Light-Duty Vehicle Carbon Emission Standards and the Rebound Effect

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Experiences from Australia

By

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PREFACE

Australia is planning to take action to tackle climate change via improvements in light vehicle fuel efficiency. The proposed light vehicle emissions standards are expected to reduce petroleum use as well as greenhouse gas emissions from passenger vehicles, sports utility vehicles and light commercial vehicles. Consumers of light vehicles, including private households and firms, will respond to this policy in ways that maximise their utility based on economic theory. One possible situation is that these economic agents will use less petrol, through directly purchasing more efficient new cars to react to the mandatory standard. Also, the more efficient vehicle will provide an incentive for consumers to use it more as the effective cost of driving decreases. Understanding these economic and behavioural responses to the policy is crucial for policymakers. This study makes three contributions to understanding the policy and the associated rebound effect, focusing on the Australian proposed light vehicle emissions standards.

First, this study contributes to theoretical analyses of the household and firm responses to a fuel efficiency improvement by investigating the utility maximisation problem and the cost minimisation problem of the economic agents in response to fuel efficiency changes. Using microeconomic theory, specifically the consumer and production theory, the theoretical study shows that the magnitude of the rebound effect is determined by different elasticities for the household and the firm, which also change as the policy standards become more stringent.

Second, this study makes an innovative contribution that enriches the modelling of vehicle fuel efficiency changes over time. This methodological advance integrates time series analysis with a detailed engineering fleet model to provide credible forecasts for fuel efficiency changes under business-as-usual and policy scenarios. The time series approach captures the compositional changes of vehicles, or the shifts in taste over vehicle types, and gives a stock change forecast to the model year 2025. The engineering fleet model takes into account the new vehicle sales, the vehicle stock turnover, distance travelled, and fuel consumption to make the best prediction of fleet level fuel efficiency. The results from this study are crucially important for the simulations in the next study.

Third, the study contributes to the empirical studies of the rebound effect by simulating the BAU and policy scenarios in a computable general equilibrium framework. The direct rebound effect of the Australian proposed light vehicle fuel efficiency standards is shown to range between 25 per cent (%) and 30%, measured by petroleum use. Each of these policy scenarios is shown to have a much larger economy-wide rebound effect, reaching up to 50% measured by life-cycle greenhouse gas emissions. Although the stringent fuel efficiency standard generates more direct rebound effects measured as percentages than the lenient and medium standards, the stringent policy produces the most reduction in carbon emissions measured in physical units overall.

This study concludes by making policy recommendations based on the studies carried out in the previous chapters. It integrates the results from each of the individual analyses to provide a comprehensive understanding of the Australian proposed light vehicle fuel efficiency standards. The theoretical analysis of the behaviour of the household and the firm, together with the CGE simulations that use results from a detailed engineering fleet model, capture the economy-wide economic and environmental impacts of the policy that are essential for policymakers to evaluate each policy option.

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ABBREVIATIONS

ADR	Australian Design Rule
CCA	Climate Change Authority
CGE	Computable general equilibrium
FCAI	Federal Chamber of Automobile Industries
GHG	Greenhouse Gas
GVM	Gross vehicle mass
VAR	Vector auto-regressive

CHAPTER 1

INTRODUCTION AND OUTLINE

1.1 The Policy Issue

On 23 April, 2016, after the success of the Paris climate conference (COP21) in December 2015, a total of 175 countries signed the Paris Agreement at the United Nations in New York to curb climate change (United Nations 2016). Historically, Australia ratified the agreement by setting ambitious targets to reduce emissions by 26 to 28%, from 2005 to 2030 (Australia Government 2015). This target means that by 2030, emissions will be reduced to between 261.1 to 268.3 megatonnes (Mt), compared to the current level of 549.3 Mt (Parkinson 2016). The CO_2 emission mitigations planned by Australia will be crucial to the global climate targets on limiting the rise in global warming to well below 2 degrees Celsius.

