The Input-Output Modeling Analysis with Environmental Extensions for Climate Change Policy-Making: The Case Study of Saskatchewan, Canada

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ABSTRACT:
Systematically evaluating the emission intensity and total emission of industries is indispensable for understanding energy and environmental sector performance in general and to support scientific climate change policy-making. In this study, an environmentally extended input-output (EEIO) model for Saskatchewan is developed to investigate the life-cycle environmental impacts of different industries. The IO table is transformed and disaggregated based on the energy use patterns and the underlying economic structure. Key GHG emissions, including CO\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2}O, are considered and the CO\textsubscript{2} equivalent intensities of different economic sectors are calculated. An in-depth analysis of key industries is conducted to further investigate the interactions between different industries. The results show that the developed model can be effectively used to evaluate the GHG emission intensities. A significant variance exists among the GHG emission intensities of different industries. Fossil-fuel electric power generation, as an intermediate input, has a strong effect on other industries and is a key factor for emission reduction. The developed modeling framework is applied in a detailed case study of the Province of Saskatchewan, Canada, to illustrate the potential benefits of its use in the environmental policy-making field.

KEY WORDS:
Input-Output analysis; greenhouse gas; policy making; climate change; Canada
1. Introduction

The release of greenhouse gases (GHG) and their increasing concentration in the atmosphere are already having an impact on the environment, human health and the economy (ECA, 2016; Tong, Saminathan and Chang, 2016). Facing challenges in terms of conflicting economic and environmental objectives, all countries are actively seeking an effective way in order to realize GHG emission reduction targets in the most economical efficient manner (Lin and Chen, 2016; Hao et al., 2016).

At present, some existing policies such as technology improvement, industry GHG emission regulation, and carbon pricing, are capable of reducing GHG emissions and reaching environmental targets (Nejat et al., 2015; Woo et al., 2016). However, these policies may hinder economic development to varying extents (Bloch, Rafiq and Salim, 2012; Marzouk, Azab and Metawie, 2016). To more fully realize sustainable development goals, a systematic evaluation of the emission intensity and total emissions of industries is indispensable for understanding the energy and environmental performance in general and to support scientific-based climate change policy-making.

Input-output analysis (IOA) modeling has been widely used to analyze CO2 emission intensities for different economic sectors, to better inform policy-making (Lgos et al., 2015). The Environmental Impacts of Product (EIPRO) study modified the Comprehensive Environmental Data Archive (CEDA) of the U.S. to identify the products with major life-cycle environmental impacts in the EU25 (Huppes et al., 2006). A multi-regional input-output model for Africa has been developed to explore five development scenarios and understand the implications of CO2 equivalent emissions, thus to support meeting Sub-Saharan African (SSA) human development goals (Hamilton and Kelly, 2017). Su, Ang, and Li (2017) comprehensively analyzed Singapore’s CO2 emission intensities from the demand perspective using I-O framework and investigated the drivers of emission changes using structural decomposition analysis. Based on a multi-regional input-output model, consumption related household CO2 equivalent emissions for three Baltic States, including Estonia, Latvia and Lithuania, has been provided from 1995 to 2011 (Brizga, Feng and Hubacek, 2016). Besides the application in various countries or cities, some studies were focused on specific emission intensive sectors. For example, Zhang and Wang (2016) proposed a hybrid input-output approach that could account for supply-chain energy and emissions by China’s building sector. Onat, Kucukvar and Tatari (2014) extended an existing life cycle sustainability assessment (LCSA) framework by integrating several social and economic indicators to demonstrate the usefulness of input-output modeling for quantifying sustainability impacts.

Based on the classic I-O framework, different models have been introduced into the input-output analysis to address the economic-environmental issues. You, Tao, Graziano and Snyder (2011) developed a multi-objective mixed-integer linear programming model to address the optimal design and planning of cellulosic ethanol supply chains under economic, environmental, and social objectives. Aggregated carbon intensity is a useful indicator in climate policy analysis. Su and Ang (2015) developed four different models to calculate a country’s aggregate carbon intensity using input-output framework. The models are developed based on different combinations of input-output models, country import assumptions, and approaches to calculating GDP. Sensitivity analysis based on the Leontief I/O model has been applied for identifying the key factors leading to changes in CO2 emission or energy...
consumption in a competitive market from a demand perspective (Yan, Zhao and Kang, 2016).

