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RESEARCH ARTICLE

Developing a comprehensive account of embodied emissions within the Canadian construction sector

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Abstract

Construction activities are a major driver of greenhouse gas emissions worldwide. However, the majority of construction-driven emissions are indirect, meaning that these emissions occur during the manufacturing and transport of construction materials. This is in contrast with direct emissions, which are directly emitted from construction machinery. These indirect impacts are represented as embodied emissions and are difficult to quantify at scale, limiting the effectiveness of climate policymaking in the building sector. This paper presents results from a comprehensive account of embodied emissions within the Canadian construction sector, at a resolution far higher than existing global accounts, as well as novel analyses of flows and intensities of embodied emissions. It has the specific goal of serving as a baseline for future analyses of decarbonization scenarios and the more general goal of highlighting the importance of a consumption-based approach to climate policymaking in the sector. The accounts are produced via an environmentally extended input–output analysis based on Canadian supply–use tables for the year 2018, and results are presented for the 13 provinces and territories as well as 19 categories of buildings and infrastructure. Results show that demand from construction drives 13% of Canada's consumption-based emissions, residential construction is by far the largest driver of emissions, and at 0.28 $kgCO_{2eq}$ per Canadian dollar of GDP, the efficiency of Canadian construction is roughly in line with the OECD average. A disproportionate share of emissions is driven by construction in provinces that are growing fast in terms of their populations, feature significant extractive industries, and feature higher emissions intensities. The construction sectors of western provinces are highly interconnected and receive a disproportionate proportion of embodied emissions from Alberta, whose high level of emissions promises to complicate decarbonization efforts. This article met the requirements for a gold-gold *JIE* data openness badge described at http://jie.click/badges

KEYWORDS
Canada, construction, embodied emissions, industrial ecology, input–output, sectoral analysis

1 | INTRODUCTION

Climate change presents a serious environmental threat and keeping warming to below 1.5 degrees requires significant emission reductions across all sectors (IPCC, 2023; Vigier et al., 2023). Life cycle emissions associated with the construction of buildings and infrastructure sectors represent between 9% and 23% of global emissions, depending on the methodology used (Huang et al., 2018; UNEP, 2022). When added to direct and indirect operational emissions from the daily use of said buildings and infrastructure (8% and 19% of global emissions), the built environment is responsible for approximately 35%–50% of all global emissions (IEA, 2022). However, the construction sector is also central to climate mitigation and adaptation strategies, which require the rapid development of new energy-efficient housing, transportation, and energy infrastructure (Creutzig et al., 2016). It is therefore uniquely cross-pressured and will be required to improve efficiency at the same time as its role expands. Improving the climate performance of any industrial sector requires data on the origins of emissions. Models based on detailed emissions data provide context for policymakers, help identify policy levers and low-hanging fruits, allow resources to be allocated appropriately, and are essential for target setting (Süsser et al., 2021). Nevertheless, the fact that the construction is heavily decentralized, with a large number of independently managed projects and material suppliers, has meant that detailed information on greenhouse gas (GHG) emissions has been historically difficult to obtain.

As of 2023, the Canadian construction sector is the source of 1.1 million jobs, or approximately 7% of Canadian employment (Statistics Canada, 2023a), with an average yearly investment ranging from 2.3% to 2.8% of GDP (Infrastructure Canada, 2021). Canadian construction is distinct from construction sectors in other OECD nations, except for Australia, due to the relative predominance of large-scale projects serving extractive industries such as mining, oil and gas extraction, and forestry (Natural Resources Canada, 2020). The federal government's national goal of a 40%–45% reduction by 2030 and net-zero emissions by 2050 (Minister of Justice, Government of Canada, 2024) means that the construction sector will be expected to drastically improve its operational efficiency in the near future, barring significant offsets from negative emissions elsewhere in the economy.

There are two common bottom-up approaches to collecting GHG emissions data from construction, each presenting significant limitations: Life cycle analyses (LCAs), which represent a project-scale consumption-based approach, and national inventories, which represent a regional-scale production-based approach. LCAs are designed to account for all cradle-to-grave impacts, which in the context of construction include those originating from the production of all materials and components, as well as construction and demolition activities for a single project. The field of whole-building life cycle analysis (WBLCA) is mature, and many tools and standards have been designed to facilitate assessments of construction projects (Herrero-Garcia, 2020). While LCA-based approaches have successfully been used to derive estimates of construction impacts at a regional level, they are severely limited by the need for prohibitive amounts of data about a region's building stock, the need for many assumptions regarding the categorizations of building archetypes, as well as an almost exclusive focus on buildings over other forms of construction (Bischof & Duffy, 2022; Lavagna et al., 2018; Mastrucci et al., 2017; Röck et al., 2021).

Climate policymaking and scenario-design activities are instead typically supported by the data made available in national inventories, such as the Canadian national GHG inventory (ECCC, 2023). These inventories are based on guidelines from the Intergovernmental Panel on Climate Change (IPCC) and as such track production-based emissions, which are the direct emissions from individual industries located within a particular region (Buendia et al., 2019). These inventories can be used to track direct emissions from construction activities at a scale appropriate for informing policymaking. However, they are severely limited in scope as the emissions embodied within the supply chains of materials and components are not considered in production-based inventories despite representing the bulk of the construction sector's impact (Huang et al., 2018). This omission is exemplified in a study by Talaei et al. (2020) based on fuel consumption, energy consumption, and GHG emissions data from Canadian national inventories, which concludes that construction only made up 2%–3% of Canadian industrial GHG emissions despite making up almost 30% of industrial output in monetary terms.

The distortions caused by the production-based nature of national inventories, which incentivize the offshoring of polluting activities, among others, have sparked a debate with many calling for national inventories to be complemented by consumption-based accounts (Franzen & Mader, 2018; Karakaya et al., 2019; Larsen & Hertwich, 2009; Peters, 2008); however, to this day the discussion has remained mostly theoretical.