Australia's main source of carbon dioxide emissions is the consumption of fossil fuels (DoE 2014). Transport emissions represent a key climate change challenge in Australia, exceeding over 90 Mt of greenhouse gas emissions (Bureau of Infrastructure 2009). The emissions from the use of both passenger and light commercial vehicles contribute to around 10% of all Australian emissions (CCA 2014a). Therefore, the Australian Government has announced plans to reduce carbon emissions from the transport sector by establishing mandatory fuel efficiency standards for light vehicles (Frydenberg 2016; Quiggin 2016).

In fact, a recommendation for mandatory fuel efficiency standards had been proposed by the Climate Change Authority (CCA) two years earlier. On 26 June, 2014, the Climate Change Authority (CCA), an independent statutory agency of the Australian Government, released a research report proposing light vehicle carbon dioxide emissions standards to reduce greenhouse gas emissions from the private road transport sector by 59 Mt by 2030 (CCA 2014b). In essence, the light vehicle carbon dioxide emissions standards are equivalent to the fuel efficiency standards, measuring fuel efficiency by CO2 intensity (g CO2/km) and by fuel intensity (L/100 km), respectively.

From the first phase (beginning in 2018), as addressed in the report released by the CCA in 2014, all new light vehicles, including passenger cars, sports utility vehicles (SUVs), and light commercial vehicles (with a gross vehicle mass under 3.5 tonnes[1]), will be mandated to meet the fleet-average CO_2 emissions target specified in the proposition. If this policy is implemented as proposed, the progressive goal will require that the carbon dioxide emissions intensity of the new light vehicles at the fleet-average level be reduced to 105 g/km by 2025, narrowing the gap between Australia, the United States, and the European Union (CCA 2014a). In addition, the estimated extra cost of a new car complying with this policy in 2025 will be around $1,500 (2014 AUD), whereas the estimated extra savings from the decline in fuel use will be about $8,500 (2014 AUD) over the life of the motor vehicle (ClimateWorks Australia 2014). Therefore, motorists will benefit from the implementation of a policy of this kind as the lifelong benefit outweighs the lifelong cost of a new vehicle that meets the standards.

Unlike most developed economies, including the US, Canada, the EU, and Japan, and some developing countries such as China, India, and Brazil, Australia is unique in not enforcing mandatory standards on vehicle fuel economy or CO_2 emissions (FCAI 2016a). Even though the emission of carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NOx), and particulates (PM) has been under control since the early 1970s, and the target of standards on these pollutant emissions excluding carbon dioxide emissions has seen progress over the past 40 years (Department of Infrastructure and Regional Development 2017; Grenning 1983), the newly-proposed CO_2 emissions standards, if implemented, will be the first carbon dioxide emissions standards for road vehicles in Australia.

Therefore, it is claimed that the proposed Australian light vehicle emissions standards will play a significant role in carbon dioxide emissions reduction in the transport sector (CCA 2014a).

To date, however, there has been little agreement on whether the CO_2 emissions standards could achieve the target of reducing greenhouse gas emissions. A CO_2 emissions standard, or a fuel economy standard, as a policy instrument, sets the maximum level of sales-weighted average of CO_2 emissions intensity, or fuel consumption, for the new-vehicle fleet sold in the economy in a given year (CCA 2014a; Clerides & Zachariadis 2008). This policy instrument directly mandates the fuel use per kilometre

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[1] Segmentation Criteria. Federal Chamber of Automobile Industries, https://www.fcai.com.au/sales/segmentation-criteria

travelled, yet does not mandate the amount of petrol consumed. In addition, as the fuel use per kilometre travelled decreases, the fuel cost of driving will also decrease, which could lead to more fuel consumption. Hence, some economists argue that the implementation of standards is not the best policy for reducing fuel use. Mankiw (2006), for example, argues that “by making the car fleet more fuel-efficient, the regulations encourage people to drive more, offsetting some of the conservation benefits and exacerbating road congestion”.

