How Malleable are the Greenhouse Gas Emission Intensities of the G7 Nations?

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Why do countries’ greenhouse gas (GHG) intensities differ? How much of a country’s GHG intensity is set by inflexible national circumstances, and how much may be altered by policy? These questions are common in climate change policy discourse and may influence emission reduction allocations. Despite the policy relevance of the discussion, little quantitative analysis has been done. In this paper we address these questions in the context of the G7 by applying a pair of simple quantitative methodologies: decomposition analysis and allocation of fossil fuel production emissions to end-users instead of producers. According to our analysis and available data, climate and geographic size – both inflexible national characteristics – can have a significant effect on a country’s GHG intensity. A country’s methods for producing electricity and net trade in fossil fuels are also significant, while industrial structure has little effect at the available level of data disaggregation.

1. INTRODUCTION

Interest in understanding the long-term malleability of individual countries’ greenhouse gas (GHG) emissions intensities has grown in step with the seriousness of the international commitment to reduce emissions. In particular, it is important to understand whether some countries have “national circumstances” that make reducing their GHG emissions intensity relatively harder or easier compared to other countries.1 If so, this may have ramifications for emission

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1. The term “national circumstances” is used by the United Nations Framework Convention on Climate Change to denote specific characteristics of a country that influence its GHG emissions.
reduction negotiations. In this paper, we analyze the national circumstances affecting GHG intensity for each of the Group of 7 (G7) countries in 2002; this year was chosen because it is the latest for which all necessary data was available. We base our analysis on the G7 countries because data are relatively available and they form a good basis for deriving more general conclusions: while the G7 share a similar level of income and technological sophistication, their GHG intensities vary significantly.

Figure 1 presents end-use emissions per capita per sector for each country. Emissions from land use change and forestry are included for comparison; these are most substantial in Italy and the US. Electricity production emissions are reported separately from the sectors that consume the electricity; each of the other sectors is thus allocated only its direct emissions from fossil fuel combustion and GHG emitting processes. Electricity production by source for each of the G7 countries is provided in Figure 2; France uses the least fossil fuels, followed by Canada, while they dominate the generation mix in the rest of the G7.

One of the most striking results from Figure 1 is that the two North American members of the G7, Canada and the US, have emissions per capita roughly double those of the European members and Japan. These differences are mainly in transportation, industry, electricity production, agriculture and fossil fuel production. There are also significant sectoral differences between the emissions per capita for Canada and the US, despite their general similarity. Canada’s emissions per capita for making electricity are roughly half those of the US, due
to Canada’s reliance on hydropower and nuclear energy. Canada also has much larger emissions per capita from fossil fuel production.

Figure 2. Production of Electricity by Source for the G7, 2002

![Production of Electricity by Source for the G7, 2002](source: USDOE EIA Country Fact sheets)

The G7 countries are relatively equal in terms of GDP per capita and technological sophistication; despite this, the US and Canada’s GHG intensities are significantly higher. Can this difference be reduced through policy, or are there specific national circumstances that will keep US and Canadian intensity high relative to the rest of the G7? For the purposes of this article, we define a national circumstance as a characteristic of a nation that significantly influences its GHG emissions and is not easily adjusted by government policy. For example, Canada’s cold climate causes it to expend significant energy on space heating and emit GHGs in the process. Canada’s cold climate cannot be altered by government policy, and so Canada’s climate might be considered a national circumstance affecting its GHG emissions. National circumstances may also include somewhat malleable national characteristics, such as economic structure. These are characteristics that could be altered by government policy, but only in the long term, and only at a slow rate that prevents undue harm to a country’s inhabitants compared to the benefits of GHG reductions.

We analyze five possible national circumstances, and quantitatively assess their contribution to explaining differences in per capita GHG emissions in the G7. In the discussion, we also explore the degree to which each of these national circumstances is malleable by policy. The five potential national circumstances we evaluate are:

1. Canada’s reliance on hydropower and nuclear energy.
2. Larger emissions per capita from fossil fuel production.
3. Economic structure.
4. Climate.
5. Other.

2. Because of data limitations, our analysis only includes CO₂ emissions from combustion for all sectors except fossil fuel production, for which it includes combustion and fugitive emissions. All included, this covers about 75% of total GHG emissions in the G7. Our analysis also allocates emissions associated with electricity production to the final consuming sectors.
• The effect of structure on the industrial sector. The energy intensity of industrial sectors can differ widely. Countries that produce and export more energy-intense goods would be expected to have a higher energy and GHG intensity. Given that industrial structure is unlikely to be dramatically modified by policy pressures in the short term, this national characteristic might be considered a national circumstance.

• The effect of climate on the commercial and residential sectors. Colder countries have higher space heating requirements, which is the largest component of energy use in the residential and commercial sectors. Consequently, colder countries should have higher energy use and CO₂ emissions compared to countries with more moderate climates. We wished to include space cooling in this analysis, but there was insufficient data for all the G7 countries.

• The effect of population distribution on the passenger and freight transportation sectors. In larger countries and those where the population is more broadly dispersed, transportation energy requirements and CO₂ emissions may be higher.

• The effect of imports and exports of fossil fuels. Production of coal, oil, and natural gas is energy and GHG intensive. Countries that are net exporters are likely to have relatively higher emissions than those that are net importers. Ideally, we would consider trade in all products, or at least a subset that included the most GHG intense products; we found adequate data only for trade in fossil fuels.

• The effect of access to low GHG electricity. In the future, renewable power from direct solar, wind and ocean energy may provide significant amounts of electricity, but low GHG electricity has historically come in two forms, hydropower and nuclear energy. Hydropower necessitates specific hydro-geographical conditions, while nuclear energy necessitates a significant policy commitment with a long lead-time. Access to low GHG electricity might be considered a national circumstance because it is either a function of geography, or it is not easily malleable in the short term.

