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Understanding energy systems change in Canada: 1. Decomposition of total energy intensity

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ABSTRACT

Between 1995 and 2010, the total energy intensity (E/GDP, PJ/Gross Domestic Product in 2002$) of the Canadian economy declined by 23% or −2.64 MJ/$. To understand why, the Logarithmic Mean Divisia Index (LMD-I) method was used to decompose a large body of government statistical data supporting the observed E/GDP decline. The analysis shows that (a) 48% (1.27 MJ/$) of the decline was associated with an inter-sector structural change in the economy (i.e. an increased contribution to the total GDP of the low energy-using commercial and institutional sector compared with the high energy-using manufacturing and heavy industry sectors); (b) 24% (0.62 MJ/$) was attributed to the impact of the Canadian GDP growing faster than population; (c) 22% (0.58 MJ/$) of the decline was associated with an overall decrease in business energy intensity. A deeper analysis of business sectors shows a positive impact of 0.4 MJ/$ from increased energy intensity in the oil and gas sector, offset by a 0.98 MJ/$ decline due to energy intensity declines in the other business sectors; (d) 6.3% (0.17 MJ/$) of the decline was associated with an improvement in the energy intensity of households, mostly from residential energy use rather than personal transportation energy use. These results provide insights for policy makers regarding those aspects of the Canadian economy that contribute to, or work against, efforts to transform energy systems toward sustainability.

1. Introduction

Canada's per capita greenhouse gas (GHG) emissions are amongst the highest in the world, and more than 80% of these emissions are linked to energy (E, synonymous with fuel and electricity in this document) production and use. Developing strategies to transform Canada's energy systems by reducing demand, improving efficiency or changing the source of fuel and electricity to lower GHG emissions would benefit from a detailed understanding of the trends and drivers that have defined past energy use.

When historical data for Canada (1981 to 2010) are used to calculate the Kaya factors (Kaya and Yokobori, 1993), the results (Fig. 1) reveal continuous growth in population (P) and per capita GDP, stable carbon intensity (GHG/E), but significant decline in the total energy intensity of the economy (E/GDP), particularly from the mid-1990's onward (Fig. 1B).

To put these changes in energy intensity within an international context we note that in 1995, Canada's total E/GDP ratio was about twice than that of European countries (OECD/IEA, 2011) and over the next 15 years, it declined by 24% or −2.64 MJ/$. In comparison, the total E/GDP of European countries declined by 18%, so the energy intensity of the Canadian economy in 2010 was still 1.9 times higher than in Europe (OECD/IEA, 2011).

To decompose Canada's total E/GDP change over the 1995–2010 period, the Logarithmic Mean Divisia Index–I (LMDI-I) method of Ang (2004) was applied to the database resource embedded in the Canadian Energy System Simulator (CanESS V6) model from whatIf? Technologies Inc., Ottawa. Index decomposition analysis was first developed by Divisia (1925) for application in economics and later adapted to energy analysis by Boyd et al. (1988). Early methods utilized arithmetic means and produced imperfect factorization and problematic second order residual terms with unclear physical meaning. The introduction of a logarithmic mean approach by Ang and Choi (1997) provided a method for decomposition to produce perfect factorization of energy trends, and LMDI-I is now the preferred approach for decomposition analysis of structural, efficiency and activity trends in energy and energy intensity analyses (Ang and Zhang, 2000; Ang and Liu, 2001; Ang, 2004; Ang et al., 2010).

A sizeable literature now exists in this field (see Su and Ang, 2012), focused on industrial energy use, including studies based on Canadian data (Torrie et al., 1989; Gardner, 1993; Nanduri et al., 2002; Palmer,

