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Assessing net energy consumption of Australian economy from 2004–05 to 2014–15: environmentally-extended input-output analysis, structural decomposition analysis, and linkage analysis

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Abstract

This paper provides a comprehensive analysis of Australian net energy consumption between 2004–05 and 2014–15. Results from environmentally–extended input-output (EEIO) analysis show that the Transport sector has the largest direct effect on net energy consumption in industrial sectors, which decreased by about 35% for net energy consumption per million $AUD in the period. The Export sector has the largest direct net energy consumption while Households consumption results in the largest net energy consumption embodied in different categories of Final demand. The structural decomposition analysis (SDA) decomposes the change of net energy consumption into five drivers, in which net energy intensity mainly reduces Australian net energy consumption by about 8000 Petajoules, while the level effect of Final demand increases it by about 10000 Petajoules. Analysis of forward and backward linkages highlights the Manufacturing sector as the key industrial sector with the largest energy consumption reduction potential via minor changes in its input and Final demand. This indicates that more attention should be given to the reduction of energy demand from the consumption patterns of Households consumption, the improvement of energy intensity, and the application of cleaner technologies in the Transport and Manufacturing sectors. The Australian Environmental-Economic Accounts is combined with Australian input-output tables to construct the EEIO tables for net energy consumption. The combination of economic and environmental data sets provides a depth of understanding their potential to inform environmental policy decisions. The novelty of the research is the combination of economic and energy data sets, the application of EEIO model, the implementation of the additive SDA method, and the use of forward and backward linkages for the Australian energy system.

Keywords: Net energy consumption, Environmentally-extended input-output analysis, structural decomposition analysis, net energy intensity, forward and backward linkages, Australia.

Introduction

Energy consumption has become the inevitable consequence of the rapid development of global economy. The gross domestic product (GDP) of the Australian economy reached 1345 billion Australian dollars in 2014–15, compared with 698 billion Australian dollars in 2004–05 [1], [6] –a growth rate of 92% over the decade. Additionally, Australia consumed 22,026 petajoules (PJ) in total net energy in 2014–15, increasing by more than 20% compared with that in 2004–05 [5]. This trend of Australian energy consumption has been predicted 1% average growth from 2014–15 to 2049–50 [14]. The pattern of Australian energy production and consumption is unique in three facets:

1) The amount of Australian energy production was three times of its energy consumption, with the majority of Australia's energy production exported [16]. The Export sector plays an important role in the pattern of Australian energy consumption because of this strong export-oriented energy consumption;

2) Australian energy intensity (the ratio of primary energy consumption to GDP) has been in long term decline since 1991–92, which has also happened in major OECD countries [16], [22]. This decline means that Australia is consuming less energy per unit of GDP as time has progressed. The driving forces of changes in Australian energy intensity have previously been analysed for the period 1978–2009 [43] – however this pre-2009 time period excludes the 2010 onwards Australian resources/energy export boom. This new situation of a dominant energy export sector alongside decreasing energy intensity has yet to be analysed;

3) There are large differences between the proportions of energy consumed by different Australian industrial sectors [17]. However, previous research did not examine forward and backward linkages among industrial sectors to analyse the reduction potential for each industrial sector. The identification of more recent (2004-2015) energy consumption of Australia's major industrial sectors, and the modelling of the potential effects of various energy

intensity and sectoral changes would be useful in planning future energy reduction and sustainable manufacturing policies.

In order to recognise whether or not Australia can keep lowering energy intensity, whether it continues to be the same pattern of energy consumption as before, and which industrial sector has the most potential for the reduction of energy consumption, fundamental analysis of Australia's recent (2004-2015) energy consumption is required. This paper conducts the systematic research by the application of the environmentally-extended input-output (EEIO), structural decomposition analysis (SDA), and examining forward and backward linkages on Australian net energy consumption.

As an extension of input-output (IO) analysis, EEIO analysis has been widely used to assess the relationship between economic activities and environmental issues at the national, state, and city levels. Since the theoretical application of IO analysis to environmental pollutants was introduced by Leontief [33], EEIO analysis has become a major method for analysing energy [37], [51], carbon emission [34], [46], and waste [25], [26], [32] to explore how the total output and Final demand of each industrial sector affect these environmental issues.

A comprehensive understanding about how the driving forces affect the change of Australian net energy consumption over time should be conducted. A growing body of literature has promoted the idea of conducting more detailed analysis at the industrial sector level and environmental factors on the basis of decomposition analysis (DA) [12], [57]. Two major types of DA are applied to decompose the changes of economic and environmental indicators, which are the SDA method and the Index Decomposition Analysis (IDA) method. The IDA method has been used to study the drivers of energy use and energy-related emission in a specific energy consumption sector [45]. Compared with the IDA method, the SDA method is on the basis of the input-output framework to identify and assess changes of the driving forces in energy consumption in the economy with input-output data [29]. The Log Mean Divisia Index (LMDI) method developed by Ang [62] can decompose multiple factors with zero residual errors and of parts of incomplete data sets [66], [71]. This method has been applied to quantitatively decompose energy consumption into different drivers for different sectors in several countries, such as the cases of the Transport sector [74] in China, residential energy consumption [69] in China, and energy efficiency in several European countries [63]. The current research is conducted on the basis of IO model for the net energy consumption in different industrial sectors of the Australian economy. For these reasons, the research applies the SDA method to investigate the drivers of affecting net energy consumption in Australia because the LMDI is not on the basis of IO model, and the IDA has mainly been used for special energy consumption sector.

The IO based environmental linkages analysis has also been widely applied by researchers to specify which industrial sector has the most potential for the reduction of energy consumption. This method was introduced by Rasmussen [41] and used to solve economic issues [27], [44], [52]. With the increase of environmental pressure, the analysis of linkages has been extended to analyse forward and backward energy consumption [11], [24] and pollution generation [31], [48], [20]. Therefore, there is a benefit to conduct linkage analysis on Australian energy consumption to identify the potential of different industrial sectors' contribution for the reduction of energy consumption.

This research fills this gap by providing a comparative analysis of direct and embodied energy consumption in different industrial sectors and categories of Final demand through EEIO model. The research further applies the SDA method to investigate the driving forces, such as the technological effect, the energy intensity effect, the level effect of Final demand, the mix effect of Final demand, and the distribution effect of Final demand, which influenced the changes of Australian energy consumption during a ten year period 2004-05 to 2014-15. Finally, environmental forward and backward linkages are applied here to give the ranking sequence of which sector has the most potential for the reduction of energy consumption.

The paper is structured as follows. The basic methodology and sources of data for this study is given in Section 2. Results of EEIO analysis for energy consumption, the investigation of the driving forces, and environmental linkages' analysis for Australian net energy consumption between 2004–05 and 2014–15 are illustrated in Section 3. Section 4 provides the discussion, and Section 5 draws conclusions.

2 methodology

2.1 Environmentally-extended input-output analysis

As a top-down macro-economic methodology, the IO analysis has been extended to be the EEIO analysis [33], which accounts for the complex relationships between industrial sectors and environmental pollution in modern economies. There are three basic categories of EEIO models: generalized EEIO models, economic–ecologic models, and commodity-by-Industry models [39]. The generalized IO models consider pollution generation and abatement activities as additional rows and/or columns for the basic structure of the IO model [78]. The generalized EEIO model has been applied widely for exploring the relationship between economic activities and environmental issues through adding the emission intensity vector [64], [61] and energy consumption [19]. The economic–ecologic models are able to add additional “ecosystem” sectors into the interindustry framework to record the resource flows and environmental impacts between industrial and ecosystem sectors [67], [39]. This model has incorporating land use data [67], material flow [75], and energy consumption data [77] into IO framework to explore how industrial sectors affect resource flows and environment. The commodity-by-Industry models for environmental issues consider environmental factors as “commodities” in a commodity-by-industry input–output table through the application of supply-use matrix [39]. This can offer detailed analysis for environmental factors because an industrial sector may produce more than one commodity (pollutants). For example, a supply-use matrix has been combined into waste input-output table to analyse how industrial sectors generates 14 types of waste [32]. This research applies the generalized IO models for the net energy consumption and adds net energy flow as an additional row for the IO framework.

An introduction of the basic form of EEIO analysis can be found in [39]. The basic structure of input-output model can be expressed as

$$\mathrm{x} = \mathrm{Ax} + \mathrm{f} = (I - A)^{-1}\mathrm{f} = \mathrm{Lf} \qquad (1)$$

where x is the $n \times 1$ vector of total output by industrial sectors, I is the $n \times n$ unit matrix. A is the input coefficient of IO model. f is the Final demand of the economy. $L = (I - A)^{-1}$ is known as the Leontief Inverse matrix.