The relatively minor volume of direct emissions assigned to construction (2%–3% of industrial emissions) likely explains why discussion of the construction sector has been largely omitted from Canada's 2030 emissions reduction plan (ECCC, 2022a), apart from a brief mention in the context of improving building energy efficiency. This omission means that demand-side strategies, which would reduce the demand from the construction sector for carbon-intensive products and services, are absent from the emissions reduction plan, despite construction being responsible for driving a significant proportion of national emissions. Introducing consumption-based accounts that recognize the impact of construction as a driver of emissions in the rest of the economy would therefore shed light on the ability of the construction sector to contribute to the broader project of Canadian decarbonization.

An account of emissions that is regional, sectoral, and consumption-based is therefore the most appropriate tool for assessing the climate impacts of the Canadian construction sector. The method of environmentally extended input–output (EEIO) analysis has emerged as the principal tool for the generation of inventories satisfying these conditions and would therefore allow the gap to be bridged between the construction sector's material impacts, the assessment of which requires a consumption perspective and policymaking, which operates at the regional and sectoral level. While comparable to LCAs, EEIO models use regional data on intersectoral financial transactions to allocate environmental impacts across supply chains, rather than explicit physical data (Steubing et al., 2022). The relative ease of obtaining financial rather than physical data means that EEIO models are more easily applied at larger scales. They have been used for a variety of different ends: Besides analyses that focus on individual economic sectors ranging from construction to healthcare and public services (Eckelman et al., 2018; Larsen & Hertwich, 2009), EEIO analyses have been used to assess the consumption-based GHG emissions of individual nations such as Turkey (Mangır & Şahin, 2022), emissions embodied in multilateral and bilateral trade flows (Norman et al., 2007; Yang et al., 2022), individual final demand categories such as household consumption (Feng et al., 2021; Steen-Olsen et al., 2016), or to perform comparisons of subnational regions such as Norwegian municipalities and Chinese provinces (Larsen & Hertwich, 2010; Xu et al., 2022).

EEIO assessments of construction as a sector have been conducted at the global scale, finding that in 2009 global construction was responsible for 5.7 billion tons of CO_2 emissions, or around 23% of global emissions (Huang et al., 2018). Studies have also been conducted at the national scale in Ireland (Acquaye & Duffy, 2010), Norway (Huang & Bohne, 2012), and China (Wang et al., 2018; Zhu et al., 2023), among others. However, these existing analyses suffer from severe limitations as they do not distinguish between different types of construction activities, or do not consider the difference in embodied emissions for imported products, which is essential for a country such as Canada, which is exposed to a significant amount of international trade.

Applications of EEIO models to the Canadian context have typically required the development of independent models with a specific focus, such as assessing the impacts of major extractive industries in the province of Saskatchewan (Liu et al., 2020) or the development of an optimization tool to guide the green economy transition (Bagheri et al., 2019). Global models such as EXIOBASE are also employed due to their ease of use (Walzberg et al., 2020), though they display a low sectoral resolution and do not allow any distinction between provinces. The development of the OpenIO-Canada data tool (Agez, 2022) has significantly lowered the barrier to entry for EEIO modeling in Canada as it facilitates the creation of high-resolution multi-province EEIO models. It has been used to determine the carbon footprints of procurement by Public Services and Procurements Canada (Maxime & Lesage, 2020) and the life cycle of environmental emissions and health damages from the Canadian healthcare system (Eckelman et al., 2018).

Despite the recent uptick in Canadian EEIO modeling, only one paper touches on construction in Canada (de Bortoli & Agez, 2023). The paper uses OpenIO-Canada to perform an environmental analysis of the Canadian road network and finds that road construction is responsible for only 5% of the network's GHG emissions, with the remainder made up of emissions driven by the production and use of vehicles. Despite the ability of OpenIO-Canada to link trade to the global EXIOBASE model, the study instead makes the assumption that imported products feature the same environmental intensities as domestic products.

The primary goal of the research presented in this paper was therefore to build upon de Bortoli and Agez (2023) and generate the first comprehensive consumption-based accounts of construction-driven emissions in Canada using the EEIO approach. The research avoids the limitations of past national studies from Europe and China by incorporating imports and distinguishing between different construction subsectors, and as such, it sets a new benchmark for consumption-based analyses of construction. It makes explicit the role of construction as a principal driver of emissions in Canada and argues that demand-side strategies targeted at the construction sector must be included in any further revisions of the emissions reduction plan. The results presented here also act as a baseline for future scenario-based analyses, where the influence of specific demand-side strategies on national emissions can be modeled using the EEIO approach.

The secondary goal of the research was to take advantage of the nature of EEIO matrices to perform a series of novel analyses on the geographic flows of embodied emissions between regions where the emissions were generated and the regions where downstream products and services were used in construction, as well as an analysis of the emission intensity per unit GDP of construction subsectors for different regions. This kind of spatial analysis provides the necessary context given the importance of imports to the Canadian economy and the decentralized nature of the Canadian construction sector, itself a product of the large distances separating population centers and the highly federalized nature of Canadian governance.

The results section of this paper includes an overview of the distribution of embodied emissions by the province as well as by construction subsector (grouped into seven categories for legibility), a breakdown of the inputs into three representative forms of construction (residential buildings, roads and highways, and communications networks), an analysis of the interprovincial and international flows of embodied emissions destined for residential construction, a comparison with embodied energy, and an analysis of GHG efficiency per unit of GDP. These results are not exhaustive and are rather selected to be representative of the data available.

2 | METHODS

2.1 | Input–output methodology

EEIO analysis is a method that combines regional data on: (1) environmental impacts by economic sectors and (2) financial transactions between these same sectors over a year. The data are typically made available by national statistical agencies. The sectoral impacts are allocated and reallocated to other sectors via the network of financial transactions, and once all impacts have been allocated across supply chains to final demand groups, it is considered to represent the overall environmental impact associated with consumption by each final demand group.

