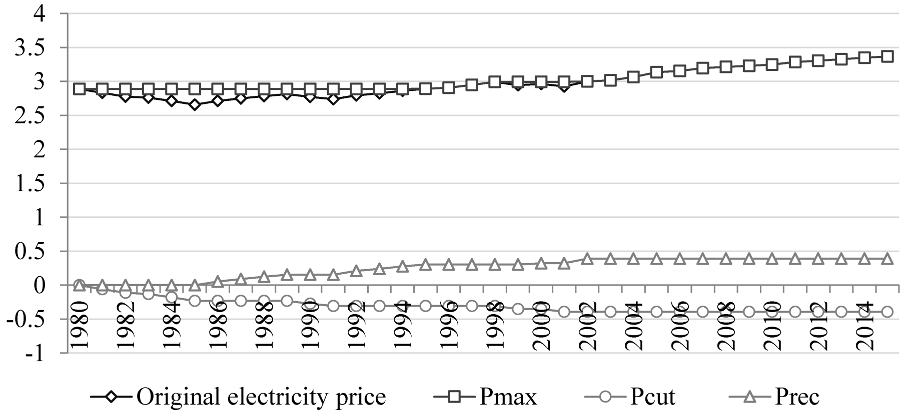


Figure 4: Natural log of decomposition of industrial electricity price

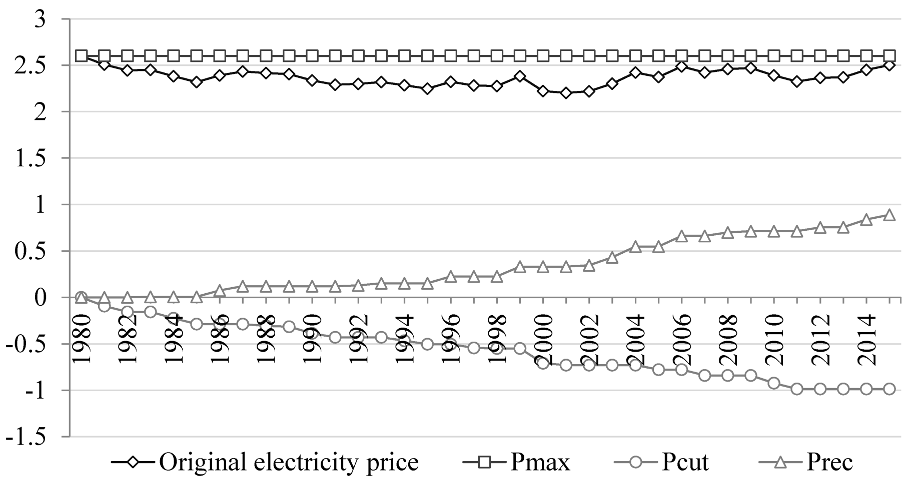


Figure 5: Natural log of decomposition of commercial electricity price

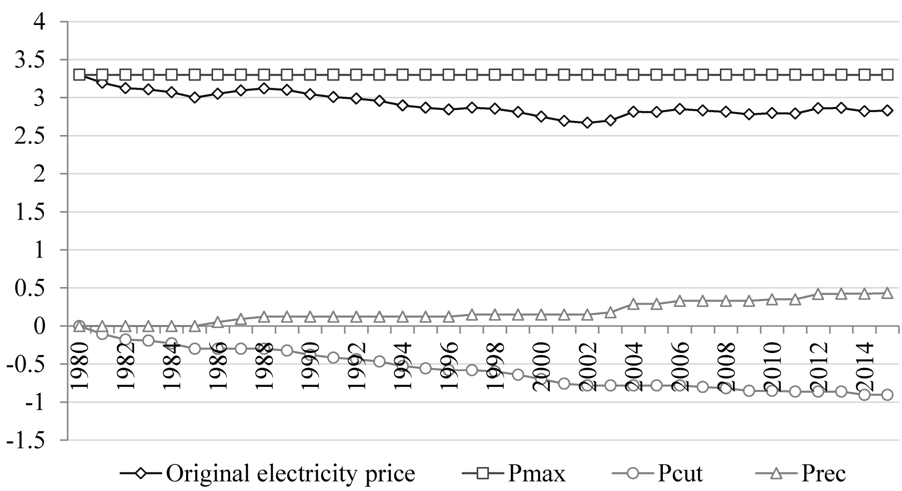
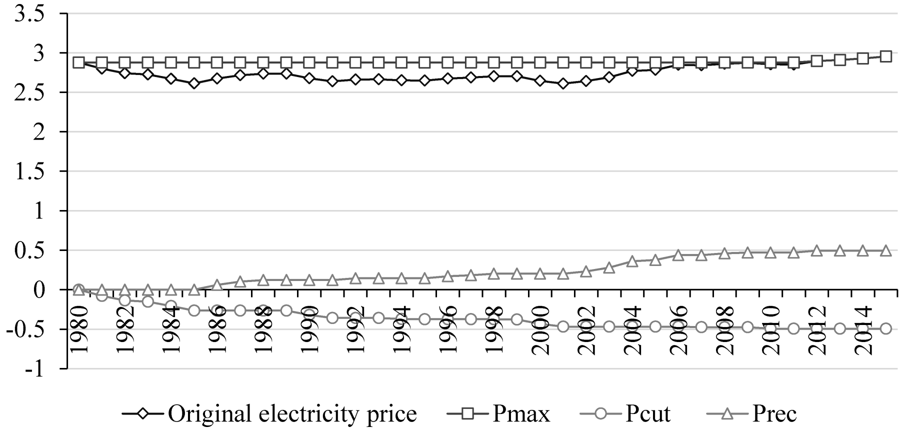


Figure 6: Natural log of decomposition of average national electricity price



cointegrating relationships in the electricity demand model (F_{LEC}) across all models. These findings differ from those of Fatai, et al. (2003), who did not find any cointegrating relationship in sectoral electricity demand.

4.1. Long-Run Estimations

As the second step, we estimate the long-run relationship of the cointegrating models and report the results in Table 5. The estimations without a rebound effect in model 1, 2, and 3 show that income, electricity and gas prices significantly influence electricity consumptions in the commercial sector while the electricity price is the only significant factor influencing demand in the industrial sector. The estimation of residential demand does not show a significant influence of electricity prices, income and temperature on the demand. Grimes, et al. (2011) found that income does not have a strong significant effect on residential electricity consumptions. Our results lend support to the conclusions of earlier studies by Howden-Chapman, et al. (2009), Isaacs, et al. (2010), Lloyd, et al. (2008), and O'Sullivan, et al. (2016) that under-heating is still a common problem in New Zealand homes because income and electricity price do not matter for residential electricity demand as homes are still poorly insulated and may be devoid of energy efficient appliance like heat pumps.[2]

We estimate models 4, 5 and 6 to account for the rebound effect and report the results in Table 5. The estimated coefficients for income and price of natural gas in the residential sector become significant while the signs of the coefficients are similar to the correlation test results in Table 2. However, the price of natural gas is eliminated in the estimation for the commercial sector due to non-cointegrating relationships. Table 5 shows significant estimated coefficients of LPE_{cut} in industrial and commercial sectors, indicating the presence of a partial rebound effect of –0.54 and –0.23 respectively. An energy conservation measure targeting 10% energy reduction in the long term will only result in 4.6% and 7.7% actual energy saving in the industrial and commercial sector respectively. In contrast, the estimated coefficient of LPE_{cut} in the residential sector is insignificant, supporting the finding by Lloyd, et al. (2008). The absence of a significant rebound effect in the residential sector suggests that New Zealand homes are still far from being energy efficient, owing

2. As an alternative to using the average temperature data, we also re-estimated the models by using the average number of frost days and average number of warm days. The results obtained were similar and are available can upon request, which confirms the robustness of our results.