The approach to construct the EEIO model for net energy consumption associated with industrial sectors is to add a vector $1 \times n$ of direct coefficients of net energy consumption output, $e = [e_i]$ (PJ/million $AUD), each element of which is the amount of net energy consumption (ε) consumed from per dollar of total output in each industrial sector.

The basic structure of EEIO model for net energy consumption can be shown as

$$\begin{bmatrix} \mathrm{x} \\ \varepsilon + \mathrm{f}^* \end{bmatrix} = \begin{bmatrix} A \\ e \end{bmatrix} \begin{bmatrix} \mathrm{x} \\ \varepsilon + \mathrm{f}^* \end{bmatrix} + \begin{bmatrix} \mathrm{f} \\ \mathrm{f}^* \end{bmatrix} \qquad (2)$$

$$\varepsilon' = \hat{e}\mathrm{x} = \hat{e}(I - A)^{-1}\mathrm{f} \qquad (3)$$

where ε' is the transpose of the $1 \times n$ vector of net energy consumption (PJ) in each industrial sector. f^* represents $1 \times n$ vector of net energy consumption (PJ) by Final demand, which indicates direct effects of net energy consumption for Final demand. $\hat{e}$ with the "hat" over a vector e denotes a diagonal matrix with the elements of the vector along the main diagonal. For instance, if $e = [e_1 \quad e_2 \quad e_3]$ then $\hat{e} = \begin{bmatrix} e_1 & 0 & 0 \\ 0 & e_2 & 0 \\ 0 & 0 & e_3 \end{bmatrix}$. $\hat{e}L$ represents the total effects of net energy consumption for Australian industrial sectors. Equation 3 can be expressed as follows:

$$\varepsilon' = \hat{e}L\mathrm{f} \qquad (4)$$

Final demand (f) is the summation of Households consumption (f_{hc}), Government consumption (f_{gc}), Gross fixed capital formation (f_{gfcf}), Change in inventory (f_{cii}), and Exports (f_{export}). We have analysed the net energy consumption embodied in the Households consumption (ε_{hc}) by Eq. (5), the net energy consumption embodied in the Government consumption (ε_{gc}) by Eq. (6), the net energy consumption embodied in the Gross fixed capital formation (ε_{gfcf}) by Eq. (7), the net energy consumption embodied in the Change in inventory (ε_{cii}) by Eq. (8), and the net energy consumption embodied in the Exports (ε_{export}) by Eq. (9).

$$\varepsilon'_{hc} = \hat{e}L\mathrm{f}_{hc} \qquad (5)$$

$$\varepsilon'_{gc} = \hat{e}L\mathrm{f}_{gc} \qquad (6)$$

$$\varepsilon'_{gfcf} = \hat{e}L\mathrm{f}_{gfcf} \qquad (7)$$

$$\varepsilon'_{cii} = \hat{e}L\mathrm{f}_{cii} \qquad (8)$$

$$\varepsilon'_{export} = \hat{e}L\mathrm{f}_{export} \qquad (9)$$

2.2 Structural decomposition analysis

The aim of this section is to apply the SDA method to investigate the drivers of net energy consumption in Australia. Previous researches have revealed characteristics of the application of the SDA method on energy consumption: time period, driving forces, and mathematical approaches for the decomposition process (multiplicative and additive).

Time period: The time period of the SDA approach depends mainly on the availability of input-output data and the corresponding environmental accounts. SDA studies are characterized by time periods more than 5 years because a long period of SDA studies can diminish the occurrence of a time-independent zero-mean error term [40]. The time period of most of studies in the domain of energy are more than 5 years, such as 10 years [36], [42], [76], 20 years [59], 26 years [53]. The long time-series IO tables can better represent the effects of the economic cycle. The SDA method has been proposed to assess the impacts of driving forces on environmental pollution since the 1970s [12].

Driving forces: The driving forces of energy consumption include structural changes, technological changes, pollution intensity, and Final demand. The driving forces of the demand of energy sectors and other sectors have been analysed through categorising the demand structure of IO model into the structure of energy sectors and other sectors [30]. The SDA method has been proposed to analyse the differences of energy intensities of industrial sectors caused by structure and demand effects in European Union countries [10]. The categories of Final demand, such as capital, exports, government consumption, have been identified as important driving forces for total energy usage [54]. The driving forces, which include energy intensity effects, Leontief effect, and Final demand effect, have been applied to assess the indirect energy consumption and air emission changes [19]. How the effects of energy intensity, changing structure, and Final demand on energy consumpution have been illustrated in China [59]. How the energy flows were affected by different variations of the Final demand, which present the absolute variation and production of Investment, private consumption, and exports [36].

Multiplicative and additive: The choice of the mathematical methods for the decomposition procedure of the SDA method depends on the IO framework [20]. It will also affect the interpretation of the results [45]. The multiplicative SDA framework has been applied to analyse the energy consumption change [59] and the aggregate energy intensity [47]. The application of additive decomposition in the SDA has been discussed for the differences of energy intensities of industrial sectors [10] and the driving forces of CO_2 emissions in Beijing [55]. The SDA method has also illustrated that India's emission and intensity are mainly driven by private consumption [60]. A residual of decomposition indicates that the sum of the drivers' effects has overestimated or underestimated the total indicator change, which means that a complete decomposition has no residual [29]. The additive method can make the residual of decomposition equal 0 while the multiplicative method make the residual of decomposition equal 1. Therefore, the study applies the additive method to decompose the drivers of net energy consumption in Australia. In addition, only one study of the SDA focuses on Australian environmental issues, which analyses the driving forces of Australian greenhouse gas emissions [57].

This study analyses the driving forces of net energy consumption by applying additive structural decomposition analysis, which has been introduced [39]. The net energy consumption for industrial sectors (ε) is decomposed into structurally significant factors for Australian net energy consumption. Based on Eq. (3), changes of net energy consumption between t_1 and t_0 $(t_0 < t_1)$ can be formulated as

$$\Delta\varepsilon = \varepsilon^1 - \varepsilon^0 = \hat{e}^1 L^1 \mathrm{f}^1 - \hat{e}^0 L^0 \mathrm{f}^0 \qquad (10)$$

The driving forces of net energy consumption in Eq. (10) are decomposed into energy input coefficient change, technology change, and Final demand change by the following formula:

$$\Delta\varepsilon = \left(\frac{1}{2}\right)(\Delta\hat{e})(L^0\mathrm{f}^0 + L^1\mathrm{f}^1) + \left(\frac{1}{2}\right)(\Delta L)[\hat{e}^0\mathrm{f}^1 + \hat{e}^1\mathrm{f}^0] + (1/2)(\hat{e}^0L^0 + \hat{e}^1L^1)(\Delta\mathrm{f}) \quad (11)$$

The first term on the right-hand side represents the change of net energy input coefficient assuming that the multipliers (technology) and Final demand have remained constant. The second term on the right-hand side is the change of the total multipliers without the change of net energy input coefficient and Final demand, which means the change of technology structure. The third term on the right-hand side indicates the change of Final demand if net energy input coefficient and the total multipliers keep stable.

The second term on the right-hand side in the Eq. (11) can be further decomposed because the changes in the Leontief inverse matrix L depend on the changes in the input coefficient matrix A [28]. The changes in the Leontief inverse matrix L cam be written as:

$$\Delta L = L^1(\Delta A)L^0 \qquad (12)$$

Here, we disaggregate the ΔA into column specific changes. For an input coefficients matrix with n-sectors [39],

$$A^1 = A^0 + \Delta A = \begin{bmatrix} a_{11}^0 + \Delta a_{11} & \dots & a_{1n}^0 + \Delta a_{1n} \\ \vdots & & \vdots \\ a_{n1}^0 + \Delta a_{n1} & \cdots & a_{nn}^0 + \Delta a_{nn} \end{bmatrix} \qquad (13)$$

Let $\Delta A^{(j)} = \begin{bmatrix} 0 \cdots \Delta a_{1j} \cdots 0 \\ \vdots \quad \vdots \quad \vdots \\ 0 \cdots \Delta n_{1j} \cdots 0 \end{bmatrix}$ represent changes in sector j's technology. Then

$$\Delta A = \Delta A^{(1)} + \cdots + \Delta A^j + \cdots + \Delta A^n \qquad (14)$$