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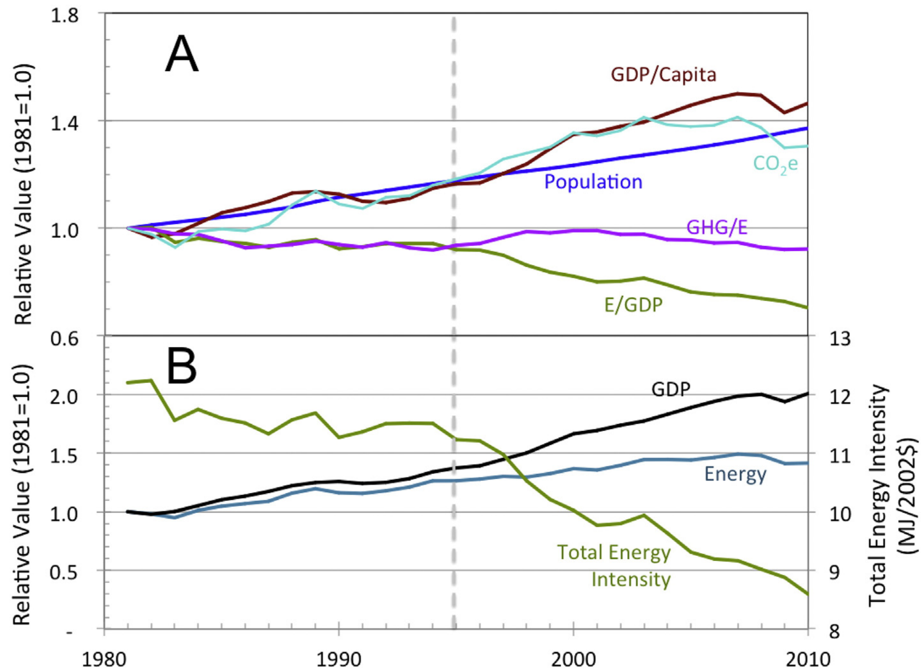

Fig. 1. A. Changes in Kaya factors for energy-based emissions in Canada, 1981–2010 where CO_2e [Mg] = Population [capita] × GDP/Population [\$/capita] × Energy use/GDP [GJ/\$] × GHG/Energy use [$MgCO_2e$/GJ]. B. The decoupling of GDP and energy growth after 1995.

2003; Bataille and Nyboer, 2005; Steenhoff and Weber, 2011; De Cian et al., 2013; Ang and Xu, 2013). The majority of these studies focus only on changes in energy use within the business sectors of the economy.

This work differs from previous decomposition analyses of Canadian energy use by (a) including all primary and secondary fuel and electricity use from both the business and household economies; (b) conducting separate decomposition analyses for the business economy energy use (on a per GDP basis) and the household economy energy use (on a per capita basis, linked to the comprehensive analysis by GDP/capita); (c) applying the decomposition analysis to the total Δ(E/GDP) values rather than changes in energy use, and (d) generating a one-to-one correspondence between GDP and E values that produces decomposition factors which sum exactly to the total Δ(E/GDP). The goal was to generate a comprehensive and internally-consistent factorization of the Δ(E/GDP) for the Canadian economy over the 1995–2010 period.

2. Methodology

2.1. Data sources

The population, economic (GDP) and energy data used for this analysis are from CANSIM (2015), the main socio-economic statistical database maintained by the Government of Canada. CANSIM employs the North American Industry Classification System (NAICS) that facilitates the pairing of energy and economic data sets. For GDP and population data, CANSIM was accessed directly, but for the energy data we rely on the Canadian Energy Systems Simulator (CanESS, Version 6.0) from whatIf? Technologies Inc. (Ottawa, ON). CanESS uses CANSIM energy data to develop a detailed, historical calibration of Canadian fuel and electricity production and consumption by province, fuel source and sector. CanESS also draws on specialized information from various sources for energy consumption by sub-sector and end-use. For the industrial sectors, we also make use of the CIEEDAC Database on Energy, Production and Intensity Indicators for Canadian Industry (CIEEDAC, 2015).

2.2. Sectoral classification of E and GDP data

For these calculations, a data set is required that contains annual data for 1995 to 2010 for energy use by each of the business economy as well as for the household economy. To achieve this comprehensive coverage, total energy use (E) is separated into that portion directly associated with producing the goods and services that comprise GDP (i.e. the business economy, E_B) and that portion associated with residential and personal transportation (i.e. the household economy, E_H) such that:

$$E = E_B + E_H \tag{1}$$

$$\text{with } E_B = \sum_i E_i \tag{2}$$

$$\text{and } E_H = E_{Res} + E_{PT} \tag{3}$$

where;

i is an index representing sectors of the business economy (defined in Table 1),
E_{Res} is residential fuel and electricity consumption, and
E_{PT} is personal transportation energy consumption.