2. PREVIOUS LITERATURE

To date, very few studies have compared the GHG intensity of countries using quantitative methods. Schipper et al. (2001) present perhaps the most intensive and relevant international comparison to date. Using a method they describe as “Mine/Yours” analysis, they begin with a standard mathematical identity, where GHG emissions are the product of activity, structure, sectoral energy intensity and the carbon intensity of a sector’s fuel mix, to describe GHG emissions in each end-use sector in each country in their data set. They then substitute the average characteristics of all other countries in the data set in place of those of the country

3. While space cooling is a significant consumer of energy in the residential and commercial sectors, current energy consumption for this end-use is a magnitude less than space heating in most countries. Its use is growing, however, and while we desired to include it, the necessary data was not available for France, Germany, the UK and Italy. Were the data to become available, inclusion of this end-use would allow a significant improvement to this work.
being analyzed; this allows them to compare how individual characteristics of end-use sectors in each country differ from the data set average, and what influence this has on the emissions of each country. They found that per capita activity levels, particularly in the transportation and service sectors, electricity production GHG intensity, and energy intensity were the components that most differentiated international GHG intensity. Schipper et al.’s study noted limitations with their “Mine/Yours” methodology. Most importantly, it does not account for interactions between different terms. As a result, it cannot be used to make conclusions about why total GHG emissions differ between two countries, since there will be significant unexplained errors or residuals.

There are, however, several methods available to decompose changes within an identity such as that used in Schipper et al. that account for interactions between the terms (e.g., the Paasche, Laspreyes, Refined Laspreyes, Simple Average Divisia, Arithmetic Mean Divisia, Adaptive Weighting Divisia, Fisher Ideal, and LMDI methods). While these methods are more typically used to explain why a country’s energy emissions change over time, cross-country data can be used in place of time-series data to understand why emissions differ between countries at a single point in time. Perhaps the most robust and easy to use method is a recent advance called the Logarithmic Mean Divisia Index I (LMDI I), which has the additional advantage of being residual free (Ang, 2005; Ang, 2004; Ang and Liu, 2001). Zhang and Ang (2001) also provide evidence that the LMDI I method is superior to other methods for cross-country decompositions.

To date the LMDI I technique has only been used twice for cross-country decomposition studies of CO₂ emissions (Lee and Oh, 2005; Zhang and Ang, 2001). Lee and Oh decomposed the difference in CO₂ emissions between the APEC countries into the following effects: population, per capita GDP, energy intensity, share of fossil fuels in total energy consumption effect, and CO₂ emissions per unit of fossil fuel used. By analyzing total primary energy consumption rather than end-use consumption at a sectoral level, they found per capita GDP and population to be the most important factors influencing total CO₂ emissions. Zhang and Ang compared differences in CO₂ emissions between three world regions (OECD countries, former Soviet Union countries, and Rest of World), using a similar methodology to that used by Lee and Oh. They also found per capita GDP to be an important factor in explaining differences in CO₂ emissions intensity between countries. However, the results from both papers provide little explanatory power and have limited usefulness in setting future country-specific targets because they both used highly aggregated data, incorporated no data at the end-use level, and focused on world regions rather than specific countries.

4. Ang, 2004 and 2005; Ang and Liu, 2001; Ang and Zhang, 2000; Ang et al., 2004; Boyd and Roop, 2004; Cornillie and Fankhauser, 2004; Diewart, 1978; Greening et al., 1997; Krackeler et al., 1999; Liu and Ang, 2003; Nanduri, 1998; Nanduri et al., 2002; OEE, 2004; Padfield, 2001; Schipper et al., 1996; Schipper et al., 1997; Schipper and Marie-Lilliu, 1999; Schipper et al., 2001a; Schipper et al., 2001b; Sun, 1998; Unander et al., 2000; USDOE, 2004.

5. The Fisher Ideal index is also residual free, but is not as easy to use as the LMDI I.
This paper builds on the subject literature in several directions. We bring together the data intensive end-use level analysis of Schipper et al. (2001) together with the residual-free LMDI I decomposition technique used by Lee and Oh (2005) and Zhang and Ang (2001). We extend the methodology to incorporate climate effects in the decomposition analysis, based on methods used by Natural Resources Canada (OEE, 2004), and extend this technique to calculate the effects of population density on a country’s GHG intensity. Finally, by allocating fossil fuel production emissions to the country in which the fuel is consumed, we provide an explicit method for analyzing the effects of fossil fuel trade on GHG intensity.

3. METHODS AND DATA

3.1. Decomposition Methodology

Our decomposition analysis starts with an identity that accounts for seven factors that influence CO₂ emissions from fossil fuel consumption (Equation 1). It is adapted from Ang (2005) and OEE (2004), the latter of which introduces a climate term to the basic identity. We have further extended it to include the effect of population density on the personal transportation emissions.

\[
\frac{C}{Pop} = \sum_{ij} \left( \frac{Act\_G}{Pop} \cdot \frac{Act_i}{Act} \cdot \frac{E_{i,-W}}{E_i} \cdot \frac{E_{ij}}{E_{ij}} \cdot \frac{C_{ij}}{E_{ij}} \cdot \frac{E_i}{E_{i,-W}} \cdot \frac{Act}{Act\_G} \right) 
\equiv \sum_{ij} (A \cdot S_i \cdot I_i \cdot F_{ij} \cdot U_{ij} \cdot W \cdot G) 
\]