An EEIO analysis requires the compilation of several data tables, primarily a symmetric input–output table (IOT). IOTs are compiled from supply–use tables (SUTs), which record the products produced by industries, as well as the products consumed by both industries and final consumers. The conversion of SUTs to an IOT can be conducted in several different ways. This study makes use of the industry-technology assumption to create product–product IOTs, represented by the following equation:

$$Z = U\left(\hat{g}^{-1} V^{T}\right), \tag{1}$$

where U represents the use matrix for intermediates (value of products used by industries in 2018 Canadian dollars), $\hat{g}$ represents a diagonalized vector representing total industry output in Can$, and V^T represents the transposed supply matrix for intermediates (products supplied by industries in Can$). Z represents the IOT for a region and can be converted to a normalized "technology matrix" A, representing the dollars of inputs per dollar of output for each product, using the following formula, where $\hat{x}$ represents a diagonal matrix of total product output:

$$A = Z\hat{x}^{-1}. \tag{2}$$

The technology matrix can be used to calculate the total environmental impacts associated with each category of final demand, represented by the letter E, using the following formula:

$$E = S(I - A)^{-1}Y + \mathrm{FY}, \tag{3}$$

where S represents the direct impacts associated with the production of each product category normalized by dollar of output, I is the identity matrix, Y represents spending by final demand categories, and FY represents direct impacts associated with final consumption itself rather than intermediate production, such as the burning of gasoline in personal vehicles.

Further detail on compiling IOTs and assembling EEIOs can be found in Brown et al. (2021), Eurostat (2008), Joint Research Centre et al. (2006), and UN Department of Economic and Social Affairs (2018).

2.2 | Data sources and tools

The primary data-processing tool used for this study was OpenIO-Canada v2.4, an open-source Python class developed by the International Reference Centre for the Life Cycle of Products, Processes and Services (CIRAIG) whose codebase (Agez, 2022) was adapted for this study. OpenIO-Canada is also sometimes used to refer to the dataset generated from the original version of the tool. The modified OpenIO-Canada class was used in this study to compile the underlying EEIO matrices into Python multi-indexes and connect them to international trade data.

The monetary data used to construct the U, V, and Y matrices as well as the g and x vectors were obtained from the supply and use tables provided by Statistics Canada (2021). These tables follow the Supply and Use Product Classification (SUPC) and break down the Canadian economy into 492 commodities for each of the 13 provinces and territories, 19 of which represent the outcomes of construction and include different forms of buildings and infrastructure. The tables also feature data on demand by final consumers, such as households, governments, and gross fixed capital formation (GFCF), separated into 279 final demand categories. Fifty-four of these categories are grouped as part of the construction subcategory of GFCF, with each category representing an industry or government service's demand for the 19 forms of construction. Although Statistics Canada also develops their own symmetric IO tables, they only exist in industry–industry form.

Data on annual carbon, methane, and dinitrogen monoxide emissions were obtained from Statistics Canada's physical flow accounts (Statistics Canada, 2023c) and were reallocated to the SUPC. The remaining GHG emissions were obtained from the National Pollutant Release Inventory (ECCC, 2022b). Data on end energy use (EEU), which is measured in joules and is defined by the Canadian energy use accounts as the annual consumption of energy products (including coal, diesel, natural gas, and electricity) by domestic end users for energy purposes, were also obtained as part of the physical flow accounts (Statistics Canada, 2023d). Further detail on Canadian environmental–economic accounting can be found in the methodological guide (Statistics Canada, 2023e).

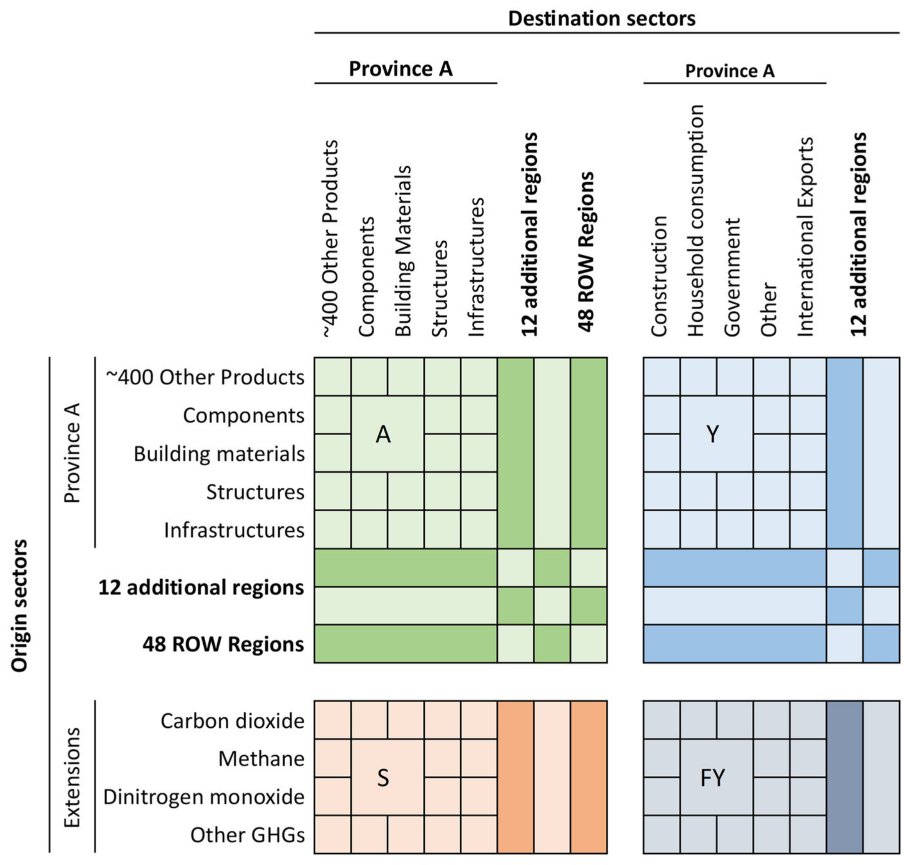

FIGURE 1 Diagram representation of the matrices making up the environmentally extended input–output (EEIO) model. From the top left clockwise are the *A* matrix (technology matrix), *Y* matrix (spending by a final demand category), FY matrix (direct emissions associated with the consumption), and *S* matrix (normalized greenhouse gas [GHG] emissions of production).

This data are used to construct the *S* matrix. *A* and *S* matrix coefficients for international trade were obtained from EXIOBASE version 3.8 (Stadler et al., 2018), an open-source global multi-regional EEIO model featuring 44 mostly European countries and 5 rest-of-world regions. The structure of the *A*, *Y*, *S*, and *FY* matrices is presented in Figure 1. Finally, the IMPACT World+ 2.0 database was used to characterize the various GHG emissions into kgCO2eq at GWP100 (Agez et al 2022; Bulle et al., 2019).