In fact, this counterintuitive consequence is not limited to fuel efficiency improvement. Any source of energy efficiency improvement could lead to more use of the product, undermining the energy savings. This study sets out to investigate the effect of energy efficiency improvement on energy consumption and answers the question of whether energy efficiency improvement could achieve the goal of reducing energy consumption. Furthermore, this research examines how much energy will be conserved by the proposed Australian light vehicle emissions standards in a computable general equilibrium (CGE) model.

There are three hypotheses to be tested in the CGE chapter of the study. The first hypothesis is no rebound -- that fuel savings will be approximately equal to mechanical effects. The second hypothesis is rebound -- that much of the savings will be offset by rebound effects. And the third hypothesis is backfire – that fuel use and emissions will increase.

1.2 Statement of the Problem

While energy efficiency mandates have become one of the most popular policy instruments around the world in climate change, according to many economists, this policy may encourage consumption of energy goods and services, thus offsetting the desired energy conservation. This phenomenon has been termed the “rebound effect” by economists (Greene 1992; Sorrell, Dimitropoulos & Sommerville 2009). Consider for a moment the case of the fuel efficiency improvement of a passenger vehicle. Suppose also that this technological improvement is costless and exogenous. First, the fuel requirement per kilometre driven is reduced, and if the motorist travels the same distance as before, the direct reduction in fuel use is the product of the fuel efficiency progress and the total distance travelled. This direct effect of a fuel efficiency improvement is termed the “mechanical effect” in this study. Second, as fuel use per kilometre decreases, so does the fuel cost per kilometre. Following the law of demand, which states that as the price of a good or service (distance travelled by a private motor vehicle) decreases, demand for it will increase, if the good or service is normal, *ceteris paribus*, the distance travelled by the vehicle will increase. The difference between the fuel use for the new distance travelled in the new car and the fuel use for the old distance travelled in the new car is termed the “behavioural effect”. The rebound effect is the ratio of the behavioural effect to the mechanical effect, usually expressed as a percentage. When the rebound effect is large, the energy conservation becomes small. If the rebound effect is 100%, for instance, the expected energy savings are completely offset by the behavioural effect. If the rebound effect is larger than 100%, more energy is required to meet the growth in demand, a phenomenon termed “backfire” by rebound researchers (Turner 2013).

Since economic agents – consumers, producers, and government – make rational choices to maximise their utility as defined in conventional economics, they may consume more energy goods and services once the costs of these goods and services are lowered. Therefore, the rebound effect is not confined to consumers. To demonstrate, imagine how a steel manufacturer responds to an energy efficiency improvement. First, this improvement reduces the energy requirement per unit of steel produced. Second, if the production process allows for substitution between energy and labour, the manufacturer will substitute energy for labour, as energy is now relatively cheaper in the sense that the effective price of energy decreases. Third, after adjusting the input combinations in the steel manufacture to minimise the cost of production, the price of steel will drop once the market for steel is competitive. As a consequence, the demand for steel will increase, which returns to the previous example of the fuel efficiency improvement.

It is also noteworthy that the scope of the rebound effect could reach both the indirect and the economy-wide realms. For example: after purchasing a hybrid vehicle, the motorist does not drive more. Instead, $600 is saved annually from adopting the hybrid vehicle; these savings are spent on air travel. Although this behaviour does not cause any direct rebound effect, taking air flights indirectly causes energy consumption and greenhouse gas emissions, as providing this service requires energy as an intermediate input.

The importance of understanding the mechanism of the rebound effect on different scopes has implications for economic theory as well as for climate policy. As described previously, the rebound effect is the phenomenon where actual energy savings are often less than those predicted by engineering calculations. The engineering calculation of energy savings, or the mechanical effect, is obtained directly by multiplying the energy efficiency improvement by energy consumption prior to the technological change. These ex-ante savings are derived from the assumption that energy use remains the same after the energy efficiency improvement. Economic theory suggests that energy efficiency improvement leads to a reduction in the effective energy price, thus encouraging energy use after technological progress in energy efficiency (Jevons 1865; Khazzoom 1980; Owen 2010; Sorrell, Dimitropoulos & Sommerville 2009).