The absence of process detail for sectors in Input-Output (I-O) tables has been pointed out as a limitation of I-O analysis in environmental-economic life cycle assessment (Lindner, Legault, and Guan, 2013). The so-called aggregation bias problem should be addressed even if it is based on partial information to match the size of environmental satellite accounts, which will lead to smaller relative error (Lenzen, 2011). The previous studies about the disaggregation methods were mainly focused on the economics. Till now, there are several effective disaggregation methods. For example, in Wolsky’s approach (Wolsky, 1984), output weights are formed using the output ratio of the new sectors in relation to the aggregated sector they originate from. Heijungs and Suh (2002) present a methodology in which process-based life cycle assessment (LCA) data is tiered with I-O tables to express some sectors in more detail. This hybrid LCA approach overcomes truncation errors of process LCA, enhances the sector detail of the environmental-economic input–output framework (Ferrao and Nhambiu, 2009), and is widely used. Wiedmann et al. (2011) follow this approach and use the Ecoinvent database to disaggregate the wind power subsector from the electricity sector in the UK.

However, the electricity-generation sector was often treated as emission source in the past. Nevertheless, being a secondary industry, this sector could not cover all combustion-related emissions, especially for supporting climate change related policy-making. This may further lead to inaccurate IO tables given that disaggregation methods are chosen according to characteristics of the electricity generation sector. Consequently, the results obtained from the input-output model were inaccurate and unable to support the climate change policy-making well.

What’s more, there have been very limited studies on GHG emission analysis from a Canadian perspective. In different countries, the economic structure and the relationships among various industries are quite different. Canada, as the world’s fifth largest oil producer and fourth largest oil exporter, is unique in its energy use pattern. In 2014, more than 50% of Canadian GHG emissions were caused by oil and gas (Environmental and Climate Change Canada, 2016). Canada targets to achieve an economy-wide emission objective by reducing its GHG emissions 30% below 2005 levels by 2030 (INDC, 2015). A comprehensive study with regard to the GHG emission of Canada is desired.

Therefore, the objective of this paper is to develop an environmentally-extended input-output (EEIO) model with a detailed disaggregation on energy sectors. The developed modeling framework will be applied in a detailed case study of the Province of Saskatchewan, Canada, to illustrate the potential benefits of its use in the environmental policy-making field. More specifically, the I-O table will be transformed and disaggregated based on the energy use pattern and economic structure of the Province of Saskatchewan. Main GHG emissions, including CO2, CH4 and N2O, will be considered and the CO2 equivalent intensities of different economic sectors will be calculated. In-depth analysis will be conducted to further investigate the interactions between different industries. The key sectors for GHG

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1 Satellite accounts are frameworks designed to expand the analytical capacity of the national accounts without overburdening them or interfering with their general purpose orientation. In general terms, the variables cover: use of energy; emission of main greenhouse gases; emission of other main air pollutants; use of mineral and fossil resources; land use; and water use. Environmental satellites are environmental variables of relevance for analysis, expressed mainly in physical units, which are juxtaposed to the monetary Supply and Use Table (which is similar to an I-O table) framework.
emission mitigation will be revealed. The results will provide a scientific basis for supporting the formulation of effective climate change policies under new carbon-mitigation requirements.

2. Overview of Saskatchewan’s environmental and socio-economic system

Saskatchewan’s economy is influenced by the state of the global economy, commodity prices and the weather, but is also diversified across a number of sectors providing a high level of resilience (Economic Review, 2014). There are 35 sectors and 66 commodities listed in its related IO table.

Oil is Saskatchewan’s largest commodity with sales totaling $12.4 billion in 2011. Nearly 70% of Saskatchewan’s oil is sold to American refiners. High oil prices motivated accelerated drilling activities within the province before 2014. The sudden and dramatic decline in oil prices has had a significant impact on the provincial economy, most notably in the oil industry itself, but also in supporting industries (Economic Review, 2014). Saskatchewan is the world’s largest potash producer. The majority of potash was sold to the United States (Cocker, Orris and Wynn, 2014). Saskatchewan farms have continued a long standing trend towards fewer and larger farms. Based on the 2011 Census of Agriculture, there were 36952 farms in Saskatchewan in 2011, with the average size of a farm equal to 1282 acres. Net farm cash income from operations hit an all-time high of $5.8 billion in 2015, caused by lower fuel costs, high cattle prices, an above-average harvest and continued inventory liquidation (Census of Agriculture, 2015).