As shown in Table 1A, the sector definitions for the business economy reflect well-defined industries (e.g. oil and gas, electric power) or a group of activities with similar E/GDP ratios (e.g. energy intensive industry, commercial and institutional buildings). The sector definitions also allow a one-to-one mapping of national energy and economic databases at the level of the six defined sectors so that individual sector E_i/GDP_i values can be calculated for each year over the study period.

The result is a partitioning of total E/GDP for Canada into two additive components that form the basis for our decompositional analysis:

$$\frac{E_B}{GDP} = \sum_i \left[\frac{GDP_i}{GDP} \times \frac{E_i}{GDP_i}\right] = \sum_i S_i I_i \tag{4}$$

Table 1
Definitions of sectors for E/GDP decomposition analysis.

i	Sector	Description
A. Business economy sectors		
OG	Oil and gas industry	Oil and gas extraction, refineries and pipelines. Production included conventional oil, synthetic crude, bitumen, natural gas and refined petroleum products
PG	Power generation	Electricity production from all sources
EII	Energy intensive industry	Mining, aluminum smelting, steel making, primary metals smelting, cement making, pulp and paper and energy intensive chemical production (NAICS codes 3251, 3252 & 3253 while all other chemical Industry production was included in i = 4)
MOI	Manufacturing and other industry	All manufacturing not elsewhere classified, plus agriculture, fishing, forestry, and construction
CI	Commercial and institutional	Including offices, retail, education, hospitals, warehouses, water and sewage utilities, other building types
FT	Freight transportation	Truck, rail, air, marine (pipelines are included with oil and gas industry)
B. Household economy sectors		
Res	Residential	Single family detached, attached, apartments, other
PT	Personal transportation	Car, truck, air, rail, public transit, other modes, non-motorized

$$\text{and } \frac{E_H}{GDP} = \frac{E_H/\text{capita}}{GDP/\text{capita}} \tag{5}$$

where

$S_i = \frac{GDP_i}{GDP}$ and is the structural factor (the share of GDP generated by sector i)
$I_i = \frac{E_i}{GDP_i}$ and is the intensity factor (the energy use per dollar of value added in sector i)
and $GDP = \sum_i GDP_i$.

Note that in Eq. (5) GDP/capita provides the link between total GDP and the energy intensity of the household economy, which is analyzed on a per capita basis. This methodological innovation fulfills our objective of producing a comprehensive and integrated analysis of Δ(E/GDP) total energy intensity on a per GDP basis, while at the same time facilitating the decomposition analysis of E_H to be performed on a per capita basis.

2.3. LMDI-I factorization of Δ(E/GDP)

The decompositional analysis of Δ(E/GDP) over time was conducted through the application of the Logarithmic Mean Divisia Index (LMDI-I) method as developed and refined by Ang and his colleagues (Ang and Liu, 2001; Ang, 2004, 2005; Su and Ang, 2012). Application of the LMDI method to Eqs. (4) and (5) produces the following four factors that sum exactly to the total change in energy intensity, Δ(E/GDP), over the study period defined by the start (T_1) and end (T_2) dates. These equations were applied to sector data for the study period, using annual chained analysis.

A. The inter-sector structural change resulted from the change in the relative contributions to total GDP of the defined sectors of the business economy. Since business sectors vary greatly in the energy intensity (MJ/$) of their operations, changes in the structure of the economy can have an impact on the total E/GDP.

$$\Delta\left(\frac{E}{GDP}\right)_{\text{inter-sector structural change}} = \sum_i L\left((E_i/GDP)^{T_2}, (E_i/GDP)^{T_1}\right) \ln\left(\frac{S_i^{T_2}}{S_i^{T_1}}\right) \tag{6}$$