3 | RESULTS

3.1 | Placing construction emissions in context

One of the major advantages of the EEIO approach is that an entire economy is modeled simultaneously, meaning that different economic subsectors can be compared in a consistent manner. In 2018, Canada's overall consumption was responsible for driving 647 million tCO_2eq, or 17.4 tCO_2eq per capita. This is consistent with the value of 18.0 tCO_2eq derived for the year 2017 by de Bortoli and Agez (2023), who showed in turn that their value is consistent with other models such as Global Carbon Project (2021), with values of 15.7 tCO_2eq in 2017 and 14.4 tCO_2eq in 2018. Canada's construction sector was responsible for driving 86.9 million tCO_2eq, or 2.3 tCO_2eq per capita. This is higher than per capita values calculated for China (1.9 tCO_2eq per capita in 2020), the United States (1.2 tCO_2 per capita in 2009), and Norway (1.1 tCO_2eq per capita in 2007) (Huang & Bohne, 2012; Huang et al., 2018; Zhu et al., 2023).

As depicted in Figure 2, emissions driven by Canadian construction can also be compared to those driven by government spending (56 million tCO_2eq), the production of commodities destined for international export (469 million tCO_2eq, though these emissions are not counted as part of Canadian consumption), and household consumption (447 million tCO_2eq). The underlying data for Figure 2 are available in table T2 of the data repository https://zenodo.org/records/11183234. The Canadian construction sector, represented by the construction GFCF final demand category of the Canadian supply and use tables, therefore drives approximately 13% of overall national consumption emissions. This is slightly up from the value of 12% in 2017 identified by de Bortoli and Agez but is lower than the global average of 23% for 2009 (Huang et al., 2018), or values for China

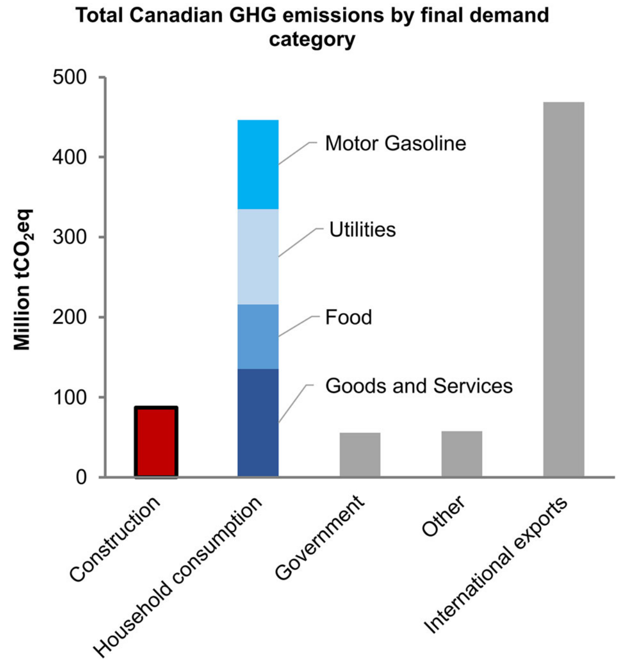

FIGURE 2 Total greenhouse gas (GHG) emissions driven by Canadian spending in different final demand categories. These correspond to the columns of the *Y* matrix in Figure 1. *Construction* represents gross fixed capital formation for construction products. *Government* includes defense services, educational services, and health services, among others. *Other* is defined as gross fixed capital formation for machinery and equipment as well as intellectual property. The underlying data for this figure can be found in table T2 of the data repository https://zenodo.org/records/11183234.

in 2005 (14.3%) and 2020 (25.2%) obtained by Zhu et al. (2023). The climate impact of Canadian construction is roughly equivalent to the impact of food consumption (12%) and is below emissions from housing (here defined as utilities and other operational impacts from housing) as well as gasoline for private vehicles (18% and 17% of Canadian consumption emissions, respectively).

3.2 | Geographic and sectoral distribution of Canadian construction emissions

Disaggregating construction-driven emissions by the construction subsector shows that emissions are dominated by residential buildings (34 million tCO_2eq), followed by non-residential buildings (14 million tCO_2eq). Following these building categories are oil and gas extraction works (12 million tCO_2eq) and transportation infrastructure works (10 million tCO_2eq). While residential buildings are responsible for the largest share of construction-driven emissions nationally (39%), it is not the case in all provinces, with Alberta and Saskatchewan displaying a larger proportion of emissions from oil and gas extraction works. Figure 3 shows construction-driven emissions disaggregated by the province or territory in which the construction took place. The 19 forms of buildings and infrastructure have been aggregated into seven categories for legibility. The underlying data for Figure 3 are available in table T3 of the data repository (https://zenodo.org/records/11183234).

Results also show that construction emissions are disproportionately driven by activity in western Canada (British Columbia, Alberta, and Saskatchewan), relative to the province population. This is partly due to the contribution of oil and gas extraction works, which dominate construction emissions in Alberta and Saskatchewan (driving 38% and 43% of their provincial construction emissions, respectively). Another contributing factor is the high quantity of emissions driven by residential construction occurring in British Columbia and Alberta: 35% of national emissions driven by residential construction are the result of construction in these two provinces. This is in line with the distribution of population growth in Canada, where, despite representing only 25% of the Canadian population, they accounted for a 34% share of national population growth in the 5 years leading up to the study year of 2018 (Statistics Canada, 2023b). A final contributing factor is the high emission intensity of electricity generation in Alberta, which increases the climate impact of any production activities upstream of construction (see Section 3.5).