Canada intends to achieve an economy-wide emission target by reducing its greenhouse gas emissions 30% below 2005 levels by 2030, according to the Intended Nationally Determined Contribution (INDC) Canada to the United Nations Framework Convention on Climate Change (UNFCCC) (INDC, 2015). In different provinces, emissions can be significantly different due to effects of population, energy source, and economic structure. Saskatchewan’s economy largely relies on resource extraction, for example, most electricity generated comes from fossil fuels (NIR, 2016; Lin et al., 2010). This is why the GHG emissions of Saskatchewan were increased by 8.6% (6.0 Mt) from 2005 to 2014, meanwhile the GHG emissions of Ontario, British Columbia, and Quebec, which were long considered as high emission areas, were stabilized or gradually decreased (NIR, 2016). The GHG emission can be divided into four types, including energy-related emissions, industrial processes and product use emissions, agriculture emissions and waste-related emissions. The crop production and animal production cause 16% of the total GHG emissions. The combustion-related emission is still the main GHG emission. In this study, we will focus on the energy sector and its GHG emissions.

In Saskatchewan’s energy system, crude oil plays an important role. The production of natural gas liquids is relatively low, while the Province has comparatively modest reserves of natural gas. Coal also accounts for a significant portion of Saskatchewan’s energy economy. Most of the production is used for electricity generation in the Province (Annual report of SaskPower, 2014). Renewable energy, such as hydropower, wind power, is also used for electricity generation, but is currently available at higher unit costs (Lin et al., 2010; Huang et al., 2006). In addition, both fossil fuel energy and renewable energy have significant indirect impacts on other industries in the whole socio-economic system. The combustion-related GHG emission analysis will not only support the formulation of climate change
policies, but also facilitate the resources management and industrial development planning (Qin et al., 2007; Li et al., 2010).

3. Development of an EEIO model

3.1 The framework of the EEIO model

An EEIO model is developed to facilitate the analysis of GHG emission intensities of different industries. The two main inputs of the model are I-O tables and the emission factors of various emission source sectors. According to the analysis objectives, the I-O table should be aggregated and disaggregated to fit the environmental satellite accounts. The disaggregation method should be chosen based on data availability and sector characteristics to ensure the accuracy of model inputs. The emission factors of different energy sources vary due to region and utilization. In-depth surveys and research are thus needed to obtain the emission factors for one specific region. After data collection and processing, detailed analysis and comparative analysis can be conducted to reveal the emission intensities of various industries and the interactions among them. The EEIO model is based on the Leontief framework (Leontief, 1986). In this section, we first outline the I-O Leontief framework.

Consider an economy with \( N + 1 \) sectors where each sector \( i \) produces a unique good. The total output of good \( i \) from the \( i \)th sector is noted \( x_i \) and the amount of good \( i \) that sector \( j \) consumes from sector \( i \) is noted \( z_{ij} \). The total output \( x_i \) corresponds to the sum of the intermediate consumption by the economy and the final demand \( f_i \) (Leontief, 1986).

\[
x_i = \sum_{j=1}^{N} z_{ij} + f_i \quad \text{for } i = 1 \text{ to } N + 1
\] (1)

In the I-O Leontief framework, it is assumed that the industry flow from sector \( i \) to sector \( j \) depends linearly on the total output of sector \( j \). If sector \( j \) needs \( a_{ij} \) units of good \( i \) to produce 1 unit of good \( j \), Equation 1 can be rewritten as

\[
x_i = \sum_{j=1}^{N} a_{ij}x_j + f_i \quad \text{for } i = 1 \text{ to } N + 1
\] (2)

Writing Equation 2 in matrix form and inverting the system leads to

\[
x = (I - A)^{-1} \times f = Lf
\] (3)

where \( A \) is the technical coefficient matrix, \( I \) is the identity matrix of size \((N + 1) \times (N + 1)\) and \( L \) is the Leontief inverse matrix. The \( ij \)th coefficient in the inverse Leontief matrix \( L \) represents the total
requirement of goods from sector $i$ to meet the final demand of sector $j$ (Leontief, 1986).