B. Per capita GDP impact. This factor results from the partition of total energy into a component directly associated with the production of GDP, E_B, and a component comprised of residential and personal transportation energy use, E_H. The ratio E_H/GDP is defined as a compound fraction (Eq. (5)), with GDP/capita as the denominator. This allows the intensities to be identified on a per capita basis – E_r/capita and E_t/capita – while at the same time allowing the analysis to be integrated within our overall Δ(E/GDP) framework. This is variation on a method used by Ang and Liu (2001) to factor E/GDP, and when E_H/GDP is factored in this way, changes in per capita GDP will contribute to Δ(E/GDP) according to:

$$\Delta\left(\frac{E}{GDP}\right)_{\text{per capita GDP impact}} = L\left((E_H/GDP)^{T_2}, (E_H/GDP)^{T_1}\right) \ln\left(\frac{\left(GDP/\text{capita}\right)^{T_1}}{\left(GDP/\text{capita}\right)^{T_2}}\right) \tag{7}$$

The impact of changes in GDP.capita on Δ(E/GDP) is the result of the factoring of E_H/GDP in Eq. (5) and is independent of any influence that changes in per capita GDP may have on per capita use of fuel and electricity in the household sector (which we capture in our analysis of E_H/capita) or on the energy embodied in the goods and services purchased by households (which we capture in our analysis of E_B, and in particular in the analysis of the effect on E_B of inter-sectoral shifts in GDP).

C. Business energy intensity impacts result from the cumulative impact of changes in the energy intensity of each sector ($I_i = E_i/GDP_i$) on the total Δ(E/GDP) of Canada.

$$\Delta\left(\frac{E}{GDP}\right)_{\text{business energy intensity}} = \sum_i L\left((E_i/GDP)^{T_2}, (E_i/GDP)^{T_2}\right) \ln\left(\frac{I_i^{T_2}}{I_i^{T_1}}\right) \tag{8}$$

D. Household energy intensity impacts result from the cumulative impact of changes in per capita residential and personal transportation energy use (i.e. household energy use, E_H) on the total Δ(E/GDP) of Canada:

$$\Delta\left(\frac{E}{GDP}\right)_{\text{per capita intensity}} = L\left((E_H/GDP)^{T_2}, (E_H/GDP)^{T_1}\right) \ln\left(\frac{\left(E_H/\text{capita}\right)^{T_2}}{\left(E_H/\text{capita}\right)^{T_1}}\right). \tag{9}$$

For Eqs. (6) to (9), L(a,b) is the logarithmic mean of two numbers, a and b, calculated as:

$$L(a,b) = \frac{a-b}{\ln(a/b)}, \text{ for } a \neq b \tag{10}$$

$$\text{and } L(a,b) = 0 \text{ when } a = b. \tag{11}$$

2.4. Assessing variability in trends over the study period

The decomposition of Δ(E/GDP) was carried out with data that covered the entire 15 year study period. However, to assess whether the observed differences in the overall observed trend were consistent throughout the study period, decomposition analysis was carried out for an additional 9 different study periods, each representing 12 to 14 years. For each study period, Δ(E/GDP) values were expressed per year, and then all 10 study periods were averaged to calculate the mean, standard error (SE = Standard Deviation / $\sqrt{n}$) and the SE as a percent of the mean (%SE) for each parameter for all 10 study periods. In presenting the results, a triple asterisk (***) indicates a %SE value of ≤5%, a double asterisk (**) denotes a %SE of ≤10%, and a single asterisk, a %SE of ≤15%.

3. Results and discussion

Over the 1995–2010 period, the E/GDP ratio for Canada declined by 2.64 MJ/$, or 23.5%, from 11.24 MJ/$ to 8.60 MJ/$ (Fig. 1B) in units of constant 2002 dollars. Compared to the other Kaya factors, the decline in E/GDP was the largest moderating factor in the growth of GHG emissions in Canada.

To understand the factors leading to this change, Eqs. (6) through (9) were applied to the data, resulting in a disaggregation of total Δ(E/GDP) into the four factors illustrated in Fig. 2. The contribution of the household sector to total Δ(E/GDP) is the sum of the contribution from the change in per capita household energy intensity and the impact of GDP/capita (−0.17–0.62 = −0.79 MJ/2002$), as compared to the contribution from the business economy, which is the sum of the impacts of the changes in inter-sectoral composition and the changes in the business sector energy intensities (−1.27–0.58 = −1.85 MJ/2002$).