The ΔA^j in the Eq. (14) represents the technology change in sector j. The decomposition of ΔA can be introduced into the second term on the right-hand side of the Eq. (11), which is shown like this:

$$\left(\frac{1}{2}\right)(\Delta L)[\hat{e}^0\mathrm{f}^1 + \hat{e}^1\mathrm{f}^0] = \left(\frac{1}{2}\right)[L^1(\Delta A^1)L^0][\hat{e}^0\mathrm{f}^1 + \hat{e}^1\mathrm{f}^0] + \cdots + \left(\frac{1}{2}\right)[L^1(\Delta A^n)L^0][\hat{e}^0\mathrm{f}^1 + \hat{e}^1\mathrm{f}^0]$$

(15)

As for the composition of changes in Final demand,iIf the Final demand matrix has dimension $n \times p$, where p is the number of Final demand categories. We decompose the Final demand into the following determinant effects by the method shown [38]:

$$\Delta \mathrm{f} = (1/2)\Delta f(B^0\mathrm{d}^0 + B^1\mathrm{d}^1) + (1/2)(f^0\mathrm{d}^1 + f^1\mathrm{d}^0)(\Delta B) + (1/2)(f^0B^0 + f^1B^1)(\Delta \mathrm{d}) \quad (16)$$

Here f means the level of Final-demand expenditure over all sectors. The matrix B is defined as the bridge coefficients matrix, which equals the Final demand matrix elements divided by their corresponding column sums. The vector d represents the distribution of each Final demand category in the total Final demand. The first term of the right-hand side in the Eq. (16) means the level effect of Final demand. The second term of the right-hand represents the mix effect of Final demand. The third term of that means the distribution effect of Final demand.

The study decomposes Eq. (17) by Equations 10, 11, 15, and 16 to assess effects of the changes of net energy consumption input coefficient, technology effects, and Final demand effects on net energy consumption. The process of decomposition by these effects can be summarised as:

$$\Delta \varepsilon = \left(\frac{1}{2}\right)\underline{(\Delta\hat{e})(L^0\mathrm{f}^0 + L^1\mathrm{f}^1)} + \left(\frac{1}{2}\right)\underline{(L^1(\Delta A)L^0)[\hat{e}^0\mathrm{f}^1 + \hat{e}^1\mathrm{f}^0]} + \left(\frac{1}{4}\right)$$

$$\underline{(\hat{e}^0L^0 + \hat{e}^1L^1)(\Delta f(B^0\mathrm{d}^0 + B^1\mathrm{d}^1) + (f^0\mathrm{d}^1 + f^1\mathrm{d}^0)(\Delta B) + (f^0B^0 + f^1B^1)(\Delta \mathrm{d}))} \quad (17)$$

The first term of the right-hand side means net energy intensity change, which means changes in net energy consumption per unit of total economic output. The second term of the right-hand represents technology change, which indicates changes of net energy consumption caused by the change of industrial structure. The third term of that means the Final-demand change, including the level effect of Final demand, the mix effect of Final demand, and the distribution effect of Final demand. The level effect of Final demand is to illustrate the change of net energy consumption due to the change occurring in the overall level of Final demand. The mix effect of Final demand shows how shifts of the proportions in different categories of Final demand cause the changes of net energy consumption. The aim of the distribution effect of Final demand is to assess how the change of the distribution of each Final demand category in the total Final demand affects the change of net energy consumption.

2.3 Forward and backward linkages

The aim of the forward and backward linkages is to describe key sectors which can be adjusted to consume less energy with minor changes of their economic activities. The character of each industrial sector's net energy consumption has been identified by applying inter-industry linkages [31]. The calculation of forward linkage is used to summarise elements g_{ij} of the Ghosh inverse $G = (I - M')^{-1}$, which indicates the change in the total output of industrial sector j caused by change per dollar in the primary input in industrial sector i [20], [57]. It is shown as follows:

$$P = \sum_{j=1}^{n} g_{ij} \tag{18}$$

Here P represents the forward linkage.

The backward linkage is used to summarise the elements l_{ij} of the Leontief matrix L, which represent the change in output in industry i per dollar change in Final demand in industrial sector j [20], [41]. The formula of backward linkage is

$$Q = \sum_{i=1}^{n} l_{ij} \tag{19}$$

Here Q represents the backward linkage.

Therefore, we can analyse the energy forward linkage (P_i^E) of sector j, which consumes energy with the change per dollar in the primary input in corresponding industrial sector, by multiplying $\sum_{j=1}^{n} g_{ij}$ with ε_j. Likewise, the energy backward linkage of each sector (Q_j^E), which consumes energy with the change of per dollar in Final demand in corresponding industrial sector, by multiplying $\sum_{i=1}^{n} l_{ij}$ with ε_i.

And then we identify key factors for illustrating the impacts of sectors on net energy by normalising the measurement of the backward and forward linkages [20], [41]. They are shown as

$$FL_i^E = \frac{P_i^E}{(\sum_{j=1}^{n}(g_{ij} \times \varepsilon_j))/n} \tag{20}$$

$$BL_j^E = \frac{Q_j^E}{(\sum_{i=1}^{n}(l_{ij} \times \varepsilon_j))/n} \quad (21)$$

$FL_i^E > 1$ indicates that an increase of one AUD dollar in the input of an industrial sector i will result in an above-average increase of net energy consumption, and $BL_j^E > 1$ illustrates an increase of one AUD dollar in the Final demand of an industrial sector j will cause an above-average increase of net energy consumption and vice-versa [20]. The backward and forward linkages about net energy consumption in each industrial sector aims at identifying the contribution of key sectors for energy consumption.

2.4 Data sources

Australian IO Tables for 2004–05 [2], 2009–10 [4], and 2014–15 [8] were used in this study. The IO table in 2004–05 has 108 industrial sectors, while the IO tables in 2009–10 and 2014–15 have 114 industrial sectors. For harmonisation purposes, these IO tables were each aggregated to a harmonised 7 industrial sectors. All the monetary values were deflated to constant 2004–05 prices based on the method developed by Wood [58].

The Australian Bureau of Statistics has published the Australian Environmental-Economic Accounts [5], [7], which has illustrated the net energy consumption occurs in seven industrial sectors and Final demand from 2002–03 to 2014–15. The energy account shows the net energy consumption in three categories of Final demand, including the Households consumption, the Government consumption, the Change in inventory, and the Exports. Based on the information offered by Lisa [35], there is no direct energy consumed by the Gross fixed capital formation.

Based on the Australian and New Zealand Standard Industrial Classification [3], these IO tables have been aggregated into seven industrial sectors corresponding to industrial sectors shown in Australian Environmental-Economic Accounts.

3 Results

3.1 Environmentally-extended input-output analysis of net energy consumption

Australian direct net energy consumption by industrial sectors are shown in Fig. 1. The amounts of direct net energy consumption in seven Australian industrial sectors (aggregated from the 108 or 114 industrial sectors) have been compared to analyse the structure of net energy consumption from 2004–05 to 2014–15. Figures 1 and 2 show that the total amount of direct net energy consumption has increased steadily from 2004–05 to 2014–15 by 20.2%. The three largest industrial sectors consuming energy were identified as the Manufacturing sector, the Transport sector, and the Mining sector. Their combined share in net energy consumption of Australian industrial sectors increased slightly from 69.7% in 2004–05 to 71.2% 2009–10, and then decreased to 70.6% in 2014–15.