In order to perform the analysis of embodied CO2 emissions per dollar of final demand for each sector, the Leontief matrix is multiplied by the CO2 satellite account $e$, as shown in Equation 4.

$$ e = e (I - A)^{-1} $$

where the CO2 satellite account $e$ is a row vector whose size is identical to the Leontief inverse matrix. The components corresponding to the emission sources sector are the satellite emission factors and other matrix components are zero (Miller and Blair, 2009).

### 3.2 Transformation of the I-O table

Different countries use different formats for their I-O tables around the world, but a common format is the combined I-O table as Leontief first developed (Leontief, 1986). In Canada, the I-O tables are three separate tables, including an output table, an input table, and a final demand table. Thus, a transformation must be done to get the common forms Industry-Industry I-O table and Commodity-Commodity I-O table. A step-by-step description of the transformation is given by below.

A mirror transition on negative numbers in the input table and output table was first conducted. If the $z_{ij}$ in the input table is negative and its value is $N$, then the $z_{ij}$ is adjusted to 0. Meanwhile, the $z_{ij}$ in the Output table is modified by adding $-N$ (Miller and Blair, 2009). The mirror transition for the Output table is done with the same method. Then, the total commodity output and total industry output are calculated by equation (5) and equation (6).

$$ q_j = u_{j1} + u_{jn} + f_j $$

$$ x_j = m_{i1} + m_{nj} $$

where $q$ is the total commodity output, $u$ is the matrix in the input table, $f$ is the final demand, $x$ is the total industry output, and $m$ is the matrix in the output table.

Next, technical coefficients for the industry-industry I-O table ($A_{cc}$), which represent the input of commodity $i$ to produce unit commodity $j$, and the commodity-commodity I-O table ($A_{n}$), which represents the input of industry $i$ to produce a unit in industry $j$, were obtained using equation (7) to equation (10).

$$ b_{ij} = u_{ij} / x_j $$

$$ d_{ij} = m_{ij} / q_j $$
\[ A_{cc} = B \times D' \]  
\[ A_{II} = D' \times B \]  
(9)  
(10)

where \( b \) is the production coefficient for the commodity-commodity I-O table, which means the input of commodity \( i \) to produce per unit of industry \( j \); \( d \) is the produce coefficient for industry-industry I-O table, which means the input of industry \( i \) needed to produce per unit commodity \( j \); \( u_{ij} \) is the commodity \( i \) used in industry \( j \); \( x_j \) is the total output of industry \( j \); \( m_{ij} \) is the commodity \( j \) produced in industry \( i \); \( q_j \) is the total output of commodity \( j \) (Miller and Blair, 2009).

The industry-industry I-O table (\( IO_{cc} \)) and the commodity-commodity I-O table (\( IO_{II} \)) are calculated following the steps represented by equation (11) to equation (14). The final demand of the commodity-commodity I-O table is the data in the final demand table. The value added of the industry-industry I-O table is the value added in the input table (Miller and Blair, 2009).

\[ IO_{cc} = A_{cc} \times \text{diag}(Q) \]  
\[ IO_{II} = A_{II} \times \text{diag}(X) \]  
\[ II_{cc-vd} = V \times B \]  
\[ IO_{II-fd} = D' \times F \]  
(11)  
(12)  
(13)  
(14)

where \( \text{diag}(Q) \) is the diagonal matrix of \( Q \); \( \text{diag}(X) \) is the diagonal matrix of \( X \); \( II_{cc-vd} \) is the value added of the commodity-commodity I-O table; \( IO_{II-fd} \) is the final demand of the industry-industry I-O table.

3.3 Aggregation and disaggregation of the I-O table

The existing I-O table of Saskatchewan contains 35 sectors, as listed in Table 1. Although aggregation of some types of industries may have only a minor effect on the overall economy displayed in an I-O table, the aggregation of sectors with a high impact on the environment has important consequences (Morimoto, 1970; Lenzen, 2011). For instance, the “mining, quarrying, and oil and gas extraction” sector contains “oil extraction”, “gas extraction”, and “coal mining”, which are significantly different in input requirements, outputs, and emission factors. Another example is the electricity sector,
where CO₂ emissions associated with a unit of output from fossil fuels are very different from those of a unit of output from renewable energy sources. But all generation units are generally combined in one sector (i.e. utility) in the I-O table. Moreover, in order to simplify the calculation process, some sectors were aggregated in this study due to their consistency in emission-related activities, such as the ten public administration related sectors (Lindner, Legault and Guan, 2012).