Table 2: Results of the Correlation test

Variables	LEC	LY	LPE	LPE_{max}	LPE_{cut}	LPE_{rec}	LPG	LT
				Residential sector				
LEC	1.00							
LY	0.27	1.00						
LPE	0.05	0.96	1.00					
LPE_{max}	0.03	0.95	0.97	1.00				
LPE_{cut}	–0.64	–0.83	–0.69	–0.68	1.00			
LPE_{rec}	0.49	0.88	0.83	0.74	–0.93	1.00		
LPG	–0.12	0.80	0.90	0.86	–0.44	0.62	1.00	
LT	0.07	0.35	0.27	0.29	–0.22	0.20	0.15	1.00
				Industrial sector				
LEC	1.00							
LY	0.14	1.00						
LPE	–0.57	0.35	1.00					
LPE_{max}	NA	NA	NA	NA				
LPE_{cut}	–0.41	–0.54	0.06	NA	1.00			
LPE_{rec}	0.39	0.56	0.01	NA	–0.99	1.00		
LT	0.15	0.20	–0.04	NA	–0.25	0.22		1.00
				Commercial sector				
LEC	1.00							
LY	0.95	1.00						
LPE	–0.80	–0.80	1.00					
LPE_{max}	NA	NA	NA	NA				
LPE_{cut}	–0.95	–0.96	0.91	NA	1.00			
LPE_{rec}	0.92	0.95	–0.63	NA	–0.89	1.00		
LPG	0.70	0.73	–0.42	NA	–0.63	0.74	1.00	
LT	0.32	0.33	–0.23	NA	–0.26	0.24	0.38	1.00
				Aggregate electricity consumption				
LEC	1.00							
LY	0.77	1.00						
LPE	0.11	0.62	1.00					
LPE_{max}	–0.95	–0.87	–0.25	1.00				
LPE_{cut}	0.11	0.48	0.58	–0.32	1.00			
LPE_{rec}	0.76	0.96	0.71	–0.86	0.48	1.00		
LPG	0.32	0.74	0.89	–0.44	0.36	0.80	1.00	
LT	0.25	0.35	0.17	–0.21	0.15	0.24	0.18	1.00

to possible factors such as poor insulation and lack of heat pumps installations requiring further policy attention and research. Our results also suggest a backfire effect at the aggregate level. An energy conservation measure targeting 10% energy reduction in the long term will increase aggregate energy consumption by 15.3%. An earlier study by Sorrell, et al. (2009) documented that the direct rebound effect for household energy services in the OECD should generally be less than 30%, although such evidence does not exist in the context of New Zealand.

Meanwhile, temperature does not significantly influence electricity demand in all models except for the commercial sector. A 1% temperature increase in the commercial sector reduces electricity consumption by 0.49%. Figure 7 reports that all estimated models pass the stability tests of the Cumulative Sum of Squares (CUSUMQ) since the statistic values fall within the two critical values.