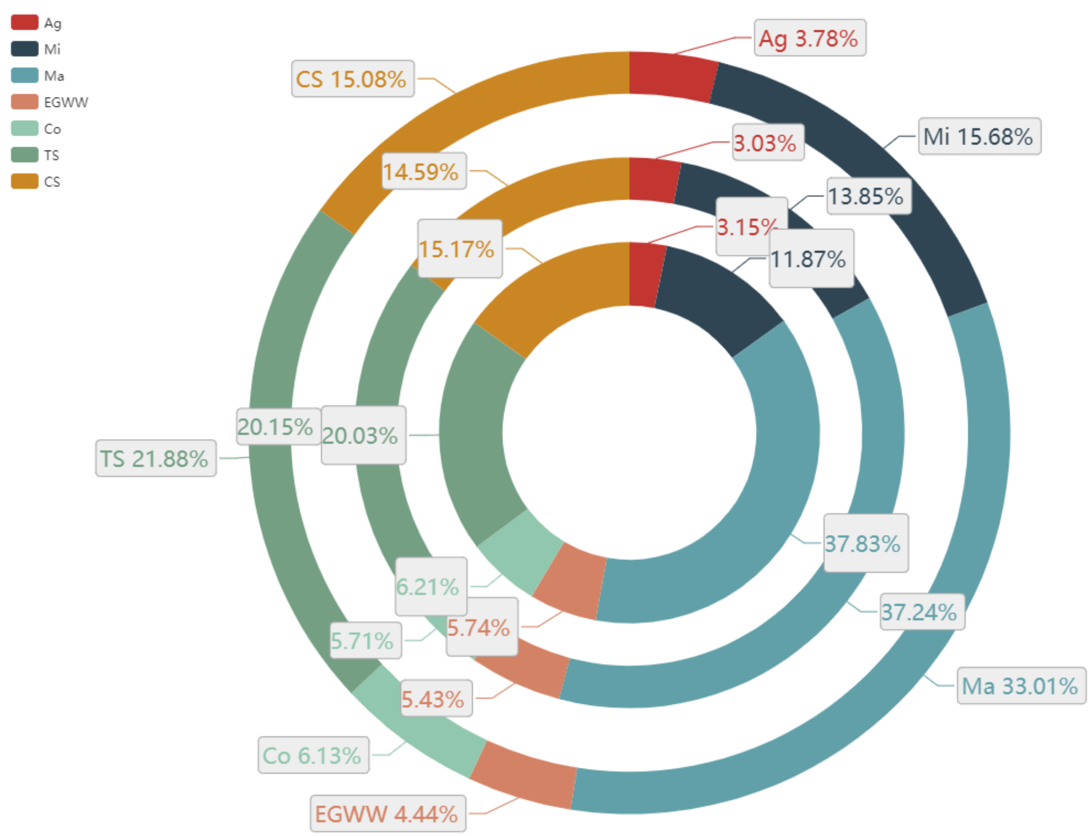


Fig. 1. Direct net energy consumption by seven industrial sectors in 2004–05, 2009–10, and 2014–15, PJ. The circles represent the total amount of direct net consumption by Australian industrial sectors. The

inner circle represents the year of 2004–05, the middle circle represents the year of 2009–10, and the outer circle represents the year of 2014–15.

Note: Agriculture, forestry, and fishing = Ag; Mining = Mi; Manufacturing = Ma; Electricity, gas, water, and waste = EGWW; Construction = Co; Commercial and Services = CS; Transport =TS.

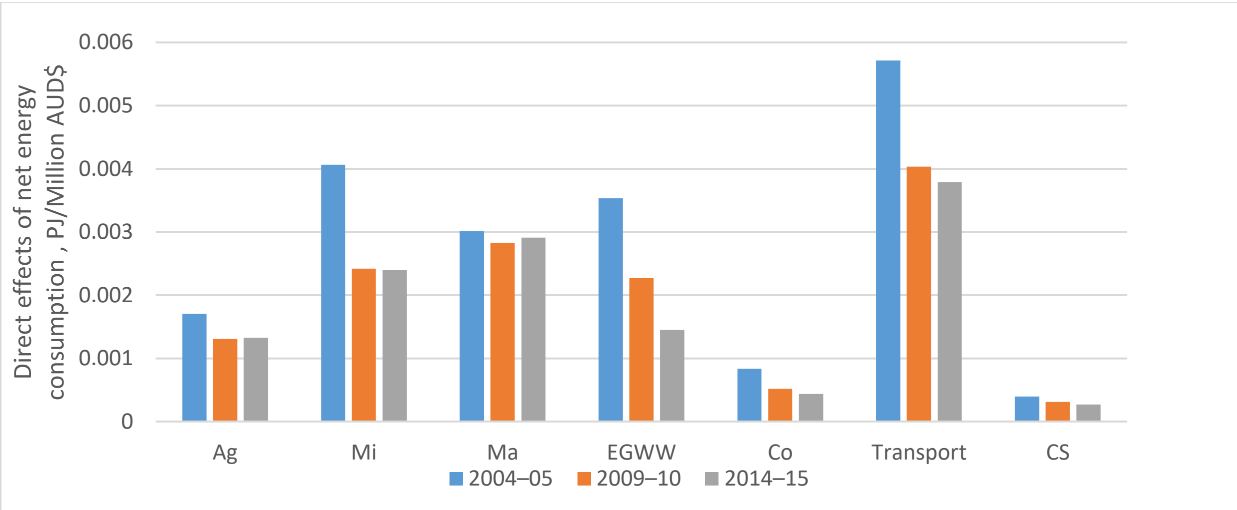


Fig. 2. Direct effects of net energy consumption for Australian industrial sectors in different periods.

Figure 2 presents the direct effects of net energy consumption for Australian industrial sectors in the three years, in PJ per million Australian dollars. The Transport sector has the largest direct effect of net energy consumption, which means that the output per million AUD dollar in the Transport sector has consumed about 0.0057PJ in 2004–05, more than 0.004PJ in 2009–10, and about 0.0037PJ in 2014–15, a 35% decrease. The smallest direct effect has happened in the Commercial and Services sector, which indicates the output per million AUD dollar in the Commercial and Services sector has consumed about 0.00083PJ in 2004–05, more than 0.00051PJ in 2009–10, and about 0.00043PJ in 2014–15, a 48% change. Industrial sectors have experienced a decreasing trend of the direct effects of net energy consumption.

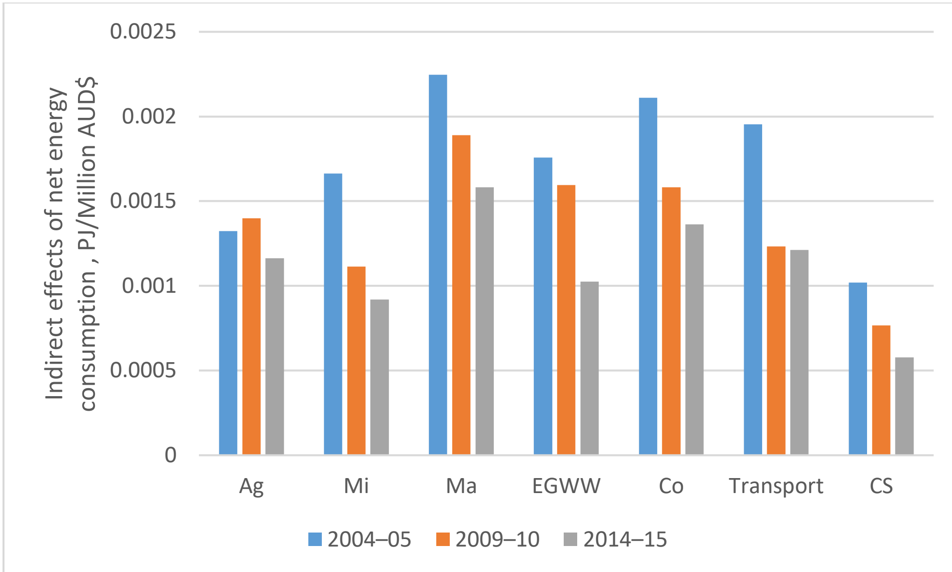


Fig. 3. Indirect effects of net energy consumption for Australian industrial sectors in different periods.

Indirect effects of net energy consumption for Australian industrial sectors in different periods are shown in Figure 3. The Manufacturing sector has the largest indirect effect of net energy consumption in corresponding periods. Although the Construction sector has the second largest indirect effect of net energy consumption in 2004–05, the indirect effect of it was slightly surpassed by that of the Electricity, gas, water, and waste sector in 2009–10. It shows that the indirect effects of net energy consumption for all industrial sectors have experienced a decreasing trend.