3.3 | Breaking down sources of emissions within construction subsectors

Results from contribution analyses of the individual construction subsectors show which inputs to construction are responsible for driving emissions. A breakdown of 3 of the 19 forms of construction (residential buildings, roads and highways, and communication networks) is displayed

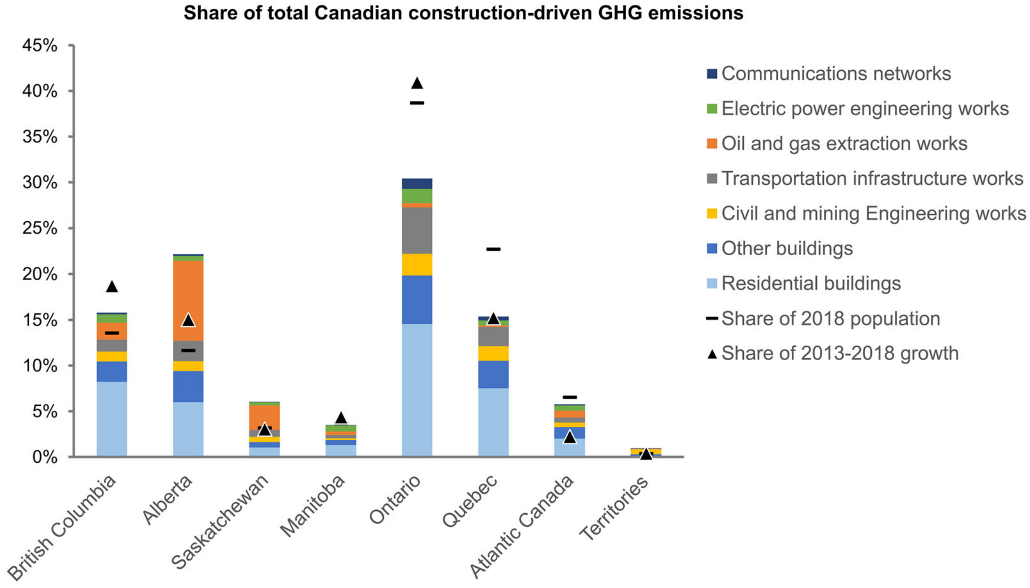

FIGURE 3 Distribution of construction-driven emissions across Canada. Provinces are arranged from west to east. The provinces of New Brunswick, Nova Scotia, Prince Edward Island, Newfoundland, and Labrador have been aggregated into a single category for legibility, as were the territories. The underlying data for this figure can be found in table T3 of the data repository https://zenodo.org/records/11183234.

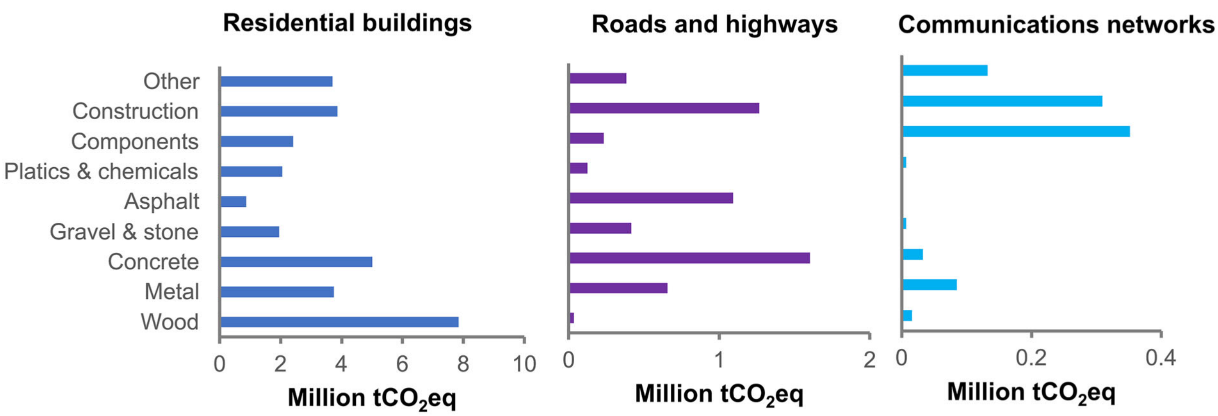

FIGURE 4 Sources of embodied emissions driven by residential building construction (left), road and highway construction (middle), and the construction of communication networks (right). The underlying data for this figure can be found in table T4 of the data repository https://zenodo.org/records/11183234.

in Figure 4. The underlying data for Figure 4 are available in table T4 of the data repository (https://zenodo.org/records/11183234). Sources of embodied emissions have been aggregated into nine major categories for legibility (aggregations are available in the supplementary materials).

Figure 4 shows that the emissions driven by residential building construction are sourced relatively evenly, with 12% of emissions driven by construction activities, 16% from concrete consumption, 12% from metal, and 25% from wood. The potential storage of biogenic carbon is not accounted for in this analysis. Results for roads and highways show that emissions are primarily driven by construction activities (22%), asphalt (19%), and concrete (28%). These results for roads and highways replicate those of de Bortoli and Agez (2023). Finally, emissions driven by communications networks are primarily driven by construction (33%) and manufactured components (37%).

The construction activity sector is not directly analogous to direct emissions from construction, as it also includes emissions from the manufacture of the construction machinery and emissions associated with design services. Nevertheless, it provides an idea of the scale and variation of direct emissions relative to the remaining sources of embodied emissions. In all three cases, direct emissions are a small fraction of the total (less than 12%–33%), while the relative weights of direct emissions from roads and highways and communications networks are roughly double and triple the weight of direct emissions from the construction of residential buildings.