Taking into account the rebound effect, the proposed Australian light vehicle fuel efficiency standards may not be as effective as projected. To illustrate the rebound and mechanical effects in this case, suppose that the fuel intensity of an automobile reduces by 20%, from 10 L/100 km to 8 L/100 km, or the fuel efficiency improves by 25%.[2] Suppose also that a motorist drives 13,000 km per year before new fuel efficiency standards are applied. Total fuel use per year is the product of the fuel intensity and the total distance travelled per year. Using engineering calculations, the mechanical effect of fuel efficiency improvement will yield fuel savings of up to 260 litres. However, if the motorist drives 10% more, the fuel savings will reduce to 156 litres. When considering the behavioural adjustment of the motorist, the rebound effect is 40%; in other words, 40% of the expected savings is taken up by the behavioural effect. Following is a table listing the calculation of the rebound effect.

Figure 1-1 provides a graphical illustration of the rebound effect, limited to the direct use of fuel. Using the previous example of fuel efficiency improvement of cars, the direct rebound effect is 40%; the supposed fuel use reduction or the mechanical effect is 260 litres while the increase in fuel use in addition to the fuel reduction is 104 litres. For the rebound effect, the proportion of this increase in fuel use in the mechanical reduction in fuel use is 60%. The figure below illustrates the direct rebound effect in three steps. The first bar on the left represents the fuel use before energy efficiency improvement. The bar in the middle represents the fuel use after a fuel efficiency improvement, calculated by multiplying the percentage change in fuel intensity by the initial distance travelled. The difference between the two bars is the mechanical effect. The rebound effect is the

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[2] Fuel efficiency (km/L) is the inverse of fuel intensity (L/100km). For example, a fuel efficiency of 10 L/100 km is equivalent to a fuel intensity of 10 km/L and, similarly, a fuel efficiency of 8 L/100 km is equivalent to a fuel economy of 12.5 km/L. Therefore, the fuel efficiency improvement in this case is 25%. A detailed definition on energy efficiency can be found in Chapter 2.

difference between the final fuel use (considering behavioural adjustments such as an increase in distance travelled) and the fuel use (without taking into account such behavioural changes). How much the behavioural effect offsets the fuel efficiency change caused by the mechanical effect is the rebound effect, often measured by a percentage.

Table 1-1 Calculations on the mechanical, behavioural and rebound effects of a fuel efficiency improvement of a motor vehicle.

	Before Fuel Efficiency Improvement	After Fuel Efficiency Improvement without considering the Behavioural Effect	After Fuel Efficiency Improvement and considering the behavioural effect
Fuel Intensity	10 L/100km	8 L/100km	8 L/100km
Kilometres travelled	13,000 km	13,000 km	14,300 km
Total Fuel Use	1,300 L (1)	1,040 L (2)	1,144 L (3)
Mechanical Effect	260 L = (1)-(2)		
Behavioural Effect	104 = (3)-(2)		
Rebound Effect	40% = BE/ME		