Table 3: Unit Root Test Results

Variables	*I(0)*-1	*I(0)*-2	*I(0)*-3	*I(1)*-1	*I(1)*-2	*I(1)*-3
			Residential sector			
LEC	–2.99**	–2.05	0.52	–5.30*	–6.31*	–5.37*
LPE	1.12	–4.09**	2.22	–4.76*	–5.13*	–2.81*
LPG	–0.8	–3.35***	0.2	–4.43*	–4.50*	–4.48*
LY	0	–5.55*	2.27	–3.92*	–3.92*	–3.02*
LT	–4.21*	–4.31*	0.12	–7.95*	–7.82*	–8.07
LPE_{cut}	–5.56*	–3.79**	1.6	–4.31*	–4.98*	–3.93*
LPE_{rec}	–1.77	–0.18	1.83	–4.35*	–4.79*	–3.55*
			Industrial sector			
LEC	–3.31**	–1.75	1.11	–4.74*	–6.04*	–4.67*
LPE	–2.94***	–2.72	–0.35	–6.24*	–6.54*	–6.35*
LY	–1.79	–2.12	0.69	–5.21*	–5.11*	–5.28*
LPE_{cut}	–1.65	–4.21**	2.87	–6.11*	–6.12*	–4.42*
LPE_{rec}	1.19	–1.82	3.74	–5.19*	–6.31*	–2.12**
			Commercial sector			
LEC	–3.51**	–3.13	3.59	–3.48**	–3.82**	–3.04*
LPE	–2.91***	–1.89	–1.93***	–4.28*	–4.34*	–4.24*
LPG	–2.05	–3.63**	–0.16	–6.34*	–6.23*	–6.43*
LY	–0.54	–2.13	2.86	–4.78*	–4.71*	–3.47*
LPE_{cut}	–3.38**	–2.33	1.65	–4.58*	–4.76*	–3.51*
LPE_{rec}	0.2	–1.88	2.39	–5.24*	–5.22*	–4.36*
			Aggregate electricity consumption			
LEC	–4.81*	–1.73	2.39	–3.93*	–4.76*	–3.65*
LPE	–0.56	–2.79	0.31	–4.02*	–4.28*	–4.02*
LPG	–0.85	–3.13	0.49	–3.84*	–3.80**	–3.83*
LY	–0.12	–2.39	2.07	–4.03*	–3.99**	–3.30*
LPE_{cut}	–3.23*	–2.65	1.23	–4.38*	–5.15*	–3.84*
LPE_{rec}	–0.00	–2.67	0.63	–2.71***	–2.60	–1.96**

Note: *I*(0)-i and *I*(1)-i specify that unit root tests are conducted in level and first differences respectively. *i* is the assumption used in the test (i.e. 1 for a constant, 2 for a constant with a trend, and 3 for no constant). The rejection of the null hypothesis of unit root at 1, 5, and 10% is indicated by asterisks (*), (**) and (***) consecutively.

Table 4: Results of Bound Test for Cointegration

	Critical value bounds		
ARDL models	1%	5%	10%
Without rebound effect			
1–Residential sector: $F_{LEC}(LEC\|LY,LPE,LPG,LT)$ = 3.81**. ARDL (3,4,2,3,0)	3.07–4.44	2.26–3.48	1.90–3.01
2–Industrial sector: $F_{LEC}(LEC\|LY,LPE,LT)$ = 4.25**. ARDL (1,3,4,0)	3.65–4.66	2.79–3.67	2.37–3.20
3–Commercial sector: $F_{LEC}(LEC\|LY,LPE,LPG,LT)$ = 6.10*. ARDL (4,4,4,1,4)	3.29–4.37	2.56–3.49	2.20–3.09
4–Aggregate: $F_{LEC}(LEC\|LY,LPE,LPG,LT)$ = 5.80**. ARDL (1,0,0,0,0)	4.59–6.37	3.28–4.63	2.70–3.90
With rebound effect:			
5–Residential sector: $F_{LEC}(LEC\|LY,LPE_{cut},LPE_{rec},LPG,LT)$ = 3.01***. ARDL (1,0,0,0,0,0)	2.82–4.21	2.14–3.34	1.81–2.93
6–Industrial sector: $F_{LEC}(LEC\|LY,LPE_{cut},LPE_{rec},LT)$ = 5.97*. ARDL (3,0,0,0,0)	3.74–5.06	2.86–4.01	2.45–3.52
7–Commercial sector: $F_{LEC}(LEC\|LY,LPE_{cut},LPE_{rec},LT)$ = 8.17**. ARDL (3,0,3,1,0)	3.29–4.37	2.56–3.49	2.20–3.09
8–Aggregate: $F_{LEC}(LEC\|LY,LPE_{cut},LPE_{rec},LT)$ = 9.75**. ARDL (3,0,1,1,0)	4.28–5.84	3.06–4.22	3.29–4.37

Note: The assumption used in the test is a restricted constant. The asterisks (*), (**) and (***) show the cointegration significant at 1%, 5%, and 10% respectively.