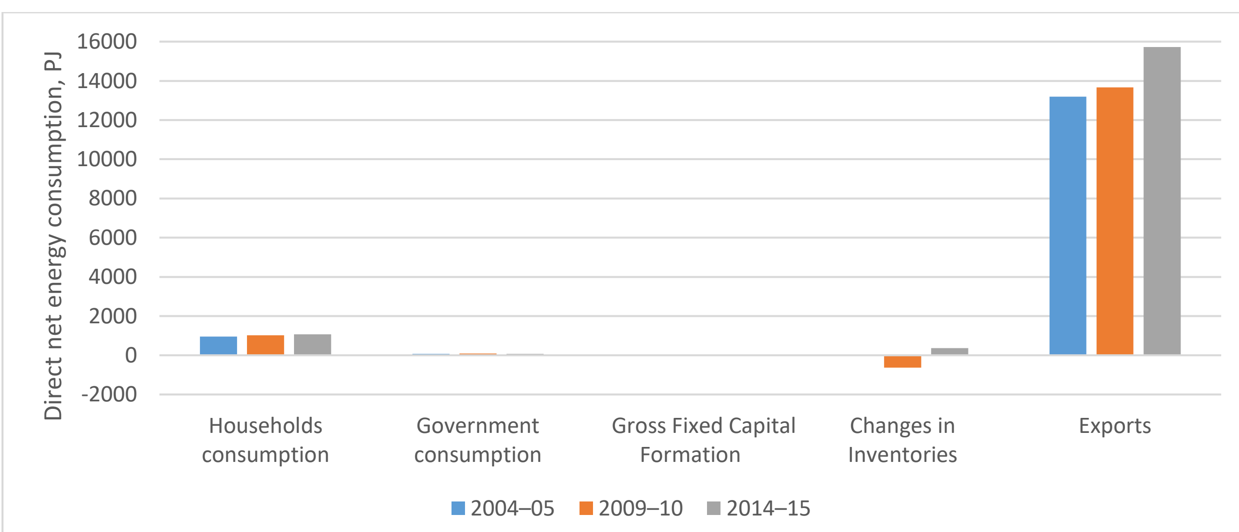


Fig. 4. Direct net energy consumption in different categories of Final demand.

Based on the Australian environmental accounts, Figure 4 has described the direct net energy consumption of different categories of Final demand, including Households consumption, Government consumption, Gross Fixed Capital Formation, Changes in Inventories, and Exports. The Exports is the largest category of direct net energy consumption, which has accounted for more than 90% of direct net energy consumption in Final demand. The amount of direct net energy consumption of the Exports sector have increased slightly (3%) from 13185 PJ in 2004–05 to 13668 PJ in 2009–10, and then have grown by over 15% to 15725 PJ in 2014–15. The amount of direct net energy consumed by the Gross fixed capital formation is considered as zero [35]. Because the definition of Gross fixed capital formation is the net increase in physical assets (investment minus disposals) within the measurement period. It causes the energy consumption (indirectly) but does not consume energy directly. It is clear that the majority of growth in energy consumption of Final demand is because of the increase of energy exported.

Net energy consumption embodied in different categories of Final demand means the net energy embodied in products and services consumed by Final demand. The net energy consumption embodied in different categories of Final demand are calculated in terms of the EEIO analysis in Section 2.1. The largest category of net energy consumption embodied in Final demand is the Households consumption, which has been estimated to sharply increase by 1856.68 PJ (~ 188.9%) from 2004–05 to 2009–10, and then slightly decrease by 1771.79 PJ (~ 62.4.0%) from 2009–10 to 2014–15 (Fig. 5). Other categories of Final demand have the similar trend that increased in the former period and decreased in the latter period, except the Changes in Inventories.

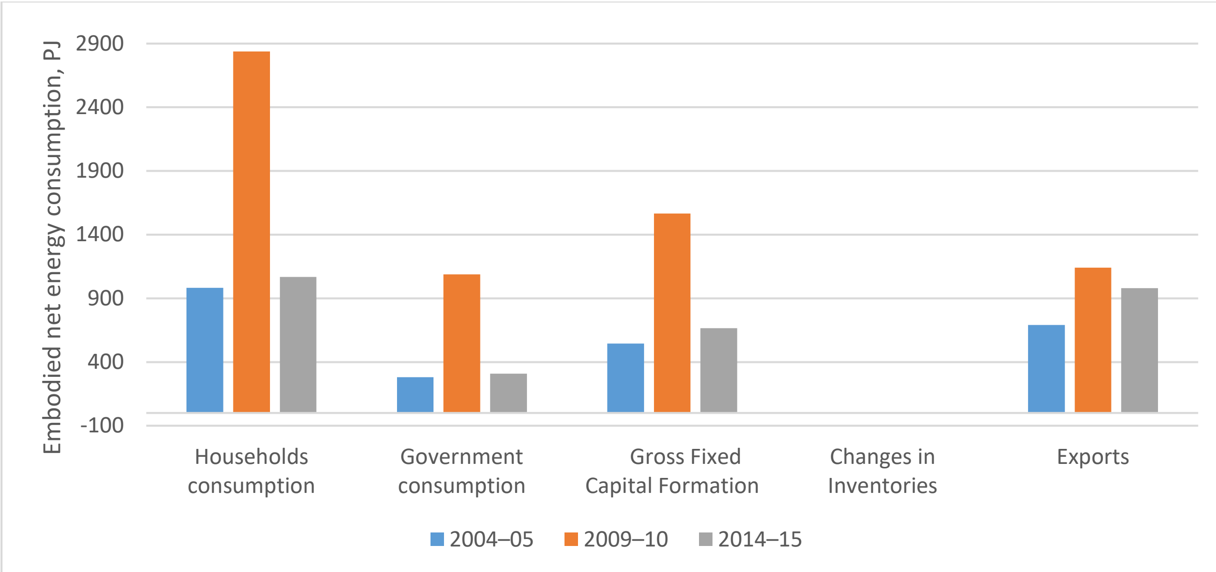


Fig. 5. Net energy consumption embodied in different categories of Final demand.

Australian net energy embodied in Final demand by industrial sectors in different periods is shown in Table 1. The largest portions of embodied net energy consumption consumed by the Households consumption (ε_{hc}) and the Government consumption (ε_{hc}) are from the Commercial and Services sector. For the Gross fixed capital formation (ε_{gfcf}), the Change in inventory (ε_{cii}), and the Exports, the main embodied net energy consumption is attributable to the consumption of goods and services from the Manufacturing sector. Consumption of goods and services generated from the Mining sector contributed its largest embodied net energy consumption to the Export (ε_{export}).

Table 1 Net energy Embodied in Final demand by industrial sectors in 2004–05, 2009–10, and 2014–15 (unit: PJ).

Industrial sectors	ε_{hc}			ε_{gc}			ε_{gfcf}			ε_{cii}			ε_{export}		
	2004–05	2009–10	2014–15	2004–05	2009–10	2014–15	2004–05	2009–10	2014–15	2004–05	2009–10	2014–15	2004–05	2009–10	2014–15
Ag	31.21	31.80	38.04	4.73	6.36	6.61	14.03	19.11	22.49	3.41	-0.25	0.94	25.62	28.98	45.92
Mi	53.72	45.25	46.26	10.60	8.68	9.76	27.77	57.82	70.24	-1.37	2.63	4.29	207.27	278.62	342.45
Ma	395.53	389.53	344.61	67.78	74.14	63.67	212.37	275.97	244.60	5.40	-11.00	-9.26	268.92	328.35	352.38
EGWW	83.58	84.10	77.57	16.04	13.86	12.89	29.48	42.80	26.65	0.28	-0.19	-0.03	14.63	18.30	16.92
Co	11.69	77.83	18.69	7.37	29.28	6.86	133.08	602.31	148.55	0.08	-0.05	0.08	3.79	38.29	10.83
Transport	200.76	101.22	291.56	84.65	41.33	103.16	78.93	37.08	100.78	3.33	-0.86	-0.50	135.33	80.02	165.00
CS	206.33	2109.76	250.97	88.61	914.56	105.19	49.32	531.04	53.14	0.87	-1.71	0.30	35.86	368.15	45.40

3.2 Decomposition results of net energy consumption changes

In order to reveal the importance of drivers for the changes of net energy consumption in Australia, structure decomposition analysis was conducted on national scale during the period from 2004–05 to 2014–15. There are five major drivers to be investigated by using Eq. (10–17), including net energy intensity, technology change, level effect of Final demand, mix effect of Final demand, and distribution effect of Final demand. A summary of the major drivers of changes in Australian net energy consumption is shown in Fig. 6. The changes of energy intensity, the technology effect, the mix effect of Final demand, and the distribution effect of Final demand mainly contribute to the decrease of net energy consumption while the change of the level effect of Final demand results in the increase of net energy consumption. The change of the level effect of Final demand has the largest effect on the increase of net energy consumption of about 9845 PJ from 2004–05 to 2014–15. The change of the level effect of Final demand from 2004–05 to 2009–10 (the former period) on net energy consumption (about 1500 PJ) is more than that (by more than 500 PJ) from 2009–10 to 2014–15 (the latter period). This result means that the growth of Final demand in each industrial sector plays the most significant role on the increase of net energy consumption. The change of the energy intensity contribution has played the most important part on the reduction of net energy consumption from 2004–05 to 2014–15. It results in a reduction of net energy consumption of more than 8000 PJ from 2004–05 to 2014–15. The changes of the technology effect, the mix effect of Final demand, and the distribution effect of Final demand have minor effects on the reduction of net energy consumption in the same period, which has resulted in the reduction of net energy consumption of more than about 1900 PJ, about 1000 PJ, and more than 2800 PJ, respectively.