3.1. Inter-sector structural change

Changes in sectoral composition of the business economy contributed 1.27 MJ/$ to the E/GDP decline over the 1995–2010 period, fully 48% of the net total decline of 2.64 MJ/$ (Fig. 2). For the six aggregate sectors defined for this analysis, sectoral energy intensity (E_i/GDP_i) in 2010 varied from a low of 1.3 MJ/$ in the commercial and institutional sector to 35–45 MJ/$ for the oil and gas and energy intensive industrial sectors, to more than 60 MJ/$ for power generation (Fig. 3A). With such large variations in sectoral energy intensities, shifts over time in the composition of the GDP in Canada (Fig. 3B) have a significant impact on the total energy intensity of the nation's GDP.

For example, the GDP share of the relatively low energy intensity commercial and institutional sector increased from 62% to 68%, and there was a corresponding decline in the share of GDP held by the more energy intensive sectors such as oil and gas, power generation, and some other industries (Fig. 3).

3.2. Per capita GDP change

The independent contribution of GDP/capita to Δ(E/GDP) results from the representation of E_H/GDP in Eq. (5) as [(E_H/capita)/(GDP/capita)]. Between 1995 and 2010, GDP/capita increased by 26%, from $28,800 to $36,200 (data not shown), contributing, through the link to E_H/GDP, 23.5% or 0.62 MJ/$ of total Δ(E/GDP), as calculated using Eq. (7) and as shown in Fig. 2.

In Canada, as in other rich, industrial countries, energy for residential and personal vehicle use is highly saturated and tends to grow primarily with population rather than GDP. Therefore, increases in GDP per capita will have the effect of reducing the contribution of personal energy use to the total E/GDP, all else being equal.

Together, the inter-sectoral structural change and the per capita GDP change accounted for 71% of the 2.63 MJ/2002$ decline in total E/GDP over the 1995–2010 period (Fig. 2).

3.3. Business energy intensity

The increase in the Canadian GDP between 1995 and 2010 was accompanied by a decrease in the overall energy intensity (MJ/$GDP) of the business sectors that produced the economic output. As shown in Fig. 2, sectoral intensity changes in the business economy contributed 22% (0.58 MJ/$) to the overall decline in the total energy intensity of the Canadian economy.

These results were further disaggregated using Eq. (8) to identify the contributions to total Δ(E/GDP) of the energy intensity changes in each of six business economy sectors (Fig. 4). The contributions of the changes in the individual sector intensities (Δ(E_i/GDP_i) to total Δ(E/GDP)) were weighted by the sector shares of total GDP (GDP_i/GDP), which themselves change over time. The product of the sector intensity change and the average sector GDP share over time approximates the individual sector contributions to the change in E/GDP. This is considered a reasonable approximation since for the 1995–2010 period, the sum of approximations for the individual sector intensity contributions to Δ(E/GDP) is −0.55 MJ/$, compared with the more precise aggregate intensity impact of −0.58 MJ/$, as calculated using Eq. (8).

Note that the sectoral energy intensity of the oil and gas industry increased by 7.63 MJ/$ or 27% over the study period (data not shown), and when weighted by its roughly five percent share of GDP, this translated to a positive 0.40 MJ/$ contribution to the total Δ(E/GDP) of the Canadian economy.

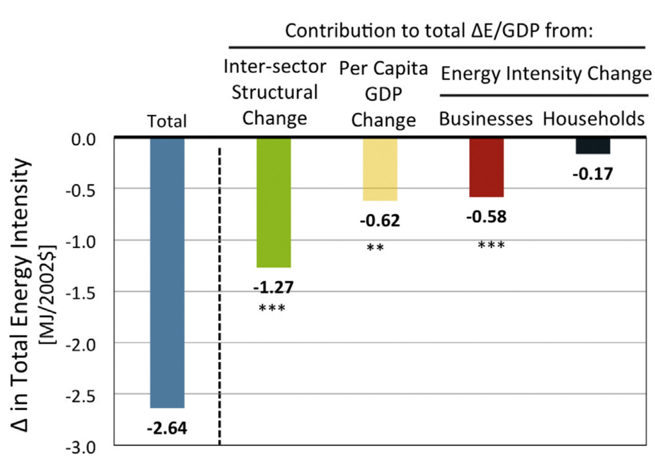

Fig. 2. The contribution of various components of the Canadian energy system to the observed change in total energy/GDP over the period 1995–2010. Energy intensity for businesses is in terms of MJ/$, while energy intensity for households is in terms of MJ/person.