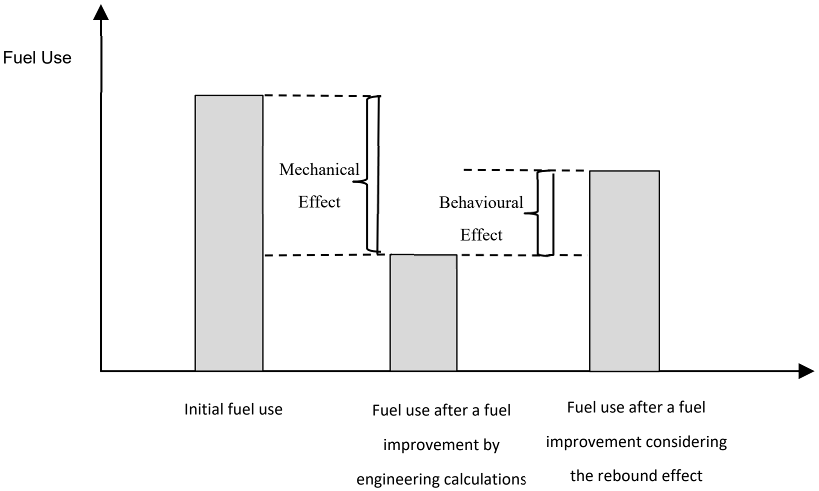

Figure 1-1 An illustration of the direct rebound effect of an energy efficiency improvement.

The rebound effect depicted above does not signify the end of the impact of an energy efficiency improvement. While the direct rebound effect is confined within the energy used in producing a certain good or service that is the recipient of the energy efficiency improvement, the rebound effect is not limited to directly capturing the increase in the energy used in this specific good or service solely. Economic theory suggests a price change in one good may lead to changes in the consumption of other goods. Producing nearly all goods requires energy input; therefore, the rebound effect could occur indirectly from the supply side as the consumption of all other goods increases. The same theory applies to the industrial sector, where energy serves as an intermediate input in the production of certain final goods. Similarly, almost all industries use various sources of energy as intermediate inputs. When the demand for other final goods changes, the demand for the intermediate input energy will also change. Consider household consumption as an example. The cost savings obtained from a more fuel-efficient vehicle could be spent on a recreational trip by airplane. Powering this air flight requires energy input, such as aviation turbine fuel. Therefore, there is an increase in the energy demand for other goods, which is indirectly induced by the fuel efficiency improvement in the automobile.

On the other hand, a fuel efficiency improvement at the industrial level may contribute to GDP growth, the same role played by any technological improvement. The growth in GDP may drive up private consumption, government expenditure, and exports. All these changes may indirectly lead to a potential rebound effect that may offset the expected energy savings from energy efficiency improvement.

1.3 Definitions and Classifications of the Rebound Effect

1.3.1 Definitions of the rebound effect

Full comprehension of the definition of the rebound effect is crucial for analysing the rebound effect. Researchers widely agree that rebound effects are the behavioural adjustments of economic agents that offset supposed energy savings (Sorrell, Dimitropoulos & Sommerville 2009). The rebound effect could equally be expressed based on a unit of greenhouse gas emissions, which could differ from the rebound measured by energy, for the emissions are not always generated by energy consumption but from other activities, such as rumination of cattle on a farm.

One of the classic examples of the rebound effect – how the consumer adjusts the demand for energy after a fuel efficiency improvement of the car – has been explained in the previous section. However, this example of fuel efficiency improvement only considers a direct rebound effect. The following section describes the classification of the rebound effect and the definition of each type of the rebound effect.

1.3.2 The classification of the rebound effect

Although a number of studies have empirically estimated the rebound effect, a limited number of researchers have contributed to its classification. While the first classification proposed by Greening, Greene and Difiglio (2000), consisting of four types of rebound effect, provides a detailed and thorough picture of the rebound effect, the simpler three-type classification by Sorrell, Dimitropoulos & Sommerville (2009) is now widely accepted. Both classifications of the rebound effect cover micro- and macro-economic adjustments of economic agents, but the latter focuses on the consumer.

Greening, Greene and Difiglio (2000) categorised the rebound effect into four types:

(1) direct effects;

(2) secondary fuel use effects;

(3) market equilibrium price and quantity adjustments (economy-wide rebound effects); and

(4) transformational effects.