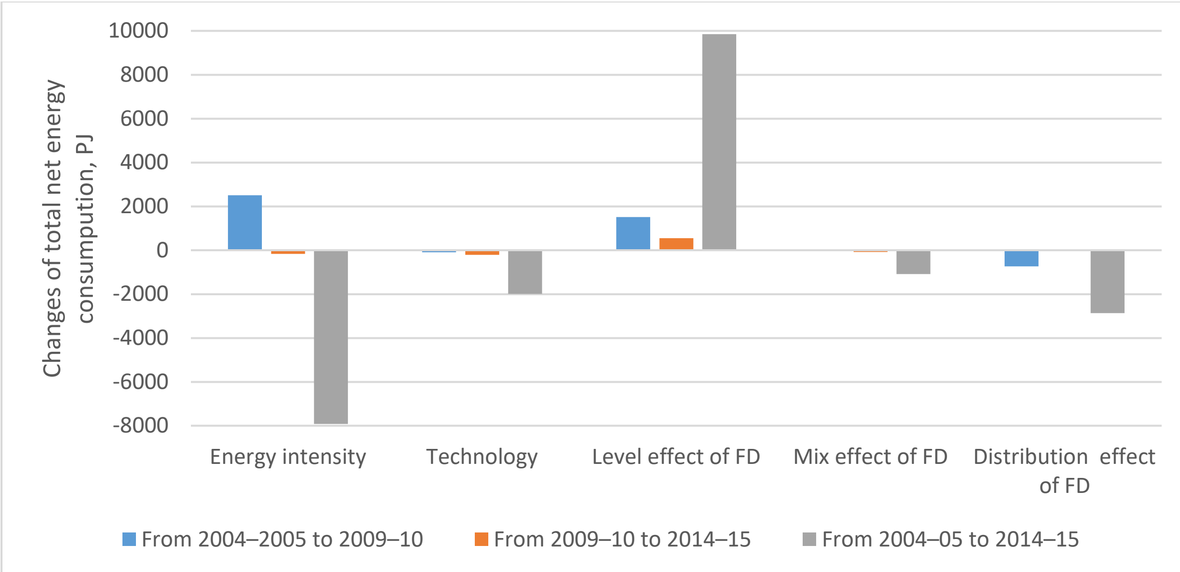


Fig. 6. SDA results of changes in Australian net energy consumption in different periods: major drivers.

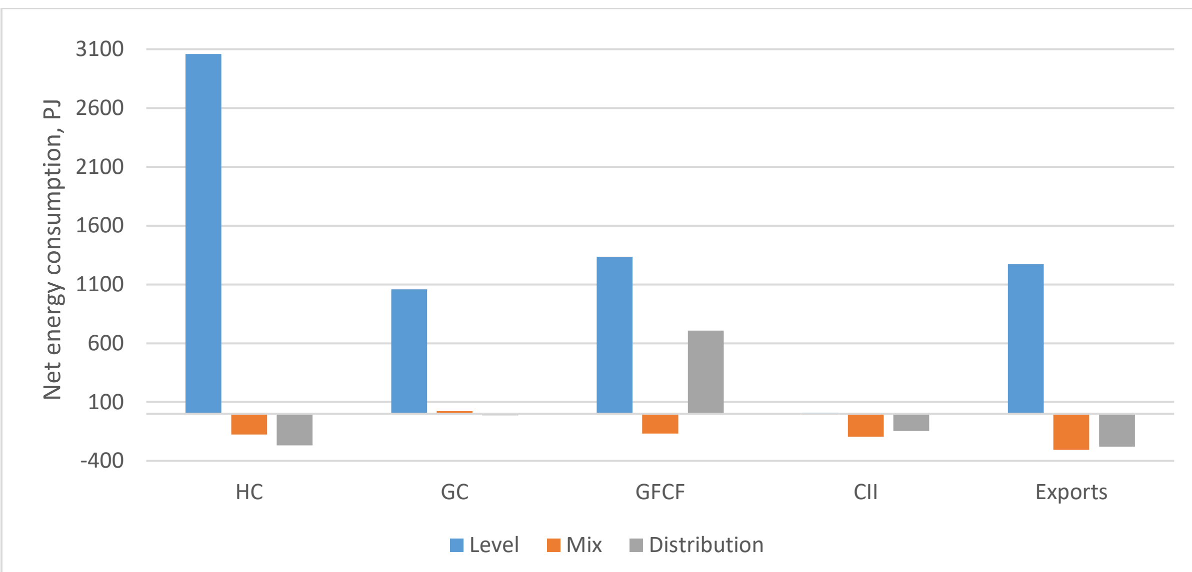
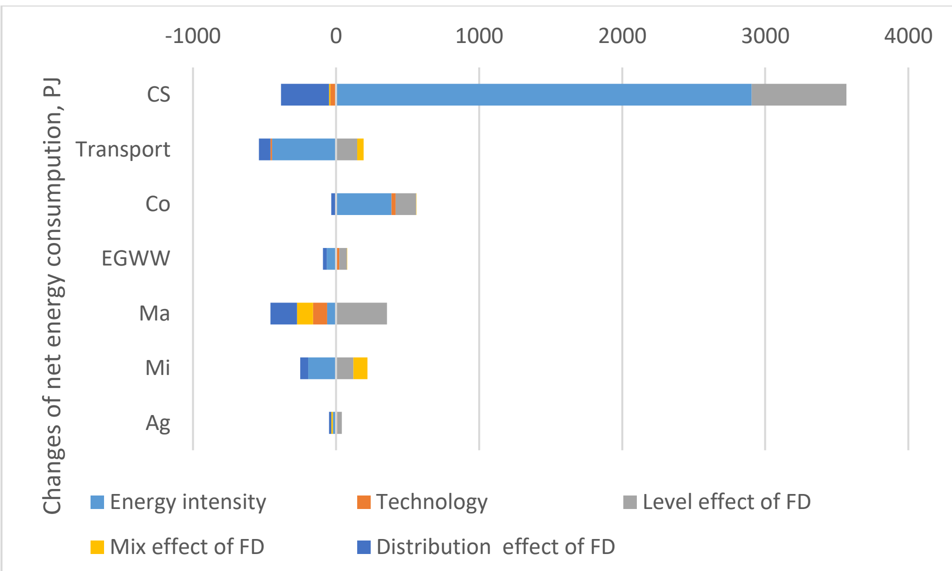
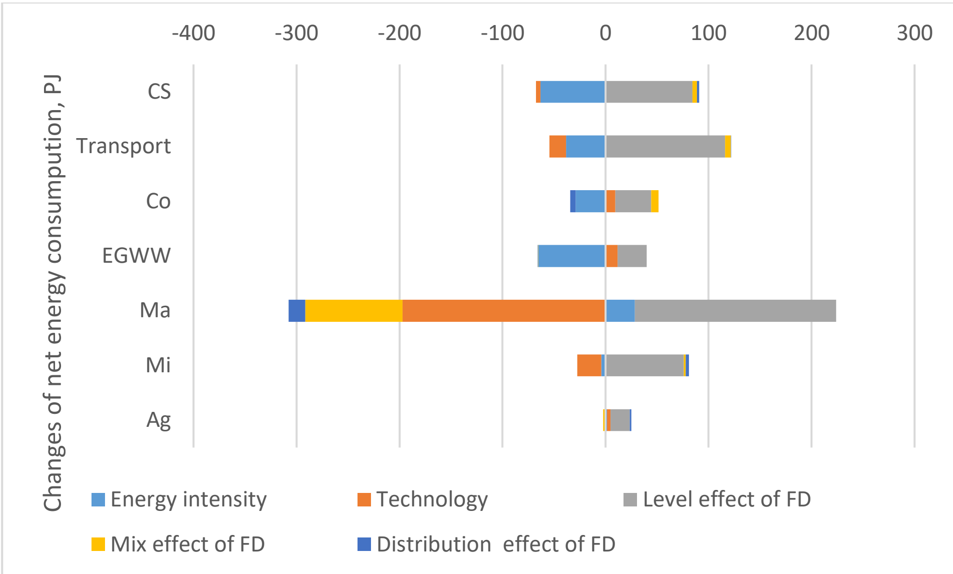


Fig. 7. SDA results of changes in Australian net energy consumption from 2004–05 to 2014–15, categories of Final demand.