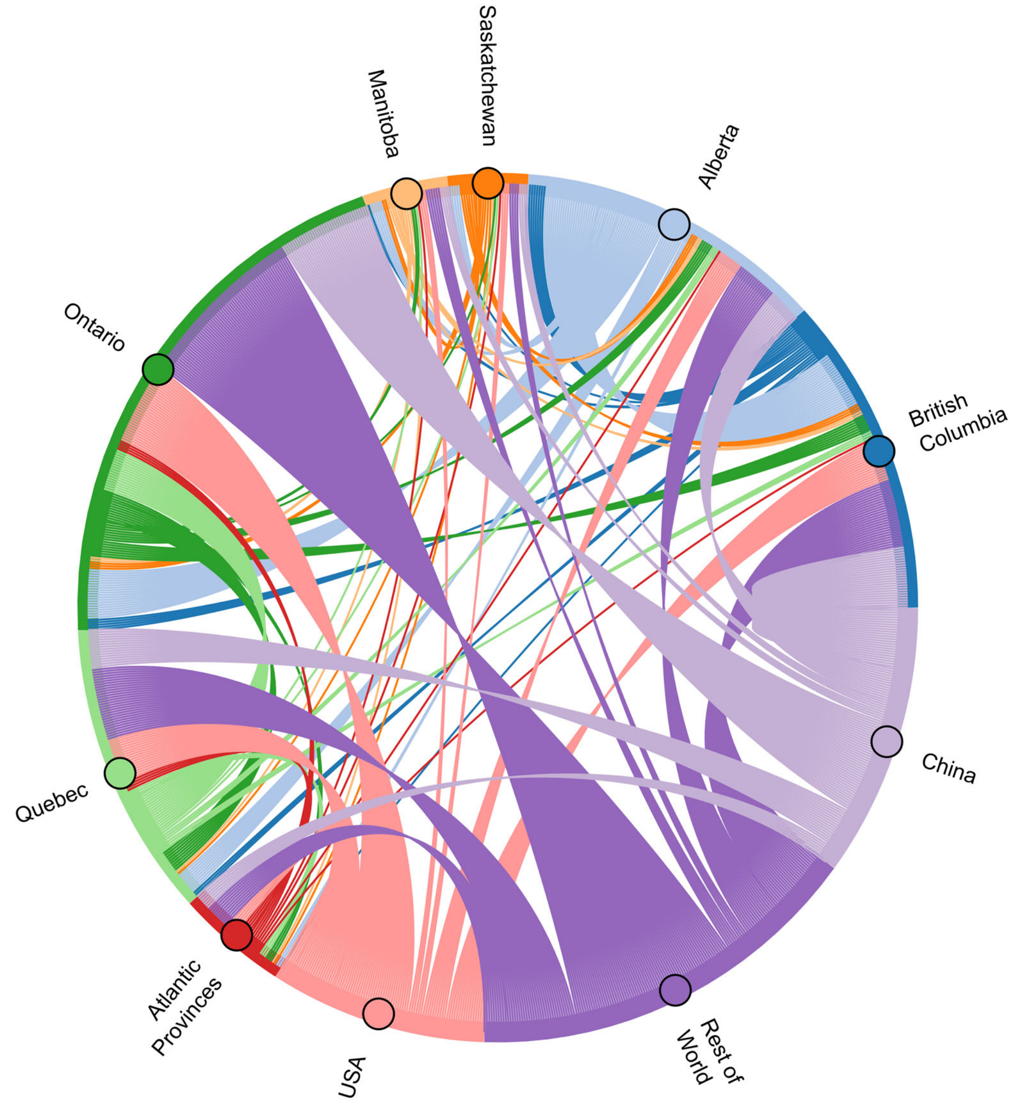

FIGURE 5 Representation of bilateral flows of embodied emissions to provincial residential construction. Flows internal to each province, as well as exports destined for non-Canadian construction sectors, have not been depicted. Canadian Territories have not been represented due to the small size of their flows. The underlying data for this figure can be found in table T5 of the data repository https://zenodo.org/records/11183234.

3.4 | Mapping flows of embodied emissions in residential building construction

There are significant interprovincial as well as international flows of emissions embodied in the materials and services used in construction. The results of an analysis of the flows driven by residential construction are depicted in Figure 5. The underlying data for Figure 5 are available in table T5 of the data repository (https://zenodo.org/records/11183234). Although this analysis can be performed for all construction subsectors, only residential construction is presented here for brevity. The origin of a flow represents the region where emissions were generated during the manufacturing of any materials or the provision of any services at any step along a supply chain that flows to a construction sector. The destination of a flow represents the region where construction took place using materials and services whose upstream emissions have been accounted for. For instance, GHGs emitted during the manufacture of a particular component in region A, which is then further assembled in region B before being used as part of a residential construction project in region C, is depicted as a flow from A to C. Emissions from the assembly in region B is depicted in a second flow from B to C.

Figure 6 represents the origins of embodied emissions in more detail. In all provinces approximately 30%–40% of embodied emissions destined for residential construction are imported from outside Canada. The underlying data for Figure 6 are available in table T6 of the data repository (https://zenodo.org/records/11183234). The proportion of locally produced emissions varies more substantially, from 22% in Manitoba to 59% in

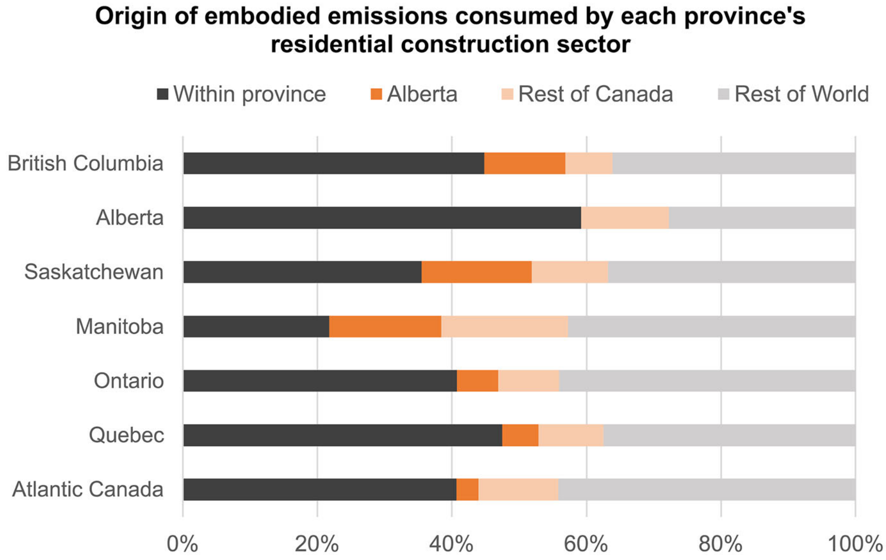

FIGURE 6 Origins of emissions embodied in residential buildings by the province. Provinces are arranged from west to east. The underlying data for this figure can be found in table T6 of the data repository https://zenodo.org/records/11183234.