Place Table 1 here

According to Saskatchewan’s environmental-economic conditions, the I-O table used in this study was further disaggregated and aggregated into 20 sectors, as listed in Table 1. All combustion-related emission resources have been disaggregated to facilitate the GHG emission intensity analysis, including coal, crude oil, petroleum products, non-marketable natural gas, and marketable natural gas. Other sectors that are sensitive to the raw emission sources have also been disaggregated, such as the transportation, fossil-fuel electricity power generation, and clean electricity power generation (Druckman and Jackson, 2009). Ten service related sectors and ten public administration related sectors have been aggregated into a combined service sector and a combined public administration sector.

Based on the Leontief framework, the technical coefficient matrix \( A \) has been used to aggregate and disaggregate the I-O table (Leontief, 1986). When aggregating several sectors, the technical coefficients can be added easily. When disaggregating one sector to several sectors, different methods should be adopted according to the available information and the sectors’ characteristics. In this study, due to data limitations and research objectives the input coefficients, output coefficients, and intra matrix have been determined following Wolsky (1984) and Marriot (2007).

The input coefficients, which indicated in what proportion the common sectors supply the new sectors, have been determined using Equation (15).

\[
\text{Equation (15)} \quad a_{i,N+k}^* = r_{k} a_{i,N+1}, \text{ for } i = 1 \text{ to } N
\]

The output coefficients have been determined using equation (16), indicating in what proportion the common sectors purchase from the new sectors.

\[
\text{Equation (16)} \quad a_{N+k,i}^* = w_{k} a_{N+1,i}, \text{ for } k = 1 \text{ to } n \text{ and } i = 1 \text{ to } N
\]

The construction of the intra-industry matrix indicates in what proportion the new sectors supply and purchase from the new sectors. The intra-industry value is split among each entry in the new intra-matrix by multiplication with the row and column weight factor.

Specially, some exceptions needed to be considered when disaggregating the upstream energy production to downstream energy transmission. For instance, all purchases from the fossil fuel sector (e.g. crude oil, marketable natural gas) are most likely made by the fossil-fuel electricity generation sector. Also, the outputs of raw energy extraction sectors should be allocated mainly to the energy transfer sectors. Therefore, the input coefficients and output coefficients of the related energy sectors...
into the new sectors have been made according to Marriot (2007). Results of the manual allocation are shown in Table 2.

Place Table 2 here

3.4 Emission factors

The emission factors \( e_i \) quantify the embodied emissions of GHG per Canadian dollar from the five emission source sectors. Table 3 presents the numerical values used in this study. The emission factors were taken from Statistics Canada, NIR, EPA, and other references. In order to perform the emission intensity analysis for each sector, the emission factors needed to be converted into emissions per Canadian dollar. This was done using the mean price of emission sources, which were taken from Statistics Canada, SaskEnergy annual report, SaskPower report, and other data. The GHG emissions considered CO\(_2\), CH\(_4\) and N\(_2\)O. The CO\(_2\) equivalent emission intensities of different sectors can then be calculated using Equation (17).

\[
E_{f_{GHG}} = E_{f_{CO_2}} + 25 \times E_{f_{CH_4}} + 298 \times E_{f_{N_2O}}
\]

Place Table 3 here

In Saskatchewan, there is more than one type of emission sources, such as refined petroleum products. Even for one product, the emission factors for different utilizations are different. For example, the CH\(_4\) emission factor for coal used in electric utilities is 0.02 g/kg, while the value will be changed to 4 g/kg for residential and public administration use. When calculating the emission factors for the five emission sources, the emission factors given by NIR and the supply and demand table given by Statistics Canada have been adopted. The weighted sum was then used as the emission factor of the emission source. The emission factors for CO\(_2\) and GHG are shown as following:

\[
e_1 = (0,0,0,0.3928,236.6088,265,32555.6,0,0,0,8266.73,0,0,2055.6,0,0,0,0,0)
\]

\[
e_2 = (0,0,0,0.3941,25,6350,636,32765.33,0,0,0,8869.141,0,0,2109.949,0,0,0,0,0)
\]

4. Results and discussion

4.1 GHG emission intensity analysis
As shown in Table 2, the GHG emission intensities of the emission source sectors are relatively high and widely different. The emission intensity of coal is the highest, as it is still the largest fuel supply for power generation in Saskatchewan. The natural gas combined cycle (NGCC) contributes 37% of the power generation emissions, for the second largest emission intensity. In addition, natural gas is the major source for heating utilities. This indicates that Saskatchewan relies heavily on fossil-fuel energy in production, leading to increased emissions.