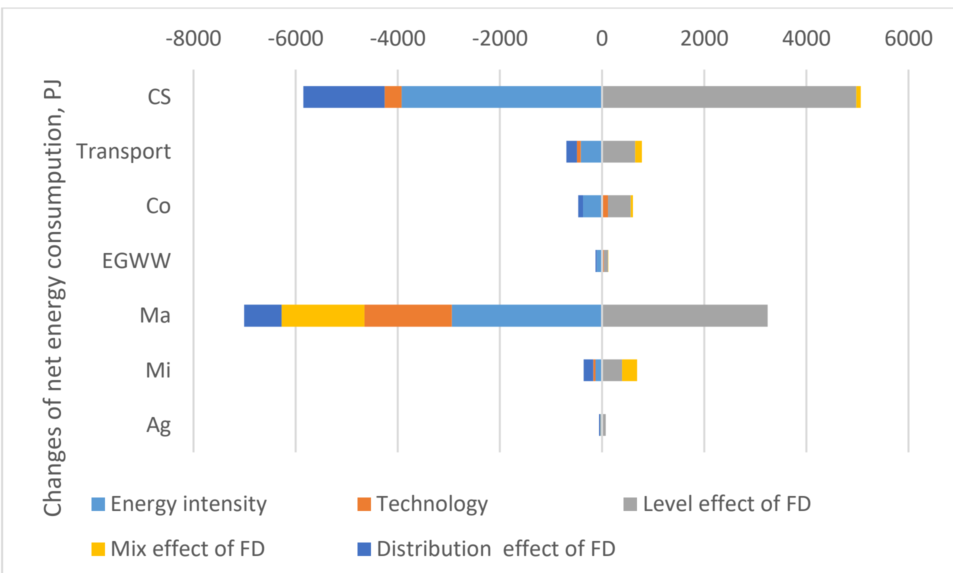
As the major effect of change of Australian net energy consumption, the effect of Final demand was further decomposed into five sub-effects based on Eq. 16. Figure 7 is a graphical representation of the SDA results by five sub-effects from 2004–05 to 2014–15. It shows that the Households consumption in the level effect of Final demand is the major cause for the growth of net energy consumption in Final demand, which has led to the increase of net energy consumption more than 3000 PJ, followed by that to the gross fixed capital formation (about 1400 PJ), the Exports (about 1300 PJ), and that to the government consumption (about 1100 PJ). The mix effect of Final demand to the Household consumption, the gross fixed capital formation, the change in inventory, and the Exports contributed to the decrease of net energy consumption, which are about 175 PJ, about 169 PJ, about 195 PJ, and about 306 PJ, respectively. The Change in inventory mainly contributed to a decrease of net energy consumption during the period, but its effect is too minor to offset the effects of other categories of Final demand on the increase of net energy consumption.



(a) Changes of net energy consumption at the Australian sector level from 2004–05 to 2009–10, PJ.



(b) Changes of net energy consumption at the Australian sector level from 2009–10 to 2014–15, PJ.



(c) Changes of net energy consumption at the Australian sector level from 2004–05 to 2014–15, PJ.

Fig. 8. Comparisons of changes in Australian net energy consumption at the sector level.

The SDA results of the decomposition at the sector level in Figure 8 show the changes of net energy consumption in seven industrial sectors due to energy intensity, technology effect, level effect of Final demand, mix effect of Final demand, and distribution effect of Final demand. Analysis in Figure 8 shows that during each period for every industrial sector, the level effect of Final demand was the major driving force on the increase of net energy consumption. The effect of the energy intensity changes reduced net energy consumption for most industrial sectors on the net energy consumption with the exception of the Mining sector from 2009–10 to 2014–15 and from 2004–05 to 2014–15. The energy intensity changes have a major effect on the reduction of energy consumption for the Commercial and Services sector and the Manufacturing sector, which offsets part of the increasing net energy consumption caused by the level effect of Final demand from 2004–05 to 2014–15. The technology effect had the largest effect for the reduction of net energy on consumption in the Manufacturing sector in these three periods. It benefits the reduction of net energy consumption for all industrial sector except for the Construction sector from 2004–05 to 2014–15. Although the mix effect resulted in the significance decrease of net energy consumption for the Manufacturing sector from 2004–05 to 2014–15, it has minor effects on the change of net energy consumption in other industrial sectors. The distribution effect of Final demand led to the decrease of net energy consumption in all industrial sectors from 2004–05 to 2009–10 and from 2004–05 to 2014–15.

3.3 Analysis of forward and backward linkages for net energy consumption

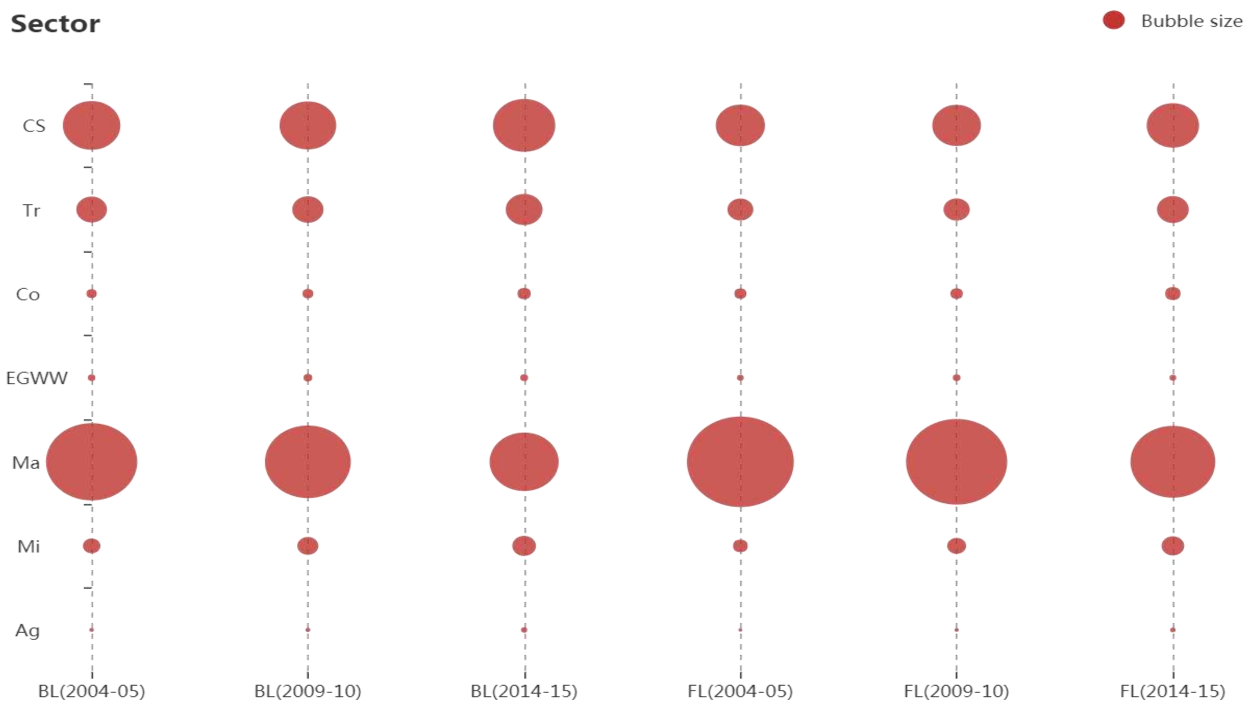


Fig. 9. Normalised backward linkage (BL) and forward linkage (FL) of net energy consumption in Australian industrial sectors in different periods.

The analysis of forward linkage or backward linkage for net energy consumption aims at describing which sector has the capacity to consume more energy than other sectors with the change of per AUD dollar in the primary input or the change of per AUD dollar in the Final demand, respectively. Figure 9 shows the normalised BL and FL of net energy consumption in Australian industrial sectors in different periods. The bubble size in the top right corner represents the standard size of bubble with “1" . In Section 2.3, the “1" indicates that an increase of one AUD dollar in the input of an industrial sector i will result in an average increase of net energy consumption. If the bubble size of an industrial sector is more than the standard size bubble size of “1" , it means the industrial sector has an above-average increase of net energy consumption with the change of per AUD dollar in the primary input or in the Final demand. A total of three industrial sectors, including the Manufacturing sector, the Commercial and Services sector, and the Transport sector have been identified as important industrial sectors of net energy consumption in the three periods. The Manufacturing sector has the biggest capacity to consume energy with the change per AUD dollar in the primary input and the Final demand because it is about three times more than the standard size, followed by the Commercial and Services sector (about two times) and the Transport sector (about one time). The smallest capacity of consuming energy is the Agriculture, forestry, and fishing sector. As the most important industrial sectors, the BL and FL of the Manufacturing sector have shown a decrease trend during the period from 2004–05 to 2014–15.