Table 5: Long-run relationships

	Estimation models							
	Without rebound effect				With rebound effect			
Variables	1	2	3	4	5	6	7	8
LY	2.40	0.32	0.41*	0.47**	0.91**	1.05**	0.53**	–1.42**
	(0.59)	(1.64)	(5.99)	(2.26)	(2.26)	(2.69)	(2.31)	(–2.57)
LPE	–3.40	–0.99*	–0.18**	–0.31				
	(–0.45)	(–5.87)	(–2.52)	(–0.83)				
LPE_{cut}					2.97	–0.54**	–0.23***	–2.57*
					(1.31)	(–2.39)	(–1.78)	(–3.49)
LPE_{rec}					0.89	–0.97*	–0.31	0.86**
					(0.74)	(–3.79)	(–1.52)	(2.11)
LPG	0.04		0.16*	–0.13	–0.44***			
	(0.06)		(3.34)	(–0.81)	(–1.92)			
LT	–2.48	–0.05	–0.09	0.24	0.23	0.38	–0.49**	0.11
	(–0.31)	(–0.19)	(–0.51)	(0.46)	(0.88)	(0.77)	(–2.19)	(0.29)
Constant		7.76*	3.80*			–2.33	3.31	22.64*
		(5.81)	(4.18)			(–0.65)	(1.62)	(4.00)
A (2)	0.13 [0.75]	0.22 [0.67]	1.22 [0.19]	0.98 (0.31)	1.15 [0.25]	1.20 [0.21]	0.59 [0.38]	1.54 [0.12]
B	1.54 [0.46]	0.21 [0.90]	0.22 [0.90]	0.43 (0.81)	3.12 [0.21]	0.77 [0.68]	1.75 [0.42]	0.66 [0.72]
C (1)	0.19 [0.65]	0.29 [0.58]	2.00 [0.16]	2.48 (0.12)	0.88 [0.34]	2.38 [0.12]	0.19 [0.65]	2.94 [0.09]
D (1)	1.55 [0.14]	0.19 [0.85]	0.25 [0.81]	0.17 (0.68)	0.77 [0.45]	0.02 [0.98]	0.39 [0.70]	0.12 [0.90]

Note: (t-statistic); *significant at 1%, **significant at 5%, and ***significant at 10%; Assumption of no fixed regressor trend specification is selected. A: Breusch-Godfrey Serial Correlation LM Stat (lags) [its probability]; B: Jarque-Bera Stat [its probability]; C: ARCH LM tests (lags) [its probability]; D: Ramsey RESET F-stat (lags) [its probability].

4.2. Short-Run Estimations

Table 6 shows the results of the estimations of short-run relationship. Income, electricity and gas prices significantly influence electricity consumptions in the estimations without a rebound effect for all sectors except the effect of income in the residential sector. The rebound effects in the short term are significant in the industrial and commercial sectors but the directions of the effects are opposite. The industrial sector has a partial rebound effect of –0.38 while the commercial sector has super conservation effect of 0.36, which implies that an electricity conservation measure aiming at 10% in electricity savings could potentially produce additional 3.6% saving in the short term. The error correction term is significant, negative and lower than unity in all models.

4.3. Policy Implications

Our results give rise to a number of policy implications that are not only relevant to the New Zealand economy but also to other economies, undertaking or aiming the initiation of energy savings programs through energy efficiency improvements. First, energy efficiency improvement polices should be targeted at the sectoral level rather than at the aggregate level in order to produce the desired energy savings results. Each sector exhibits specific consumption characteristics that need to be accounted for and therefore, a blanket energy efficiency improvement policy for reducing the aggregate energy consumption may be misleading and ineffective. For instance, our results suggest that the New Zealand government should look more into policies aimed at improving home insulation and increasing heat pump installations.