Where \( i \) indexes sub-sectors, \( j \) indexes fuel types, and:
- \( C = \) CO₂ emissions
- \( Pop = \) Population
- \( Act = \) Activity or sector output
- \( Act\_G = \) Activity or sector output corrected for geography (used only in personal transportation; the term disappears for other sectors)
- \( E = \) Energy consumption
- \( E_{i,-W} = \) Energy consumption corrected for climate in sector \( i \) (used only in the residential and commercial sectors; the term disappears for other sectors)
- \( A = \frac{Act\_G}{Pop} = \) Activity per capita
- \( S_i = \frac{Act}{Act} = \) Structure
- \( I_i = \frac{E_{i,-W}}{Act_i} = \) Energy intensity
- \( F_{ij} = \frac{E_{ij}}{E_i} = \) Fuel mix
- \( U_{ij} = \frac{C_{ij}}{E_{ij}} = \) CO₂ intensity of input end-use energy types
- \( W_i = \frac{E_i}{E_{i,-W}} = \) The effect of climate (only used in the residential and commercial sector; the term disappears for other sectors)
- \( G = \frac{Act}{Act\_G} = \) The effect of population density (only used in personal transportation; the term disappears for other sectors)
To compare the CO\textsubscript{2} emissions per capita in two regions, \( c \) and \( m \), we apply Equation 1:

\[
\frac{\Delta C}{\text{pop}} = \frac{C^c}{\text{pop}} - \frac{C^m}{\text{pop}}
\]  

(2)

\[
\frac{\Delta C}{\text{pop}} = \sum_{ij} (A\cdot S_i \cdot F_{ij} \cdot U_{ij} \cdot W_i \cdot G)^c - \sum_{ij} (A\cdot S_i \cdot F_{ij} \cdot U_{ij} \cdot W_i \cdot G)^m
\]  

(3)

\[
\frac{\Delta C}{\text{pop}} = \frac{\Delta C_{\text{Act}}}{\text{pop}} + \frac{\Delta C_{\text{Str}}}{\text{pop}} + \frac{\Delta C_{\text{Int}}}{\text{pop}} + \frac{\Delta C_{\text{Mix}}}{\text{pop}} + \frac{\Delta C_{\text{Emf}}}{\text{pop}} + \frac{\Delta C_{\text{Climate}}}{\text{pop}} + \frac{\Delta C_{\text{Geog}}}{\text{pop}} + \frac{\Delta C_{\text{Res}}}{\text{pop}}
\]  

(4)

Where:

\( \Delta C \) = Difference in total CO\textsubscript{2} emissions between region \( c \) and region \( m \)

\( \Delta C_{\text{Act}} \) = Difference due to activity

\( \Delta C_{\text{Str}} \) = Difference due to structure

\( \Delta C_{\text{Int}} \) = Difference due to energy intensity

\( \Delta C_{\text{Mix}} \) = Difference due to fuel mix

\( \Delta C_{\text{Emf}} \) = Difference due to GHG intensity of fuels

\( \Delta C_{\text{Climate}} \) = Difference due to climate (used only in residential and commercial sectors)

\( \Delta C_{\text{Geog}} \) = Difference due to population density (used only in personal transportation)

\( \Delta C_{\text{Res}} \) = Residual, zero when using the LMDI I

We use the LMDI I approach to calculate the subcomponents of Equation 4 in Equations 5-11 because it is easy to use, robust, and has no residual term (\( \Delta C_{\text{Res}} = 0 \)):

\[
\Delta(C)_{\text{Act}} = \sum_{ij} \frac{C^c_{ij} - C^m_{ij}}{\ln (C^c_{ij} / C^m_{ij})} \cdot \ln \left( \frac{A^c}{A^m} \right)
\]  

(5)

\[
\Delta(C)_{\text{Str}} = \sum_{ij} \frac{S^c_i - S^m_i}{\ln (S^c_i / S^m_i)} \cdot \ln \left( \frac{S^c_i}{S^m_i} \right)
\]  

(6)

\[
\Delta(C)_{\text{Int}} = \sum_{ij} \frac{I^c_i - I^m_i}{\ln (I^c_i / I^m_i)} \cdot \ln \left( \frac{I^c_i}{I^m_i} \right)
\]  

(7)

\[
\Delta(C)_{\text{Mix}} = \sum_{ij} \frac{F^c_{ij} - F^m_{ij}}{\ln (F^c_{ij} / F^m_{ij})} \cdot \ln \left( \frac{F^c_{ij}}{F^m_{ij}} \right)
\]  

(8)

\[
\Delta(C)_{\text{Emf}} = \sum_{ij} \frac{U^c_{ij} - U^m_{ij}}{\ln (U^c_{ij} / U^m_{ij})} \cdot \ln \left( \frac{U^c_{ij}}{U^m_{ij}} \right)
\]  

(9)
\[ \Delta(C)_{\text{Climate}} = \sum_{ij} \frac{C_{ij}^c - C_{ij}^m}{\ln \left( \frac{C_{ij}^c}{C_{ij}^m} \right)} \cdot \ln \left( \frac{W_i^c}{W_i^m} \right) \] (10)

\[ \Delta(C)_{\text{Geog}} = \sum_{ij} \frac{C_{ij}^c - C_{ij}^m}{\ln \left( \frac{C_{ij}^c}{C_{ij}^m} \right)} \cdot \ln \left( \frac{G_i^c}{G_i^m} \right) \] (11)

The first term in each of the equations is the logarithmic mean of the difference in CO$_2$ emissions between regions $c$ and $m$. This value is multiplied by the natural log of the ratio of the factor in question, e.g., the ratio of region $c$’s activity to that of region $m$, to calculate the influence of that factor on the difference in CO$_2$ per capita between the regions (Ang, 2005; Ang, 2004; Ang and Liu, 2001). For our study we compared characteristics of country $c$ to the mean characteristics of all other countries in the group: this is the group labelled region $m$ in the equations above. Using this formulation prevents countries with relatively large economies, or other defining characteristics, from exerting a strong pull on the averages to which they are compared (Schipper et al., 2001). Therefore, throughout this paper we refer to the attributes of one country compared against the “others’ average” – the average attributes of the group of G7 countries excluding the country being analyzed. This point becomes important when interpreting the results of the decomposition analyses. For example, in the decomposition analysis of the transportation sector, emissions of the transportation sector in each country are compared to the average of all other countries. For Canada, the average group excludes Canada, so the comparison group is a weighted average of the US, the European G7 countries, and Japan, with the US exerting a strong pull on the average because of its size. For the US, the average group is a weighted average of Canada, the European G7 countries, and Japan. In this case, the European G7 countries dominate the weighted average. As a result, the comparison group can have significantly different characteristics for different countries – there is no consistent baseline for the decomposition analysis when analyzing different countries.