Figure 1 shows the combustion-related emission intensity of common sectors in Saskatchewan that were obtained using Equation (4) and Equation (19). The average GHG emission intensity is 255.2 g/C$, which is much lower than the emission source sector. The intensities of different sectors have substantial deviation, where the standard deviation is 241.8 g/C$. The highest GHG emission intensity sector is construction (i.e. 853.9 g/C$), which contains residential building construction, non-residential building construction, engineering construction, repair construction, and other activities of the construction industry. The lowest GHG emission intensity sector is the clean-electric power generation (i.e. 7.4 g/C$), which is only 0.8 percent of the intensity of the construction sector.

Among the 15 common sectors, 6 sectors have higher emission intensities than the mean level, including construction, fossil-fuel electric power generation, crop and animal production, forestry and logging, other mining and quarrying, and public administration. In order to achieve environmental and economic objectives, emission reduction policies should target these high emission intensity sectors. However, some combustion-related emissions are very difficult to reduce. For instance, agriculture is one of the pillar industries in Saskatchewan. The combustion-related emissions in agriculture are mainly caused by large-scale farm equipment, which are inseparable from modern agriculture. Technology improvements that can lessen the GHG emission by using more clean energy may take a substantial period to realize. Even as new farm machines become an option in the future, the huge cost of equipment replacement is still a great obstacle. Therefore, crop and animal production and forestry and logging are not the key sectors for GHG emission reduction. Policies should focus on the other high emission intensity sectors, such as construction, fossil-fuel electricity power generation, mining and quarrying, and public administration.

4.2 Total GHG emission and final demand analysis

Total GHG emissions embodied in the final demand is also important for climate change policy-making. Thus, as shown in Figures 2 (a) and 2 (b), we calculated the total final demands and total GHG emissions of 20 industries in Saskatchewan. It is seen from these two figures that the final demand contribution of an industry is not correlated with its GHG emissions. For example, the service industry contributes 18.7 percent of GDP with only 1.18 percent of GHG emissions. On the contrary, some emission source industries, such as coal mining and oil extraction, have less final demand but cause
many more GHG emissions. It should be noted that the natural gas related industry, including non-marketable natural gas and marketable natural gas, emits only 2.64 percent of the total emissions with a high final demand of 8 percent, which indicates promising future potential for natural gas in Saskatchewan.

Place Figure 2 here

The emission source sectors and some of the high emission intensity industries (e.g. construction, agriculture, and public administration) still rank near the top for total GHG emissions, as shown in Figure 2 (a), while the relative proportion of the other two industries (e.g. other mining and fossil-fuel electric power generation) is greatly reduced. In addition, the total GHG emissions for the transportation and service industries are significant, which is caused by the large final demand. This result is related to the characteristics of the industries. The tertiary industry always has more final demand than the primary industry and secondary industry. But the primary industry and secondary industry are also the emphasis of emission reduction due to their large intermediate outputs in the production process.

The distributions of final demands for different industries are shown in Figure 3. The construction sector is the only industry whose final demands are mainly capital assets. Nine industries’ final demands are mostly composed of exports, including agriculture, mining and quarrying, petroleum refineries, transportation, and warehousing. It is worth noting that most of the tertiary industries serve domestic households and government. For instance, the consumption of public administration accounts for 88.7 percent of the total demand. All of the emission source sectors, except natural gas, are mainly exported to other provinces and countries, implying that most of the GHG emissions embodied in the final demand are exported. Therefore, the consumption-based responsibility and production-based responsibility for emission reduction in Saskatchewan are significantly different. The consumption-based responsibility system will provide better benefits to the economy in Saskatchewan based on this research.