Figure 7: Results of stability tests

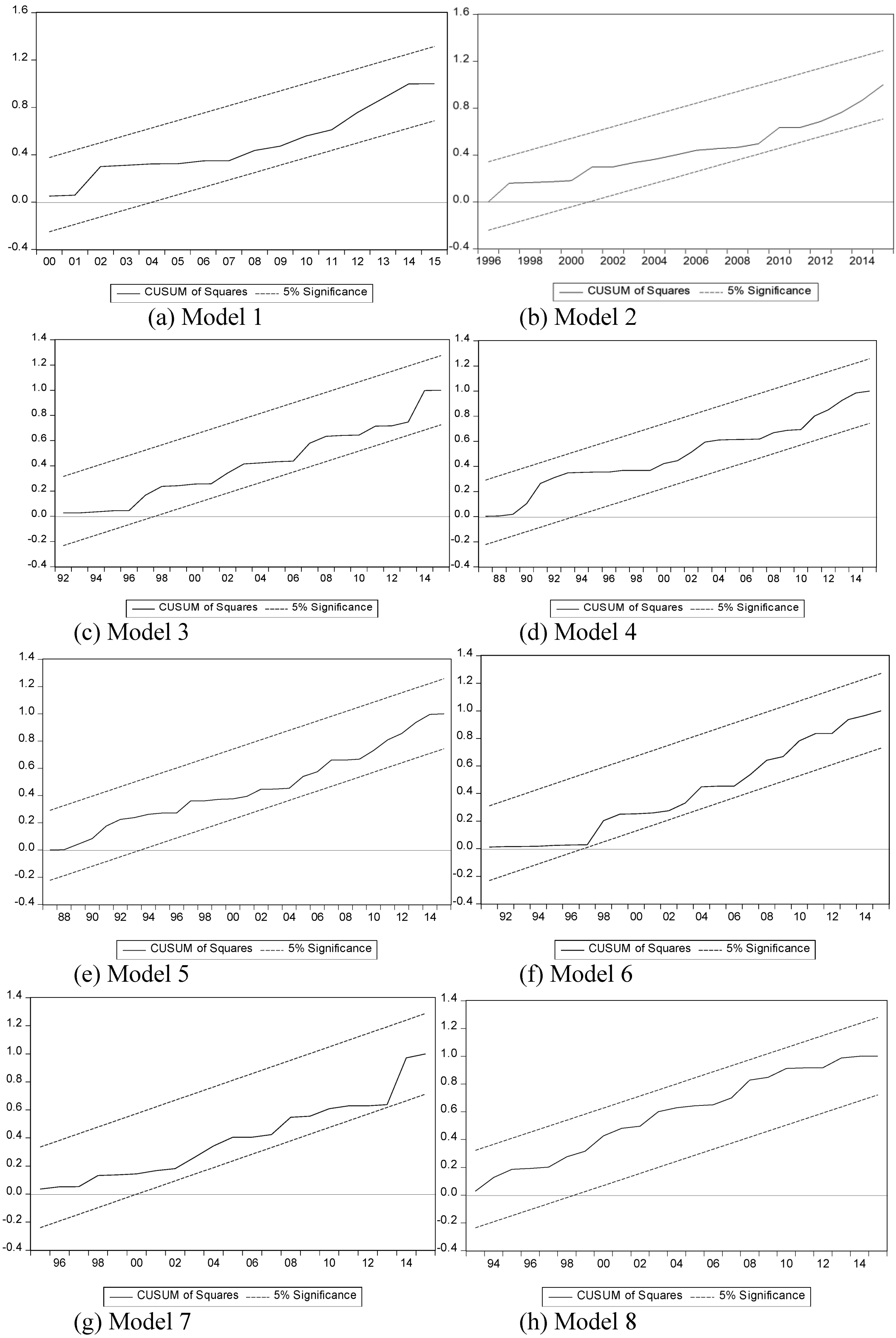


Table 6: Error correction models

	Short-run results χ^2 statistics						Long-run results
Dependent Variables (ΔLEC_t)	ΔLY_t	ΔLPE_t	$\Delta LPE_{cut,t}$	$\Delta LPE_{rec,t}$	ΔLPG_t	ΔLT_t	ECT
Without rebound effect							
Residential sector–1:	0.13	–0.21**			–0.04***	–0.07	–0.04*
	(0.89)	(–2.44)			(–1.89)	(–1.11)	(–4.89)
Industrial sector–2:	0.18	–0.30*				0.02	–0.63*
	(1.21)	(–3.73)				(0.18)	(–4.74)
Commercial sector–3:	0.23**	0.22*			0.05*	–0.03	–0.46*
	(2.51)	(3.99)			(2.86)	(–0.38)	(–9.77)
Aggregate sectoral electricity							–0.18*
consumption–4:							(–5.75)
With rebound effect							
Residential sector–5:	0.27**		0.21	–0.19	–0.02	–0.15**	–0.09*
	(2.13)		(1.24)	(–1.40)	(0.30)	(–2.05)	(–3.68)
Industrial sector–6:	0.39*		–0.38*	–0.15		–0.63	–0.27*
	(3.51)		(–2.92)	(–1.12)		(0.81)	(–6.76)
Commercial sector–7:	0.30*		0.36*	0.12		–0.18*	–0.38*
	(3.36)		(4.22)	(1.31)		(–2.86)	(–7.55)
Aggregate sectoral electricity			–0.05	0.06			0.22*
consumption–8:			(–0.38)	(0.65)			(8.44)

Second, the rebound effect certainly is a complicating factor in measuring the reduction of energy consumption from energy efficiency improvements, questioning the effects of energy saving programs. For example, our results implicate a backfire effect at the aggregate sectoral consumption as an undesirable outcome of the New Zealand energy strategy. These results suggest other intervening policies alongside energy efficiency improvements to mitigate the possibilities of rebound effects at the specific sectors in the economy. Third, the inefficiency of energy saving programs for the reduction of energy use via energy efficiency improvements due to the presence of the rebound effect necessitates that the government should allocate resources in estimating the magnitude and nature of the rebound as accurately as possible at every possible economic sector. Energy efficiency improvements can contribute to decarbonization by reducing CO2 emissions through reduced fossil-based energy use as in the case of New Zealand.