To calculate the effect of climate (Equation 10) and population density (Equation 11) on total emissions, we used a two step process. For climate, given the large variation among G7 countries, we first normalized space heating energy consumption in the commercial and residential sectors for climate by applying Equation 12:

\[ E_{i,-W} = \frac{E_i}{1 - (\sigma_H \cdot (1 - \text{HDDI}))} \] (12)

Where:

- $E_{i,-W}$ = Energy consumption for space heating corrected for heating degree days
- $E_i$ = Actual energy consumption for space heating
- $\sigma_H$ = Elasticity of energy consumption for space heating with respect to climate: a value of 0.75 was used for the commercial sector
and 1.00 for the residential sector. These are “rule-of-thumb” values commonly used by Natural Resources Canada and other international agencies.

\[ HDDI = \text{Index of heating degree days (1.00 = population-weighted mean of the other G7 countries)} \]

The ratio of \( E_i \) to \( E_{i,-W} \) is used to determine the significance of climate effects in Equation 10, and the strength of these effects is based on the HDDI for each country. An HDDI index larger than 1 will mean that a country’s space heating requirements are larger than the average of the rest of the G7, and vice versa. The energy intensity term in the decomposition equation, Equation 7, is determined using the climate corrected energy consumption values for space heating.

Similarly, in order to normalize travel activity in the passenger and freight transportation sectors to account for the effect of geography, we apply Equation 13:

\[
Act_{i,G} = \frac{Act_i}{1 - (\sigma_G \cdot (1 - GEOI))} \tag{13}
\]

Where:

- \( Act_{i,G} \) = Transportation activity (pkm or tkm) normalized to account for the effect of geography
- \( Act_i \) = Actual transportation activity (pkm or tkm)
- \( \sigma_G \) = Elasticity of transportation demand with respect to geography (we calculated values of 0.33 for inter-urban passenger transportation and 0.84 for freight transportation; calculations in Appendix)
- \( GEOI \) = Index of population weighted distance between major urban areas (ratio of \( GEO^i/GEO^m \); calculations are provided in the Appendix)

The ratio of \( Act \) to \( Act_{i,G} \) is used to determine the significance of population density effects in Equation 11, and the strength of this effect is based on the GEOI for each country. A GEOI larger than 1 will mean that a country’s population is more dispersed compared to the rest of the G7, and vice versa (Appendix). Only domestic transportation within countries is analyzed; international transportation emissions are not allocated to any country, as per current norms. The activity term in the decomposition equation, Equation 11, is determined using the geography-corrected activity values for transportation.6

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6. A reviewer noted that our geography adjustment is based on the population weighted distance between metropolitan centres, and that this would miss the effects of enhanced congestion in countries that have larger metropolitan centres. We would argue, however, that this is partly a population effect and partly a transportation planning effect: the former is partly under a country’s control, especially in terms of distribution, while the latter is a flexible characteristic under the influence of policy.
3.2. The Effect of Imports and Exports of Fossil Fuels

Assessing the effect of imports and exports of fossil fuels did not lend itself to a decomposition approach, so instead we applied a simple accounting principle in order to derive the effect of exports and imports of fossil fuels on overall GHG intensity. To calculate GHG intensity for each country normalized for fossil fuel imports and exports, we started with the base unadjusted intensity \( GHG_{\text{Base}} \), added the emissions associated with the upstream production and international transportation of imported fossil fuels, subtracted the production emissions associated with exports, and then divided the difference by population (Equation 14).

\[
GHG_{\text{Normalized}} \left( \frac{GHG_{\text{Base}} + \sum_{j} M_j \cdot I_j - \sum_{j} X_j \cdot I_j}{pop} \right)
\]

Equation 14 is calculated for each country separately; the country index has been removed for simplicity. The subscript \( j \) indexes types of traded fossil fuels (natural gas, coal, and crude oil). \( M \) refers to imports, \( X \) to exports, and \( I \) to the GHG emissions per unit of production of fossil fuel \( j \) (including fugitive emissions). GHG intensity for crude oil production is specific to each pair of importing and exporting countries to accommodate the mix of crude oil types and international transportation. Due to poor data availability, we applied a global GHG intensity value for natural gas and coal production.

3.3. The Effect of Access to Low GHG Electricity

The effect of each nation’s relative access to low GHG electricity was calculated by adding the terms for the \( CO_2 \) intensity of end-use energy from the decompositions for the industrial, residential, and commercial sectors. Since the \( CO_2 \) intensity of processed end-use coal, natural gas and refined petroleum products is roughly the same for these sectors, the difference between a nation’s \( CO_2 \) intensity of end-use energy and its others’ average is primarily due to the \( CO_2 \) content of electricity production. This circumstance is discussed along with the other results from each decomposition, and is reported collectively in Table 1 along with the other national circumstances.

3.4. Data

For each of the sectors above except fossil fuel production, we required energy consumption data by fuel type at a subsectoral level (subsectoral level data was not available for the residential and commercial sectors), as well as associated \( CO_2 \) emissions. For industry, our analysis disaggregates energy and emissions into seven subsectors (basic metals, chemicals, refineries, pulp and paper, wood and wood products, food beverages and tobacco, and other industry) and 36 fuel types,
and uses GDP as a measure of activity. For passenger transport, our analysis dis-
aggregates into five mode types (light duty vehicle, bus, train, air, and motorcycle)
and six fuel types, and uses passenger kilometres travelled as a measure of activ-
ity. For freight transportation, our analysis disaggregates into four mode types
(truck, rail, air, and marine) and six fuel types, and uses tonne-kilometres travelled
as a measure of activity. For the commercial and residential sectors, our analysis
disaggregates energy consumption into 17 fuel types, and uses floor space as a
measure of activity for the residential sector, and GDP as a measure of activity for
the commercial sector. Floor space would have been the preferred activity vari-
able for the commercial sector, but the data was not available.