Greening, Greene and Difiglio (2000) recognised the difference between consumers and producers in the direct and secondary effects. For the consumer, direct rebound effects occur when energy efficiency improvement in a household appliance effectively reduces the cost of using it. Direct rebound effects for the consumer are the same as a price effect, which can be decomposed into a substitution effect and an income effect. Similarly, for the firm, direct rebound effects of an energy efficiency improvement in producing a certain output are similar to a price change in the input of energy, which can be decomposed into a substitution effect and an output effect.

As for the secondary fuel use effects categorised by Greening, Greene and Difiglio (2000), these effects were discussed jointly by both consumers and producers. When energy efficiency improves, the demand for other energy goods may also change, which will cause secondary effects. Besides, as the demand for all other goods and services changes, this will lead to economic growth which, in turn, will increase the demand for energy. Furthermore, as the increase in real consumption contributes to economic growth, and the economic growth requires more energy consumption, the fuel efficiency improvement could cause additional secondary effects through the macro channel.

These two types of rebound effects mentioned above are based on the static analysis of economic theory. However, the third rebound effect, which is referred to as "price and quantity readjustments" or "economy-wide effects" in Greening, Greene and Difiglio (2000), involves general equilibrium thinking. An energy efficiency improvement can result in an effective and real change in fuel price; thus, the direct and secondary effects without considering the real price change are incomplete. This "market equilibrium" rebound effect captures the gap between the partial equilibrium and the general equilibrium; in other words, readjustments of price and quantity led by the energy efficiency improvement result in the economy-wide rebound effect that is beyond the scope of direct and secondary responses to an energy efficiency improvement.

The fourth effect, named the “transformation effect”, results from consumers’ shifts in taste, manufacturers’ production rearrangements, and even social institutional changes, which are the consequences of improvements in technology. However, conventional economic theory does not offer predictions of these changes, as the scope of the transformational effect is too broad to capture comprehensively. This effect remains to be investigated, and its complexity requires a time series household dataset collected over time (Greening, Greene & Difiglio 2000).

On the other hand, according to Sorrell, Dimitropoulos & Sommerville (2009), the rebound effect can be classified into three categories: the direct, indirect, and economy-wide. However, this classification indicates that the economy-wide rebound effect is the sum of the direct and indirect rebound effects. This classification implies that the indirect rebound effect is considered in a general equilibrium setting instead of partial equilibrium, where energy price is exogenously determined.

As for the indirect effect, Sorrell, Dimitropoulos & Sommerville (2009) decomposed it into an embodied energy effect and secondary effects. An embodied energy effect is the energy required to produce the equipment that could be used to achieve the energy efficiency improvement, such as the energy required to manufacture a new hybrid car. The secondary effects were characterised by five channels. First, from a consumer’s perspective, savings from an energy efficiency improvement at the household level may be spent on other goods and services. Producing these goods and services requires energy as an input. Therefore, the energy consumption from other sources may increase. For example, a consumer may spend the fuel savings from a fuel-efficient car on an air flight. For a producer, an energy efficiency improvement may reduce the cost, hence the price, of the product. The demand for other intermediate inputs, such as steel, plastic, and other materials may increase, which also require extra energy to produce. Second, the reduction in the price of this product (say, A) may lead to reductions in prices of other goods, where product A is an intermediate input for producing other goods. Therefore, as prices of other related goods reduce, the demand will increase, and so will the demand for energy. Third, from a macroeconomic scope, any technological improvement will boost economic growth, and consumption will increase correspondingly. This will encourage energy consumption. Fourth, similar to the economy-wide rebound effect defined by Greening, Greene and Difiglio (2000), an energy efficiency improvement may lead to a decrease in real energy price, which will encourage energy consumption and investment. Finally, the energy efficiency improvement will have a larger impact on the price of energy-intensive goods than on goods that are less energy-intensive. Consumers may move away from less energy-intensive goods in favour of energy-intensive goods, creating additional indirect rebound effects.