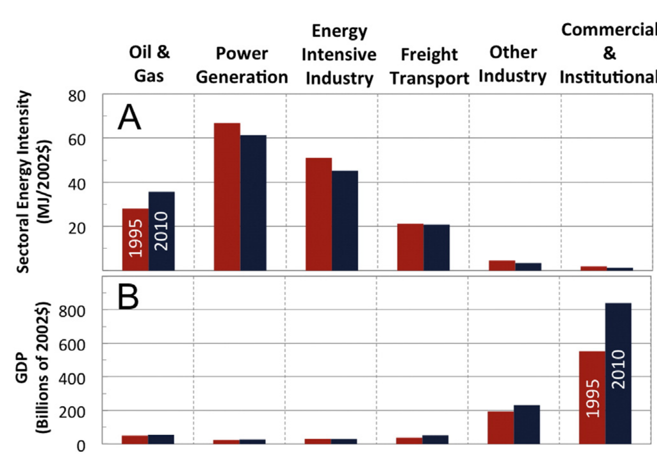

Fig. 3. Energy intensity (A) and GDP (B) associated with the business economy sectors in Canada in 1995 (red bars) and 2010 (black bars). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

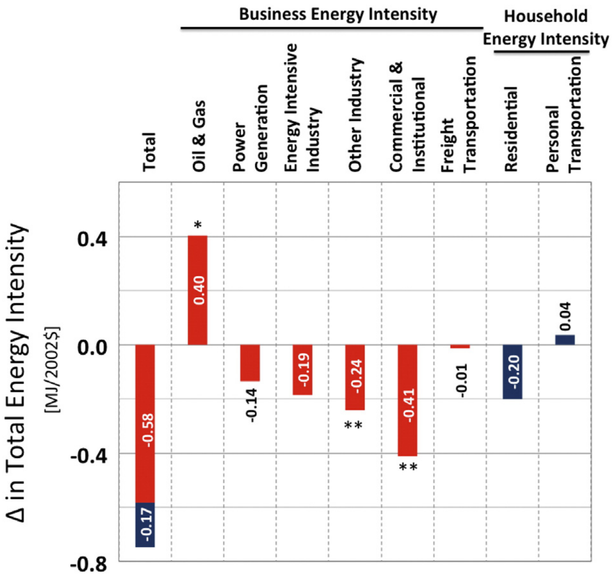

Fig. 4. Disaggregation of sectoral energy intensity contributions in the business (red bars) and household (blue bars) sectors to the total change in energy intensity of the Canadian economy, 1995–2010. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In comparison, the sectoral energy intensity of the commercial and institutional sector decreased by 0.60 MJ/$ (data not shown), but when weighted by its roughly 68% share of GDP this translated into a −0.41 MJ/$ contribution to the total Δ(E/GDP). The other sectors all exhibited a decline in energy intensity over the study period, with contributions to total Δ(E/GDP) from power generation, energy-intensive industry and other industry being −0.14 MJ/$, −0.19 MJ/$ and −0.24 MJ/$, respectively.

3.4. Household energy intensity

The change in per capita energy use of the household economy accounted for 6.3% (−0.17 MJ/$) of the total Δ(E/GDP) over the 1995–2010 period (Fig. 2), but high variance in this factor with different 12 to 15 year study periods indicates that the trends were not consistent over the 15 year study period. Further disaggregation (Fig. 4) accounts for the −17 MJ/$ as the net result of a −0.20 MJ/$ contribution from a decrease in the per capita energy intensity of residential energy use, partly offset by a small increase in per capita energy use for personal transportation.

For each business and household sector, the observed value may be the net result of two or more, sometimes counteracting influences. For example, a sector energy intensity change may be the product of a change in the physical energy intensity of production (inversed = energy efficiency) and a change in the relationship between value added (GDP) and physical activity in the sector. Ang and Xu (2013) refers to this latter term as the "physical activity intensity" or "dematerialization factor". This concept will be explored in a subsequent paper (Torrie et al., 2015).