For the fossil fuel production sector, we used IEA statistics where possi-
ble to maintain the consistency of collection method and definition. To determine
emissions intensities for each type of fossil fuel production we used a wide variety
of international and country-specific sources. Where necessary data were lacking,
such as for a consistent measurement of international natural gas and coal produc-
tion GHG intensities, we used North American industry coefficients.

The list of data sources for this study is large, and is available upon request
from the authors; we provide a data appendix at www.emrg.sfu.ca/nc. Most data
come from official national statistics agencies; some data also come from interna-
tional sources such as the IEA and the International Civil Aviation Organization.

4. RESULTS

4.1. The Effect of Structure on the Industrial Sector

Figure 3 shows the GDP per capita of the industrial sector for each G7
country disaggregated into seven sub-sectors: data did not allow further disaggre-
gation. There are only small differences in structure between the G7 countries.

Figure 4 shows the results of the decomposition analysis for all G7 coun-
tries. The rightmost bars are the actual industrial emissions per capita for each
nation. Canada has the highest industrial emissions per capita, followed by the
United States. The leftmost set of bars are the average emissions for the other 6
countries (i.e. “others’ average”), which provides the comparison set. The emis-
sion intensities for Canada and the US are higher than the others’ average, while
those for G7 Europe and Japan are lower.

“Others’ average” provides the benchmark against which the emissions
intensity of each country is compared. For instance, the US’ industrial activity per
capita and structure are almost the same as the others’ average, so these character-
istics do not significantly influence its relative GHG intensity. Its energy intensity
and CO$_2$ intensity of electricity production are much higher than the others’ aver-
age, which increase its overall CO$_2$ emissions per capita relative to the others’
average. Finally, its fuel mix is less carbon intensive than the others’ average.
As an example of how to interpret this and subsequent graphs, if the US had the
same energy intensity as other G7 countries, its industrial CO$_2$ emissions would
be about 2.2 tonnes per capita lower. If it had the same fuel mix as other G7 countries, its CO$_2$ emissions would be about 0.9 tonnes per capita higher. If it had an electricity sector with the same CO$_2$ intensity as other G7 countries, its industrial CO$_2$ intensity would be about 1.4 tonnes per capita lower; throughout this analysis we assign the emissions associated with electricity production to its end-uses.

More generally, two phenomena emerge. First, the energy intensity of the Canadian and US industrial sectors are much higher than the rest of the G7;
this may, however, be partly a matter of data disaggregation and definition of activity. There are only minor effects of structure, but this may be because consistent structural data were available only to a seven industry level for the entire G7. A deeper level of structural disaggregation might uncover more difference in intensity between sub-components, and would thus assign some of the difference currently assigned to energy intensity to structure (e.g., data show that Canada produces more pulp and less paper than the US, with the former more energy intensive than the latter). Another issue may be that activity was defined in terms of value added. A better measure would have been physical output, for which consistent international data were not available.

The other phenomenon that emerges is the sensitivity of industrial emissions intensity to CO$_2$ intensity of input end-use energy, effectively the CO$_2$ content of electricity. France and Canada have much lower than average GHG intensities for producing electricity due to their respective nuclear and hydropower systems, while the US has a much higher intensity due to its predominately fossil fuel orientated system.

4.2. The Effect of Climate on the Residential Sector

On average, 57% of energy consumption in G7 residences is for space heating. The colder a country is, as defined by relatively higher numbers of heating degree-days, the larger its space heating requirements are likely to be. Figure 5 shows how heating degree-days differ between the G7 countries. Canada has the most heating degree days, 60% more than the G7 average, while Italy has the least, 35% less than the G7 average.

Figure 5. Heating Degree Days (18°C base), 2002

Source: Natural Resources Canada; Lawrence Berkeley National Laboratory; World Resources Institute.

7. The seven sectors are (1) basic metals, (2) chemicals, (3) refineries, (4) pulp and paper, (5) wood and wood products, (6) food beverages and tobacco, and (7) other industry.
As outlined in the methodology section, decomposition of the effect of climate on residential CO\textsubscript{2} emissions required the addition of a climate term. Unfortunately, data shortages prevented the inclusion of a structure term to capture differing shares of single detached houses, single attached houses, and apartments. Consequently, the effects of structure will be mixed in with those of energy intensity. The decomposition analysis results for all G7 countries are shown in Figure 6.

The results of the residential sector decomposition highlight how each factor can affect emission patterns. Examination of US emissions in this sector is a case in point. The US has the highest CO\textsubscript{2} emissions per capita compared to other G7 countries, but the components of this are complex. Activity is defined in terms of floor space per capita, and US floor space per capita is much higher than the rest of the G7. However, US climate-corrected energy intensity per unit floor space is lower than rest of the G7, which counteracts the size of US homes. The US fuel mix is less carbon intensive than the rest of the G7 average, a result of extensive natural gas use, while its CO\textsubscript{2} intensity, a result of its GHG-intense electricity generation, is by far the highest compared to the rest of the G7. Finally, as expected, significant climate effects are seen for “cold” Canada and “warm” Italy.

4.3. The Effect of Climate on the Commercial Sector

Analysis of the commercial sector used the same climate factor methodology as was used for the residential sector. As in the residential sector, structural data was lacking, so no structure term was used and the effect of structure is included with energy intensity. Figure 7 shows the results of the decomposition analysis.

The US has the highest emissions per capita in the G7 in the commercial sector, more than double the average of the rest of the G7, followed by Canada,
while France has the lowest emissions per capita. The climate-corrected energy intensities of Canada and the US, which include some structural effects due to lack of a structure term, are much higher than the average of the rest of the G7, while those of Germany, Italy and the UK are much lower. CO\textsubscript{2} intensity of electricity production varies dramatically: France and Canada have the lowest CO\textsubscript{2} intensities because of their nuclear and hydropower electricity systems, while the CO\textsubscript{2} intensity of US electricity production is much higher than the others’ average. Finally, as in the residential sector, climate seems to play a strong role in Canada’s CO\textsubscript{2} intensity: the effect of climate is to raise Canada’s emissions almost 1 tonne per capita above the others’ average, and lower Italian emissions 0.5 tonnes per capita below the others’ average.