Place Figure 3 here

4.3 In-depth analysis of key industries

Considering the different disaggregation methods and different analysis objectives used in this study, CO2 emission intensity using the same disaggregation method and GHG emission intensity using previously used methods have been calculated to support the interaction analysis. The comparisons of the three emission intensity results are shown in Figure 4.
Firstly, CO₂ emission intensity and GHG emission intensity values with the same methods have been compared. Figure 4 (a) shows the rate of increase for the fifteen common sectors. The green line represents the average growth rate, which is 2.1%. There is no doubt that all the growth rates are positive, from the addition of CH₄ and N₂O emissions. On the other hand, there is a large difference in the growth rate across the fifteen common sectors. The highest growth rate (i.e. other manufacturing) is 3.0%, while the lowest growth rate (i.e. fossil-fuel electric power generation) is only 0.7%. This indicates that the CH₄ and N₂O emission intensities are inconsistent with CO₂ emission intensity. It would be inappropriate to judge the environmental impacts of industries solely depending on their CO₂ emission intensity. Therefore, the GHG emission intensity obtained in this study better reflects this multi-attribute perspective, which will facilitate improved climate change policy-making.

Secondly, we compared the GHG emission intensity with different disaggregation methods. Figure 4 (b) shows the ratio of two results, which is the value of the intensity with the manual allocation divided by the intensity without the manual allocation. The emission intensity of twelve common sectors was increased. Among them, the largest growth was seen for the fossil-fuel electric power generation. Meanwhile, other utilities, other manufacturing, and clean electric power generation were decreased. These can be explained by the manual allocation of the initial emission sources, as described in Section 3.3. It is worth noting that the GHG emission intensity of all the other industries that didn’t have the manual allocation were increased, which were mainly caused by the increase in fossil-fuel electric power generation emission intensity. This indicates that utilization of fossil-fuel energy, as the intermediate input, is much more emission-intensive than clean energy in Saskatchewan. Therefore, although the total GHG-emissions for fossil-fuel electric power generation caused by final demand is not the highest value, it is still the key factor for GHG emission reduction.

5. Conclusions

In this study, an environmentally extended input-output (EEIO) model has been developed and applied to the province of Saskatchewan, Canada, to investigate the life-cycle environmental impacts of different industries and to support climate change policy-making. The I-O table has been transformed, aggregated, and disaggregated to fit the GHG emission satellite factors. Three different methods have been adopted according to data availability and analysis objectives during the disaggregation process. The emission factors of five emission source industries have been confirmed by using weighted summations based upon the emission intensities of various energy types and utilizations. Following this, we computed and compared the emission intensities of the common sectors. Finally, in-depth analysis has been conducted to investigate the inter-relationships between different sectors.

It was found that a significant variance exists among the GHG emission intensities of different industries. The highest emission intensity industry in Saskatchewan is construction while the lowest one is clean electric power generation. The emission intensities of crop and animal production, as well as forestry and logging were found to be higher than the mean level, and are difficult to reduce due to the
large farm machines used in agricultural production. Fossil-fuel electric power generation, as intermediate inputs, has a strong effect on other industries and is a key factor for emissions reduction. Furthermore, since most high emission intensity industry outputs are exported to other provinces and countries, the economy of Saskatchewan will be benefit from the application of a consumption-based responsibility system.

Some limitations will be addressed in future research. First, uncertainties of the process have not been considered. It is inferred that more insight will be given by incorporating stochastic analysis methods. Second, more detailed emission factors will be adopted to reflect the effects of energy use technology. Finally, more in-depth decomposition analysis will be used to study the driving forces or pull forces of the embodied emissions.

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References


Environment and Climate Change Canada.


Lindner, Sören, Julien Legault, and Dabo Guan. "Disaggregating input–output models with incomplete


Submission of Canada Copenhagen accord (UNFCCC 2010); https://unfccc.int/files/meetings/cop_15/copenhagen_accord/application/pdf/canadacphaccord_app1.pdf.


Application of hybrid life cycle approaches to emerging energy technologies—the case of wind power in the UK. *Environmental science & technology*, 45(13), 5900-5907.


Figure 1. Emission intensities of common industries in Saskatchewan
Figure 2. The percentage of (a) total GHG emissions and (b) total final demand emissions of twenty industries in Saskatchewan
Figure 3. The distribution of final demands for twenty industries in Saskatchewan
Figure 4. Comparison of (a) GHG emission intensity and CO₂ emission intensity and (b) disaggregation method in this study and disaggregation method without manual allocation
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