In this study, we combine the definitions by Greening, Greene and Difiglio (2000) and Sorrell, Dimitropoulos & Sommerville (2009), and classify the rebound effect into three categories: direct, indirect and economy-wide; however, the definition of each category of the rebound effect is slightly different from Sorrell's three-type classification. This new classification in the study helps with framing the theoretical analysis, providing a clearer boundary when reviewing empirical studies on the magnitude of the rebound effect.

First, the direct rebound effect is defined separately for consumers and producers in a partial equilibrium setting, where the energy price is exogenously determined; the energy efficiency improvements do not alter the real energy price. For a consumer, consistent with Greening, Greene and Difiglio (2000), the direct rebound effect is a price effect of an energy efficiency improvement on energy consumption, which can be decomposed into a substitution effect and an income effect. Taken together, these effects will offset the mechanical effect of the energy efficiency improvement. However, this direct rebound effect is limited to the change in energy consumption when energy efficiency improves. For example, when the fuel efficiency of an automobile improves, the direct rebound effect only captures the fuel used by this automobile, and neglects its effects on the consumption of other forms of energy, such as electricity and natural gas. Similarly, for a producer, the direct rebound effect is a partial equilibrium price effect in the market, which can be decomposed into a substitution effect and an output effect. The direct rebound effect is again confined to the use of the energy induced by the increase in demand for this energy good or service for which efficiency is improved. How these channels work will be discussed in detail in Chapter 3.

The direct rebound effect can be measured by different units, such as direct energy use, direct greenhouse gas emissions, embodied energy use and embodied greenhouse gas emissions. When two consumers experience the same magnitude of the direct rebound effect measured by energy quantity, it does not necessarily mean that the direct rebound effects between these consumers measured by embodied greenhouse gas emissions are the same, for the latter depends on how energy is produced, distributed, and used. For example, two consumers, one situated in Tasmania and the other in Queensland, both adopt a new energy-saving LED that shows a rebound effect of 10%. The major energy source for electricity generation in Tasmania is hydropower, while the major energy source for electricity generation in Queensland is coal. This difference in energy sources implies that the carbon intensity of electricity in Tasmania is much lower than that of Queensland. Therefore, when translating into embodied greenhouse gas emissions, the size of the rebound effect may vary according to the carbon intensity of this energy.

Second, the definition of the indirect rebound effect continues to be the partial equilibrium responses of consumers and producers; however, these responses expand to all other goods and services that the consumer or the producer demand. For a consumer, the price effect of the energy efficiency improvement will flow to the consumption of all other goods and services consumed by them. Since nearly all goods and services require energy to produce, the increased demand for other goods and services will result in more energy consumed indirectly, which may not be used by the consumer directly. The increase in the embodied energy consumption of all goods and services, except the energy good or service for which energy efficiency is improved, is the indirect rebound effect of a consumer. A similar rule applies to the producer. When energy efficiency improves for a firm, the price of the product will be lowered, as the cost of production is reduced in a competitive market. Therefore, the output will increase. To meet the increased demand for the output, from consumers or other firms, other intermediate inputs will increase. Since producing other intermediate inputs requires energy, more energy may be used to meet the increase in the output of the company. The change in the embodied energy use from the increase in all the other inputs is the indirect rebound effect at the industrial level.

More often than not, the indirect rebound effect is measured by the embodied greenhouse gas emissions, for greenhouse gas emissions directly impact climate change. These embodied measurements would result in a different magnitude of the rebound effect than that measured by embodied energy. One obvious reason is that various energy sources produce different amounts of greenhouse gas emissions per unit of energy produced. For example, when energy is produced by renewable energy, such as solar power, the emissions are much lower than energy produced by fossil fuels. If an economy relies on renewable energy, even if there is a large indirect rebound effect measured by energy consumption, it does not necessarily translate to a large rebound measured by greenhouse gas emissions. Another reason these two measurements could yield different results is that some economic activities emit large quantities of greenhouse gases yet do not require much energy input. For example, raising cattle emits more greenhouse