4.4. The Effect of Geography on the Passenger Transportation Sector

Intuition suggests that larger countries whose populations are more dispersed will travel and emit more. Figure 8 shows the population weighted average distance between each of the G7 countries’ 10 largest metropolitan regions.

The US, with a large land mass and dispersed urban centres (e.g. Los Angeles in the west, Chicago in the middle and New York in the east), has the largest population-weighted average distance between cities. Canada’s level of weighted dispersal is similar. The European G7 and Japan, while varying significantly amongst themselves, typically have one-quarter the population-weighted distance between cities as the North American G7.

The effect of geography was added to the decomposition analysis in the same way as climate, except that activity levels (person-kilometres travelled) were adjusted instead of energy use. The structural term in the analysis captures the
effect of different mode shares (light duty vehicle, bus, train, air, motorcycle) in different countries. Figure 9 shows the results of the decomposition analysis for all G7 countries.

**Figure 9. Passenger Transport Decomposition Results, 2002, Tonnes CO$_2$ Per Capita (t/cap)**

US per capita emissions levels are the highest, almost triple the average of the rest of the G7. Canada’s emissions are slightly lower than the others’ average, while the rest of the G7 all emit 1 to 1.5 tonnes per capita, about half the others’ average in each country. US geography-corrected activity levels are almost double the others’ average. US structure is slightly more intense than the others’ average (reflecting a greater mode share for personal vehicles compared to other countries), while Japan’s is slightly less intense, which reflects the large share of passenger railways in Japan. Both the US and Canada’s energy intensity
is higher than others’ average (reflecting lower vehicle fuel economy), while fuel mix causes little differentiation: this owes to the uniformity of transportation fuels used in G7 countries.

Geography and population distribution have a substantial effect on the US relative to the rest of the G7: they cause CO₂ emissions per capita to be about 0.8 tonnes per capita higher than if the US had the same geography and population distribution as other G7 countries. Canada’s geography and population distribution is the same as the G7 average, while for the rest of the G7 geography and population distribution are more concentrated than the others’ average, which contributes to lower emissions in those countries.

4.5. The Effect of Geography on Freight Transportation

Our analysis only includes domestic freight transport because international transport emissions are not included in national greenhouse gas inventories. Pipeline data were also excluded due to a lack of adequate data for the European G7 countries and Japan. Figure 10 displays the results of the decomposition analysis for all G7 countries; geography and population distribution are incorporated into the analysis using the same method as for the passenger transportation sector.

Figure 10. Freight Transportation Decomposition Results, 2002, Tonnes CO₂ Per Capita (t/cap)

As with many other indicators, there seems to be a North American vs. European and Japanese divide. US freight emissions per capita are the highest, followed by Canada. Freight emissions per capita in the rest of the G7 are relatively similar, at about 25-30% of the US level.

8. The absence of pipelines is definitely significant for the US and Canada, as they account for about half the tonne-kilometres travelled. Comparable data for other nations was not available.
Despite the clear patterns at the total emissions per capita level, the subcomponents are quite complex. Geography-corrected activity levels per capita are quite varied, with no clear pattern. Canadian and US structure is considerably less CO\textsubscript{2} intense than the rest of the G7 average, due partly to longer distances which improve the economics of railway shipping, which is a relatively less GHG intense mode of transportation.

The pattern seen in actual emissions is strongly reflected in the geography and population distribution component of the decomposition, indicating its importance. US emissions are very high, and the US has the largest geography index of the G7 (Appendix). Canada’s geography is similar to the average of the rest of the G7 countries, and so the effect of geography on its emissions is negligible. Emissions in European G7 countries and Japan are much smaller than they would be if they had the geography of other G7 countries.

4.6. The Effect of Imports and Exports of Fossil Fuels

GHG emissions associated with the production of fossil fuels, or any other product, are normally allocated to the country that produces them, not the country that consumes them. If these emissions were instead allocated to the country where they were consumed, the intensities of many countries would change substantially. To analyze this effect on national emission intensities, we reallocated the emissions of the G7 such that each is allocated all the production, processing, and international transportation emissions associated with their imports of crude oil products, natural gas and coal, and subtracted the emissions associated with their fossil fuel exports.\(^9\)

Among the G7, only Canada and the UK are significant net exporters of fossil fuels (Figure 11). The US, France, Germany, Japan and Italy are substantial importers.

Figure 12 shows our calculated values for the production and processing emissions (including combustion, flaring and fugitive emissions) associated with crude oil imports from various sources.\(^10\) Differences in emissions are due to many factors, but processing method and crude type are the most important. Fugi-

\(^9\) This method could also be applied to metals, cement, wood products, or any other GHG intense commodity; we encourage expansion of this methodology to these commodities where data allow. One reviewer wondered if including trade in GHG intense commodities might open up a “Pandora’s Box” for GHG negotiations, with countries creating national circumstances from economic activity that benefits national welfare. We acknowledge this possibility, but would also argue that the choice of whether to assign emissions to a commodity’s producer or to its consumers is a somewhat arbitrary but important political decision that must be addressed. Climate policy that has less than perfect coverage of all emitters may be less than completely effective due to emissions leakage. Allocation of emissions to consumers, and the associated potential costs, would prevent leakage, and probably be more effective in causing economically efficient structural change related to GHG intensity in less than perfectly competitive markets.