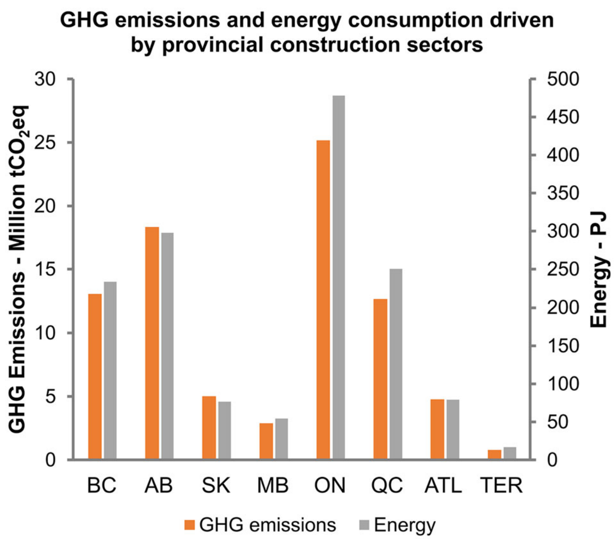

FIGURE 7 A comparison between the distributions of emissions (left) and energy (right) embodied in construction across Canadian provinces. The underlying data for this figure can be found in table T7 of the data repository https://zenodo.org/records/11183234.

Alberta. The province of Ontario is the largest Canadian source of embodied emissions, originating from 17% of emissions upstream of residential construction. However, Ontario is only responsible for 6% of interprovincial flows of embodied emissions, while Alberta is the origin of 14% of interprovincial flows. The provinces of British Columbia, Saskatchewan, and Manitoba are major consumers of embodied emissions from Alberta, with emissions generated in Alberta representing 12%, 16%, and 17% of the total consumption in each province, respectively. No other province is responsible for more than 6% of embodied emissions consumed in any other province, highlighting both the interconnectedness of the construction sectors of the western provinces as well as the high relative emissions intensity of materials and services originating in Alberta (see Section 3.6).

3.5 | Comparison with embodied energy

There is significant variability in the emissions associated with electricity production in Canadian provinces. This causes a discrepancy between the distributions of embodied emissions and embodied energy, specifically embodied EEU, across the Canadian construction sector (Figure 7). The underlying data for Figure 7 are available in table T7 of the data repository (https://zenodo.org/records/11183234) Results show that construction sectors in provinces with higher rates of clean electricity generation such as Quebec (99%), Ontario (91%), and British Columbia (90%) feature a lower intensity of embodied emissions relative to embodied energy than provinces with lower rates of clean generation such as Alberta (9%) and Saskatchewan (18%) (CER, 2023). Specifically, Quebec and Ontario construction sectors feature 9% and 5% lower embodied emissions relative to their share of embodied energy, while Alberta features 10% higher embodied emissions relative to its share of embodied energy. This implies that decarbonizing the energy grid could potentially result in a 15%–20% reduction in the embodied emissions of the Albertan construction sector. Nevertheless, the limited scale of this reduction implies that the majority of embodied emissions come from non-electricity sources, such as transportation, fuel-intensive manufacturing processes, and processes such as concrete carbonation, or are imported from other countries.

3.6 | Efficiency of construction activities

The quantity of emissions embodied in construction is driven in part by the size of each province's construction sector. To provide a measure of the efficiency of each province, it was therefore necessary to control for the size of their construction sectors, which was accomplished by defining the emissions intensity of construction in terms of emissions per dollar of spending on construction, or kgCO_2eq per dollar of GDP. In 2018, this value was 0.28 kgCO_2eq per Canadian dollar for all Canadian construction, or 0.36 kgCO_2eq per 2018 USD. This value is close to the OECD average of 0.33 kgCO_2eq per USD calculated for 2009 by Huang et al. (2018) after adjusting for inflation, though it is higher than their value of 0.27 kgCO_2eq per USD for the United States.

Table 1 shows the average intensity of the seven aggregated construction subsectors (depicted in Section 3.2) for each province as well as across Canada. A lower emissions intensity represents a higher efficiency of provincial construction. Results show that there is significant variation between provinces with Quebec displaying the lowest average emissions intensities and Saskatchewan and Alberta displaying the highest. This is again likely due to the extent of clean energy generation in Quebec as well as its absence in Saskatchewan and Alberta, though more research is necessary to establish any explicit causal relationships.

4 | DISCUSSION

Construction is responsible for driving 13% of overall consumption-based emissions in Canada, which is significantly lower than the global average of 23%. Nevertheless, the construction sector's role as a unique driver of emissions in Canada is largely absent from national decarbonization plans, as evidenced by the 2030 Emissions Reduction Plan, an omission that should be reevaluated. Demand-side strategies in construction such as material reuse and material sobriety have a significant potential to reduce national emissions alongside the more widely discussed supply-side strategies, which include the decarbonization of electricity and transportation, which would in turn also significantly reduce the impact of the construction sector. The specific extent of the potential of demand-side strategies when applied nationally remains the subject of future research.

While the per capita emissions (2.3 tCO_2eq of construction-driven emissions per capita) are approximately double those of peer countries such as the United States and Norway, the efficiency of Canadian construction (0.36 kgCO_2/USD) remains in line with the OECD average for 2009 (0.33 kgCO_2/USD) found in the literature. These high per capita emissions can be reconciled with construction's relatively low share of national consumption-based emissions by the fact that while Canada engages in significant amounts of construction per capita due to its growing population and resource extraction industries, and emissions from Canadian household consumption are even higher. Identifying explicit causal explanations should be the subject of future research. Although reducing construction emissions in net terms is important to the reduction of Canada's overall consumption footprint, even larger improvements must be made in the realm of household consumption, specifically transportation and the consumption of goods and services. Tracking the evolution of consumption-based emissions over time will necessitate the creation of multi-year datasets and should also be the subject of additional research.

The heterogeneity of Canadian provinces is an obstacle to reducing construction sector emissions as it means that a diversity of policy approaches will be needed to effectively tackle the issue. Construction-driven emissions in each province are influenced by the combined effects of (1) the extent and nature of provincial demand for construction, and (2) provincial emissions intensities per dollar of construction spending. Both factors vary by province: Provincial demand for residential construction correlates with population growth, leading to more emissions from residential construction in the fast-growing provinces of British Columbia, Alberta, and Ontario. Simultaneously, demand for oil and gas infrastructure is another form of regionalized construction demand that is especially present in Alberta and Saskatchewan. Emissions intensities per dollar correlate roughly with the proportion of clean electricity in the provincial energy mix (higher in Alberta, Saskatchewan, and the Atlantic provinces, lower in Quebec and Ontario), as well as the proportion of clean electricity in the regions from which construction products are imported from. However, this research is only capable of presenting correlations, with the statistical analyses required to assess causation left to future research.