5. CONCLUSIONS

Our study is one of the few studies in the literature about the investigation of the possibility of rebound effects in sectoral electricity consumption. The specific case of New Zealand is considered for this purpose. New Zealand is an interesting case study for analyzing sectoral electricity demand since the push towards economic decarbonization is ongoing and a 100% renewable energy target is on the horizon. The signing of the COP21 global agreement on greenhouse gases has provided impetus to decarbonize the industrial and transportation sector creating new challenges and opportunities in the electricity sector. We applied the price decomposition approach incorporating both price and non-price variables in order to examine the rebound effects that may hamper this strategy.

We find the average values of the rebound effect to be 54% and 23% for the industrial and commercial sector respectively. A partial rebound effect implies that energy policymakers are aware that most of the expected reduction in electricity use from energy efficiency improvements alone may not be achieved in the industrial and commercial sectors. We also find that the rebound effect is insignificant for the residential sector in New Zealand. Based on these findings, energy conservation policies to reduce electricity demand in New Zealand homes may still be effective. We suggest that the New Zealand government needs to consider rebound effects in sectoral electricity demand while formalizing its energy policies.

The findings of our estimations have implications towards energy conservation. The results also highlight the danger of ignoring the implications of rebound effects in sectoral electricity demand under the New Zealand Energy Efficiency and Conservation Strategy 2017–2022.