4. Conclusions

To our knowledge, this report is the first study of its kind to deconstruct an observed trend in the total Energy/GDP ratio of an economy, including separate and additive decompositions of the energy intensity of GDP-producing business sector and the residential and personal transportation energy of the household sector. The results show that in Canada between 1995 and 2010, 71% of the decline in the total Energy/GDP ratio was attributed to structural factors, while the remaining 29% was assigned to a net improvement in the sector-specific energy intensities (E_i/GDP_i) of the business economy and the per capita energy intensity of the household economy.

By including all fuel and electricity use in the deconstruction of the total Δ(E/GDP), the relative importance of energy intensity changes in the business economy and the household sector are revealed. Residential and personal transportation energy use make up a third of total fuel and electricity use in Canada, and growth in per capita GDP over the 1995–2010 period translated directly into a decline in household energy use per dollar of GDP, sufficient to account for 23% of total Δ(E/GDP). This was independent of, and in addition to, contributions to total Δ(E/GDP) from changes in the per capita use of energy in the household sector. In economies like Canada's, where a significant portion of total energy use occurs in the household sector and is driven by population growth, the contribution of changes in per capita GDP to Δ(E/GDP) can be very important.

Structural shifts in the composition of Canada's economy were more important than business sector and household energy intensity changes in contributing to the total Δ(E/GDP) over the 1995–2010 period, and this fact has methodological implications for energy system analysis. In addition to the obvious sensitivity of energy efficiency to technological change, the relationship between economic output and fuel and electricity use (E/GDP) is sensitive to both economic structure and overall productivity growth. Further, the possibilities for energy efficiency improvement are themselves dependent on the level and pattern of underlying productivity growth and economic structure. Understanding the possible future states of the energy system requires dynamic analysis of the interactions between population and productivity growth, the composition of economic output, and the potential for technological efficiency improvement. The "single baseline" approach is inadequate to the needs of modern policy and market research.

The sensitivity of future levels of fuel and electricity use to demographic and economic composition factors also has implications for policies aimed at reducing E/GDP as a means for moderating future levels of greenhouse gas emissions. In particular, standard GHG reduction initiatives (efficiency of fuel and electricity utilization, fuel switching to carbon-free energy) should be developed and deployed within a broader context that takes into account the full range of demographic and structural factors that can and sometimes do overwhelm technological efficiency improvements in determining the overall direction of energy and greenhouse gas intensity of the society. This broader approach will yield the additional benefit of revealing opportunities for E/GDP and greenhouse gas intensity reduction that lie outside the conventional scope of climate change response policies.

Increased energy intensity of the oil and gas industry stands out as the largest single sectoral source of upward pressure on E/GDP in Canada over the 1995–2010 period. A 27% increase in the sectoral intensity of this industry translates to a 0.40 MJ/$ increase in total E/GDP, compared to the overall net decrease in total E/GDP of 2.67 MJ/$. The size and the relatively high energy intensity of the oil and gas industry have ensured that the future energy intensity of the Canadian economy will continue to be heavily influenced by the level and energy intensity of production in this industry.

Commercial and institutional energy intensity was the single largest sectoral source of downward pressure on E/GDP in Canada over the 1995–2010 period. The impact of change in the energy intensity of this sector was amplified by its large share of total GDP so that the relatively small decline of sector intensity of 0.60 MJ/$ translates into downward pressure of 0.41 MJ/$ on the total E/GDP, enough to completely offset the upward pressure from the oil and gas industry.

The contributions to total E/GDP from changes in per capita residential and personal transportation energy use over the 1995–2010 period were −0.20 MJ/$ and +0.04 MJ/$, respectively — relatively modest considering the improvements in housing and vehicle energy efficiency that are known to have occurred over this period. This begs the general question: to what extent are the per capita household intensities and the per dollar productive sector intensities identified in this analysis themselves comprised of compound and perhaps counteracting influences of energy efficiency and what might be termed "intra-sectoral structural factors" (for example, larger dwellings, changing urban form and trip making patterns, intra-sectoral shifts in product mix, and changes in the real price of outputs)?

Further decomposition analysis is required to understand the internal dynamics of the aggregate sector and household energy intensity changes identified here. This is the subject of a subsequent paper (Torrie et al., 2015).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eneco.2016.03.012.

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