Nevertheless, this research does suggest that provinces with fast-growing populations should concentrate their regulatory effort on increasing the efficiency of residential construction, while provinces with large oil and gas sectors should focus on increasing the efficiency of oil and gas infrastructure construction, if not limiting its development altogether. Alberta and Saskatchewan would see the largest gains from decarbonizing

TABLE 1 Summary of regional emissions and energy intensities for five aggregated construction sectors.

	Residential buildings		Other buildings		Civil and mining engineering works		Transportation infrastructure works		Oil and gas extraction works		Electric power engineering works		Communications networks	
	$kgCO_2eq$ per CAD	MJ per CAD	$kgCO_2eq$ per CAD	MJ per CAD	$kgCO_2eq$ per CAD	MJ per CAD	$kgCO_2eq$ per CAD	MJ per CAD	$kgCO_2eq$ per CAD	MJ per CAD	$kgCO_2eq$ per CAD	MJ per CAD	$kgCO_2eq$ per CAD	MJ per CAD
British Columbia	**0.28**	*4.9*	**0.27**	*4.3*	**0.29**	*6.1*	**0.34**	*6.3*	**0.26**	*5.2*	**0.27**	*4.8*	**0.29**	*5.8*
Alberta	**0.30**	*4.6*	**0.32**	*4.7*	**0.39**	*5.6*	**0.41**	*6.9*	**0.25**	*4.5*	**0.23**	*3.8*	**0.29**	*5.6*
Saskat chewan	**0.31**	*5.1*	**0.26**	*4.1*	**0.41**	*5.2*	**0.41**	*6.1*	**0.39**	*6.1*	**0.31**	*4.7*	**0.48**	*7.3*
Manitoba	**0.28**	*5.3*	**0.25**	*4.9*	**0.26**	*4.9*	**0.30**	*6.2*	**0.35**	*6.2*	**0.28**	*4.7*	**0.29**	*5.9*
Ontario	**0.24**	*4.8*	**0.22**	*3.9*	**0.32**	*5.7*	**0.40**	*7.6*	**0.34**	*4.7*	**0.24**	*4.6*	**0.34**	*6.5*
Quebec	**0.26**	*5.4*	**0.25**	*4.5*	**0.32**	*5.3*	**0.28**	*5.9*	**0.23**	*4.5*	**0.15**	*3.1*	**0.26**	*5.8*
Atlantic Canada	**0.31**	*5.5*	**0.35**	*5.3*	**0.32**	*4.6*	**0.29**	*5.5*	**0.34**	*5.5*	**0.24**	*3.6*	**0.30**	*5.9*
Territories	**0.29**	*6.0*	**0.30**	*5.4*	**0.28**	*6.5*	**0.27**	*5.8*	**0.2**	*3.7*	**0.13**	*3.3*	**0.44**	*5.9*
Canadian average	**0.27**	*5.0*	**0.26**	*4.3*	**0.32**	*5.6*	**0.36**	*6.7*	**0.28**	*4.9*	**0.24**	*4.2*	**0.31**	*6.2*

Note: Values are in 2018 Canadian dollars.

their energy grids, with the potential for 15%–20% reductions in construction emissions. A particular focus is needed on Alberta given that it exists at the intersection of all the trends described above: The province features a disproportionate and growing share of national construction activity combined with the second-highest emissions intensity of all Canadian provinces.

This paper also highlights the importance of interprovincial and international flows. The dependence of western provinces on materials and services from Alberta is an obstacle to broader improvement, as the high emissions intensities at every step of supply chains located within its borders mean that embodied Albertan emissions are currently being exported to neighboring provinces in the form of construction materials. Part of the improvement in these neighboring provinces will have to come from decarbonization efforts within Alberta. Reducing the reliance on international imports through the use of locally produced materials and components will only improve consumption-based emissions if local manufacturing processes can be made more efficient than those abroad.

A conceptual complication to the assessment of consumption-based emissions in Canadian construction is that a significant proportion of infrastructure is being developed with the goal of supporting export-driven extractive industries. This means that, under a true consumption-based perspective, a proportion of the emissions embodied in their construction should be allocated to the exported products. Given the significant scale of emissions embodied in Canadian exports, this could lead to a significant decrease in the Canadian share of embodied emissions. How this could be implemented is unclear and reveals the limitations of the consumption-based accounting perspective when applied to construction.

Another limitation of this study concerns the omission of any potential benefits of biogenic carbon storage within the wood products used during construction, benefits which may be significant given the prevalence of wood-frame construction in the Canadian residential building sector. However, the field of biogenic carbon accounting is still evolving and there is a lack of consensus on how these benefits can be quantified for inclusion in an EEIO model, given that they arise from the temporal displacement (rather than elimination) of carbon emissions, and given the remaining uncertainty surrounding impacts from land use and land use change, among others (Hoxha et al., 2020; Ouellet-Plamondon et al., 2023).

Finally, making the data presented in this paper useful for policymakers will mostly require using them as a baseline for future scenario-based analyses, where the potential emissions savings of different policy interventions are compared to business as usual. This will be the subject of upcoming research.

5 | CONCLUSION

This research presents results from a comprehensive account of GHG emissions driven by demand from the Canadian construction sector, emissions which can also be conceptualized as being embodied within the buildings and infrastructure resulting from construction. It shows that while direct emissions from construction are limited (2%–3% of industrial emissions), demand from the sector is responsible for driving 13% of Canadian consumption-based emissions. This highlights the importance of consumption-based models such as EEIO models and illustrates their ability to provide context to the production-based accounts that currently drive much of Canadian climate policymaking. The results in this paper also show that provinces differ in the extent of their construction emissions and that this variation reflects patterns in population growth, the presence of the oil and gas industry, and differences in construction efficiency as measured in $kgCO_2eq$ per dollar of spending on construction. These differences in efficiency are themselves downstream of the cleanliness of local electricity generation, as well as the extent and origin of imported construction materials. This regional variation must be taken into account when designing potential policy interventions for the construction sector.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The code used to generate the results of the study, as well as the data itself, are accessible at https://doi.org/10.5281/zenodo.11183234

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