4 Discussion

4.1 Characteristics of EEIO analysis for Australian net energy consumption

The three-year EEIO tables for Australian net energy consumption not only indicated the relationships between Australian economic activities and net energy consumption, but enabled a comparative analysis of net energy consumption in different industrial sectors and different types of Final demand during the period.

As one of the developed countries, the Australian net energy consumption has kept a stable increasing trend from 2004–05 to 2014–15. However, the share of the major industrial sectors (the Manufacturing sector, the Transport sector, and the Mining sector) for energy consumption has slightly decreased. It indicates that the application of clean technologies in these three sectors enables the drop of energy consumption. For example, Australian manufacturers have achieved the major improvement for the energy consumption through fuel shifting from gas to solar thermal, replacement of old equipment with more efficient equipment and smart design to improve industrial process [65].

Although the total amount of net energy consumption in Australian industrial sectors increased, the direct and indirect effects of net energy consumption in industrial sectors have experienced a decreasing trend. It means that the amount of net energy consumption caused by the output per million Australian dollars decreased. As the largest industrial sector for energy consumption, the direct net energy consumption of the Transport sector dropped dramatically from 2004–05 to 2014–15. It is attributed to a range of rules and support from the Australian Government to reduce the fuel consumption including Australian Design Rules, Green Vehicle Guide, and Fuel Consumption Label [70]. At the same period, other countries have also published similar rules to lower the energy consumption in the Transport sector, such as Fuel Efficiency Standards in China [72], and Fuel Economy Rules for automobiles in the United States [73].

Decreasing indirect energy consumption for industrial sectors means that productive processes have changed to be much simpler, with short supply chain (with less energy consumed in the supply chain from the Mining sector over the Manufacturing sector to the other industrial sectors). The Manufacturing sector, the Construction sector, and the Transport sector had the major indirect net energy consumption, which indicates that the development of industrialization level for Australian Manufacturing, Construction sector, Transport sectors simplifies and shorten the supply chain, which lowers the energy consumption. For example, the improvement of the supply chain for food transport lowers the energy consumption in the Transport sector [80]. In addition, with the support of the Australian energy policies, programs, and practices, such as Energy Efficiency Opportunities Act 2006 [18], Commercial Building Disclosure (CBD) Program [15], and Energy Efficiency Information Grants [21], these sectors have enhanced the energy efficiency to lower the energy consumption.

The Export sector of Australia consuming the most amount of energy in the four types of Final demand experienced an increase from 2004–05 to 2014–15. It is noteworthy that it has been stated that the pattern of Australian energy consumption belongs to an export-oriented energy consumption, and the amount of energy consumption by the Export sector had increased during the period [16]. The Household consumption had the highest embodied net energy consumption, which plays a significant role in causing net energy consumption of industrial sectors, particularly the Commercial and Services sector.

The consumption of Australian net energy had experienced a decrease from 2009–10 to 2014–15 for direct and indirect effects of energy consumption for most industrial sectors (Figures 2 and 3). This could indicate that the Australian domestic net energy consumption has been influenced by the 2008 financial crisis, though further examination is needed with more detailed datasets.

4.2 Characteristics of the SDA for Australian net energy consumption

The SDA results show that the Australia net energy intensity change in the period have shown the effect of net energy intensity has resulted in a reduction of net energy consumption from 2004–05 to 2014–15. The net energy intensity in this period has a similar effect for the change of net energy consumption with other periods discussed by earlier studies, such as the period from 1973–74 to 2000–01[49], the period of 1978–1986 [56], and the period of 1978–2009 [43] for the trend of Australian energy intensity. The effect of energy intensity on the change of energy consumption are conformed to studies for other countries, such as the case of China [61], Italy [19], and Japan [30].

On the contrary, the growth of net energy consumption was brought about mostly by the level effect of Final Demand, which indicates that activities in each industrial sector to the Final demand is the major cause for the increase of energy consumption. This shows the important connection between the economic growth and the change of energy consumption in Australia [50]. Changes in consumption and income of households have important impacts on the level effect. The growth of Australian net energy consumption during the period from 2004–05 to 2014–15 is dominated by the Household Consumption. This was a period of the huge increase of household expenditure per week, which has increased by about 60% from 892.23 AUD dollar in 2003–04 to 1425.03 AUD dollar in 2015–16 [9].

The technology effect helps the reduction of net energy consumption from 2004–05 to 2014–15. It is another major cause for the drop of Australian net energy consumption in most of industrial sectors, such as the Manufacturing sector and the Commercial and Services sector. It can be explained by noting that the inputs for the product in these two sectors are substituted by less energy-intensive inputs. For example, the Commercial and Services sector offers the services, such as electricity for cooling and heating, to consumers. With the development of the technology (solar air conditioners) and the publishing of regulations such as the Regulation Impact Statement [68] for air conditioners, the energy consumption of air conditioners from the Commercial and Services sector becomes lower.

A further decomposition performed on the industrial sectoral level shows that, while the level effect of Final demand resulted in the growth of net energy consumption in all industrial sectors, the energy intensity limited this increase. It indicates that the best way to lower the Australian energy consumption is to apply much cleaner technologies in industrial sectors to offset the impact of the level effect of Final demand. There is a huge potential for the application of cleaner production in the Mining sector to reduce the energy consumption because the energy intensity has major effects on the reduction of net energy consumption in the Mining sector. For example, the application of large scale rock-pit seasonal thermal energy storage in underground mine ventilation can result in the energy savings of 10.9 GW h per year for heating system and 10.1 GW h per year for cooling system [23].

4.3 Characteristics of forward and backward linkages for net energy consumption

The three industrial sectors - the Manufacturing sector, the Commercial and Services sector, and the Transport sector - can play significant roles in benefiting Australia to lower the level of net energy consumption because they consume more energy than the average level of energy consumption occurring in other industrial sectors. It means that if there are relatively small changes in the primary input and in the Final demand, the amount of the net energy consumption in the Australian economy can be affected in a major way. For example, if people reduce per dollar consumption in each sector, the amount of net energy consumption in the Manufacturing sector has the largest decrease.

5 Conclusions and policy implications

The novel contributions of the research are the alignment of economic and energy data sets, the application of EEIO model, the implementation of the additive SDA method, and the use of forward and backward linkages. The research applies the EEIO model to analyse the Australian net energy consumption from the perspectives of industrial sectors and Final demand, uses the SDA method to investigate the drivers of the changes of net energy consumption, and identifies the potential of each industrial sector for the reduction of net energy consumption via small changes in economic activity by forward and backward linkages from 2004–05 to 2014–15. The results emerging from these methods yield insights about relationships between Australian net energy consumption and economic activities, the importance of drivers for net energy consumption, and the comparative analysis of the potential of each industrial sector.

The aggregated EEIO model shows that the Transport sector and the Exports sector take charge of the major direct net energy consumption from the industrial sectors and Final demand, respectively. The EEIO model for Australian energy consumption also reveals that the surprising result of the highest embodied (indirect) energy consumption has been found in the Household consumption.

The SDA method has been applied to analyse the effects of drivers on the Australian net energy consumption. It is clear that, although the effects of energy intensities on the reduction of net energy consumption cannot totally offset the growth of net energy consumption caused by the level effect of Final demand, the Australian government's efforts for energy intensity have been proven to be effective on the reduction of net energy consumption. To be more precise, energy intensity has played the important role in the reduction of energy consumption in the Manufacturing sector and the Commercial and Services sector, but there are minor effects on other industrial sectors. Therefore, the Australian government should continue to support the application of cleaner production that lowers the energy consumption.

The analysis of the forward and backward linkages has help this research identify the key industrial sectors for Australia energy consumption during the period. The Australian government should pay more attention on these industrial sectors. It is evident that lowering the amount of input and Final demand of these industrial sectors could be an effective strategy for the reduction of Australian net energy consumption.

As revealed in this study, the EEIO analysis, the SDA method, and the forward and backward linkages have been shown to be effective and useful to understand the relationships between economic activities and environmental issues in Australia. It is advised that when the IO tables and energy accounts are available for more countries, there is an important study to conduct a systematic analysis of EEIO, identify and assess the drivers for environmental issues, and the forward and backward linkages for environmental impacts globally.

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