Cointegrating relationship is found in the residential electricity consumption; however, the energy prices and income do not significantly influence the electricity demand. On the other hand, electricity price significantly influences electricity demand in the industrial sector. Similarly, electricity price as well as income have significant negative and positive influences respectively to the electricity demand in the commercial sector. A 1% growth in income increases the demand in the commercial sector by 0.41%.

Temperature, income and prices of electricity and natural gas do not significantly affect electricity consumptions in the residential sector. The rebound effect may emerge from such energy conservation policy especially, in industrial and commercial sectors but is unlikely to turn into a backfire effect. We also suggest that future research needs to consider using wood fuel prices as a substitute energy price while also implementing alternative estimation techniques such as using simultaneous equations models and a model of energy services demand to measure direct rebound effects.

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APPENDIX

- Energy demand is the annual energy consumption measured by using the historically consistent methodology or the old methodology (weightings were calculated using grid export demand data from the Electricity Authority and applied to March year consumption data collected by the Ministry to calculate both quarterly and calendar year figures). It does not include data for solar PV demand and small retailers. It is originally stated in GWh for 6 major sectors and reported for period 1974 to 2016.
- Electricity price is sales-base data of average residential, commercial and industrial costs (essentially total electricity sales divided by the quantity of electricity supplied). Prices are presented in units typical for each fuel (such as cents/liter for petrol and diesel or cents/kWh for electricity) and are displayed on a calendar year basis in both real (adjusted for inflation) and nominal terms for all available years. It is originally stated in cent/kWh for 3 major sectors and reported for period 1980 to 2017.
- Gas prices were under price control until 1993. Before electricity sector reforms, which began in the late 1980s, electricity prices were influenced by the need for government approval of wholesale prices. It is originally stated in cent/kWh for 4 major sectors and reported for period 1979

to 2016 for residential and commercial sectors; and 1999 to 2016 for industrial and wholesale sectors.
- Prices are presented inclusive of all applicable taxes and levies. Industrial and commercial prices exclude Goods and Services Tax (GST) as these sectors can generally reclaim the GST component. Real price has been constructed using Statistics New Zealand's Consumers Price Index series - CPIQ: SE9A (for retail and residential prices), and Producers Price Index (Input) series - PPIQ: SN9 (for commercial, industrial and wholesale prices).
- Value added in the service sector correspond to International Standard Industrial Classification (ISIC) divisions 50–99. They include value added in wholesale and retail trade (including hotels and restaurants), transport, and government, financial, professional, and personal services such as education, health care, and real estate services. Also included are imputed bank service charges, import duties, and any statistical discrepancies noted by national compilers as well as discrepancies arising from rescaling. Value added is the net output of a sector after adding up all outputs and subtracting intermediate inputs. It is calculated without making deductions for depreciation of fabricated assets or depletion and degradation of natural resources. The industrial origin of value added is determined by the International Standard Industrial Classification (ISIC), revision 3. Data are in constant local currency.
- Value added in industry corresponds to ISIC divisions 10–45 and includes manufacturing (ISIC divisions 15–37). It comprises value added in mining, manufacturing (also reported as a separate subgroup), construction, electricity, water, and gas. Value added is the net output of a sector after adding up all outputs and subtracting intermediate inputs. It is calculated without making deductions for depreciation of fabricated assets or depletion and degradation of natural resources. The origin of value added is determined by the International Standard Industrial Classification (ISIC), revision 3. Data are in constant local currency.
- Household final consumption expenditure (formerly private consumption) is the market value of all goods and services, including durable products (such as cars, washing machines, and home computers), purchased by households. It excludes purchases of dwellings but includes imputed rent for owner-occupied dwellings. It also includes payments and fees to governments to obtain permits and licenses. Here, household consumption expenditure includes the expenditures of non-profit institutions serving households, even when reported separately by the country. Data are in constant local currency.
- Temperature is national average temperature that is available from 1909 to 2016 and stated in Celsius degree. This dataset relates to NIWA's 'seven-station' temperature series uses temperature measurements from seven 'climate stations'.

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