\(^10\) The intensities are calculated from a multitude of sources; please contact the authors for details. Canada’s emissions include pipeline transportation to the US border where applicable.
Fugitive emissions are lower in offshore production facilities, because greater measures are taken to contain and process waste gases than for land based production, due to fire safety risks. Extracting heavy crude oil produces much more fugitive emissions than extracting light and medium crude oil. While there is methane associated with the production of all types of crude oil, it is generally economic to extract, store and sell it as natural gas only from light crude oil production; that which comes up with heavy crude oil is usually vented to the atmosphere. Finally, while combustion emissions are fairly accessible for most countries, good quality data for fugitive emissions were available only for Canada, and to a certain extent for the UK and Norway: fugitive emissions for other source countries, and thus their total emissions per barrel, are probably biased too low.

Two additional types of oil are produced in significant quantities in Canada: bitumen and synthetic crude, which is light crude oil made from bitumen. These products are relatively GHG intense: bitumen requires process heat for extraction, while synthetic crude also requires additional energy for upgrading.

Due to a lack of international data on emissions associated with natural gas and coal production, we used an estimate of North American emissions as a proxy for the global average (6.72 kg/GJ for natural gas, and 7.44 kg/GJ for coal).

Figure 13 shows by how much the intensity of each of the G7 countries would change if emissions associated with the production of coal, natural gas, and oil were allocated to the country in which they were consumed. The intensities for the net importers rise, the UK stays virtually the same, and Canada falls. For example, if one substracted all the emissions associated with Canada’s exports of fossil fuels and added those associated with its imports, Canada’s emissions...
would fall by 2.03 tonnes per capita. Furthermore, if Canada had the same relative export and import balance as the rest of the G7, i.e. if it were a net importer with an average reduction of 0.70 tonnes per capita, its emissions would be further reduced by this amount, for a total net reduction of 2.73 tonnes per capita.

**Figure 12.** Net Combustion, Flaring and Fugitive Emissions Attached to Imports of Crude Oil

**Figure 13.** Total GHG Emissions Per Capita With and Without Fossil Fuel Export Emissions Subtracted and Import Emissions Added, 2002, Tonnes CO$_2$e Per Capita (t/cap)
5. DISCUSSION AND CONCLUSIONS

Table 1 summarizes the effect of the national circumstances discussed in previous sections on the GHG intensity for each of the G7 countries. A positive value means that the national circumstance causes emissions in that country to be higher than if the country had the same characteristics as the average of the rest of the G7 countries, and *vice versa*. For example, if the UK had the same climate as the average of the other G7 countries, its emissions would be 0.10 tonnes per capita lower.

<table>
<thead>
<tr>
<th></th>
<th>Canada</th>
<th>France</th>
<th>Germany</th>
<th>Italy</th>
<th>Japan</th>
<th>UK</th>
<th>US</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHG intensity per capita</td>
<td>23.32</td>
<td>9.01</td>
<td>12.30</td>
<td>9.55</td>
<td>10.44</td>
<td>10.70</td>
<td>24.06</td>
</tr>
<tr>
<td>Inflexible characteristics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Climate</td>
<td>+1.25</td>
<td>-0.04</td>
<td>+0.44</td>
<td>-0.79</td>
<td>-0.24</td>
<td>+0.10</td>
<td>-0.11</td>
</tr>
<tr>
<td>Geography</td>
<td>+0.17</td>
<td>-1.21</td>
<td>-1.65</td>
<td>-1.04</td>
<td>-1.52</td>
<td>-1.89</td>
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</tr>
<tr>
<td>Sub-total</td>
<td>+1.43</td>
<td>-1.25</td>
<td>-1.21</td>
<td>-1.84</td>
<td>-1.76</td>
<td>-1.79</td>
<td>2.70</td>
</tr>
<tr>
<td>Somewhat flexible characteristics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fossil Fuel Exports-Imports</td>
<td>+2.73</td>
<td>-0.13</td>
<td>-0.21</td>
<td>-0.41</td>
<td>-0.50</td>
<td>0.56</td>
<td>-0.45</td>
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<tr>
<td>Industrial Structure</td>
<td>+0.01</td>
<td>-0.16</td>
<td>-0.15</td>
<td>-0.25</td>
<td>+0.25</td>
<td>-0.19</td>
<td>-0.24</td>
</tr>
<tr>
<td>Access to low GHG electricity</td>
<td>-2.80</td>
<td>-2.90</td>
<td>-0.50</td>
<td>+1.08</td>
<td>-1.51</td>
<td>-0.30</td>
<td>3.66</td>
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<tr>
<td>Sub-total</td>
<td>-0.06</td>
<td>-3.18</td>
<td>-0.86</td>
<td>+0.42</td>
<td>-1.76</td>
<td>+0.07</td>
<td>+2.97</td>
</tr>
<tr>
<td>Total</td>
<td>+1.37</td>
<td>-4.43</td>
<td>-2.06</td>
<td>-1.41</td>
<td>-3.52</td>
<td>-1.71</td>
<td>+5.66</td>
</tr>
</tbody>
</table>

If the nation had others’ average characteristics, its emissions would change by:

-6% +49% +17% +15% +34% +16% -24%

Climate and geography are national circumstances which are not malleable by policy. US emissions are 2.81 tonnes per capita higher because of the effects of its large size and dispersed population, and 2.70 tonnes per capita higher if the effects of climate (-0.11 t / CO$_2$e) are included. Similarly, Canada’s emissions would be 1.25 tonnes per capita lower if it had the same climate as the rest of the G7, and 1.43 tonnes per capita lower if the effects of geography are included (+0.17 t / CO$_2$e). Emissions intensity in the rest of the G7 would be between 1.21 and 1.84 tonnes per capita higher if these countries had the same geography and climate as the rest of the G7.

The emissions associated with fossil fuel production, industrial structure and access to low GHG electricity are all somewhat more malleable given time, all for their own reasons. Whether or not a country is an importer or exporter of fossil fuels is a function of its natural endowment of fossil fuels, domestic demand and international prices. Most of the G7 are major fossil fuel importers, except for
the UK and Canada, and as a result their emissions are lower than they would be if they produced all fossil fuels domestically. Canada’s GHG intensity is 2.73 tonnes per capita higher than it would be if its fossil fuel trade balance was the same as the G7 average, while US GHG intensity, as a major importer, is 0.45 tonnes per capita lower than it would be if the US had the same fossil fuel trade balance as the rest of the G7 countries.

Whether or not a country has an energy intense industrial structure is a function of historic domestic and international energy prices, domestic industrial policy, resource endowment, and other factors. Japan’s GHG intensity would be 0.25 tonnes per capita lower, while Italy’s intensity would be 0.25 tonnes per capita higher if each had the industrial structure of the rest of the G7. These differences would likely be larger if more disaggregated, internationally comparable data was available.

Access to low GHG electricity is primarily a matter of natural endowments in the case of hydroelectricity, as in the case of Canada, and historic energy policy in the case of nuclear power, as in the case of France. Canada and France’s GHG intensities would be 2.90 and 2.80 tonnes per capita higher if they had the same electricity system as the rest of the G7 countries. US GHG intensity, on the other hand, would be 3.66 tonnes per capita lower if it had the same electricity system as the rest of the G7, due to a relative lack of access to low GHG electricity sources.

Once the inflexible and somewhat flexible national circumstances are added together, Canada experiences the least total change relative to the average, closely followed by Italy. France’s “national circumstances” cause the largest reduction in intensity, 4.43 tonnes per capita. The US, on the other hand experiences the largest increase in GHG intensity due to national circumstances, 5.66 tonnes per capita, 24% of its total emissions.

The results of this paper show that national circumstances can affect countries’ base GHG emissions and their ability to adjust them through policy. Climate change policy commentators and negotiators know this intuitively and governments form policy based on them. The UNFCCC explicitly recognizes that national circumstances can affect GHG emissions, although it does not describe in detail how national circumstances are to be calculated and included in emissions reductions negotiations. Standardized calculation methods and explicit recognition of key uncontroversial national circumstances, such as climate and geography, would improve the transparency and credibility of country targets, and the overall climate change treaty system. This paper suggests some possible national circumstances and methods to quantitatively measure them.

6. APPENDIX

6.1. Index of Population Distribution (GEOI)

The simplest measure of population distribution in a country is population density, or the number of people per square kilometre. However, this mea-
sure does not accurately reflect the travel requirements of people within a country because it does not account for the fact that populations are usually unevenly concentrated. For example, in Canada the bulk of the population lives in the Windsor-Québec City corridor, more generally in the south of the country, and almost never travels far north. For this reason, the measure of population distribution used is the average population-weighted distance between the largest 10 census metropolitan areas (CMAs) in each country. We assumed that travel and shipping distances between the largest CMAs would capture the majority of a country’s activity, and thus would relatively accurately serve as a proxy characterizing the influence of population distribution on transportation. We calculated distances between each CMA using the spherical law of cosines\textsuperscript{11}, weighted these distances by the populations of each CMA, and calculated the average population-weighted distance between countries’ CMAs. The result is the variable \( \text{GEO} \) in Table 2. The variable \( \text{GEOI} \) in the final column of Table 2 is used in Equation 12.

### Table 2. Population-weighted Average Distances Between Metropolitan Census Areas, 2002

<table>
<thead>
<tr>
<th>Country</th>
<th>( \text{GEO} )</th>
<th>( \text{GEOI} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>673</td>
<td>418</td>
</tr>
<tr>
<td>France</td>
<td>232</td>
<td>448</td>
</tr>
<tr>
<td>Germany</td>
<td>139</td>
<td>468</td>
</tr>
<tr>
<td>Italy</td>
<td>248</td>
<td>446</td>
</tr>
<tr>
<td>Japan</td>
<td>210</td>
<td>478</td>
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<tr>
<td>UK</td>
<td>106</td>
<td>459</td>
</tr>
<tr>
<td>US</td>
<td>729</td>
<td>224</td>
</tr>
</tbody>
</table>

### 6.2. Elasticity of Travel Demand with Respect to Geography (\( \sigma_g \))

The variable \( \sigma_g \) in Equation 13 is the elasticity of travel demand with respect to geography. In both the freight and passenger transportation sectors, it represents the percentage that demand for travel would grow if a country’s geography (measured with the variable \( \text{GEO} \)) increased in size by 1\%\textsuperscript{12}. Unlike the elasticity for correcting space heating energy consumption to account for climate, we could not find published estimates of this elasticity, so we used data to calculate it. Using regression, we solved for the parameters \( \sigma_g \) in Equation 14 for both the freight and passenger transportation sectors.

\textsuperscript{11} Distance = \[ \text{acos} (\sin(L_1) \times \sin(L_2) + \cos(L_1) \times \cos(L_2) \times \cos(l_2-l_1)) \times R \]; where \( L \) is latitude, \( l \) is longitude, \( R \) is the Earth’s average radius, and 1 and 2 refer to cities 1 and 2 in a city pair.

\textsuperscript{12} In the passenger transportation sector, we assume that only inter-urban passenger transport is affected by the size of the country. For all countries, we assume that 45\% of passenger travel is inter-urban and 55\% of passenger travel is within urban centres.
\[ \ln (Act) = c + \sigma_G \ln (GEO) \]  

(14)

Both regressions produce results that are significant at the 90% confidence level, and have the expected signs and magnitudes.\(^{13}\) For inter-urban passenger transportation, we found that as distance between cities \((GEO)\) increases by 1\%, travel demand increases by 0.33\%. For freight transportation, we found that as distance between cities \((GEO)\) increases by 1\%, travel demand increases by 0.84\%.

REFERENCES


13. Passenger transportation: Coefficient (elasticity)= 0.33 (p-stat=93.1%; R\(^2\)=51%); Freight transportation: Coefficient (elasticity)= 0.84 (p-stat=98.9%; R\(^2\)=75%)


http://intensityindicators.pnl.gov/documents/index_methodology.doc, 12/06/04
