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Carbon footprints calculation in the IoT industry: Organization and Product

Autor: Oumaima Zghouda

Tutor: Dr. Francisco Hernández-Ramírez

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Resumen

En la actualidad, la sostenibilidad y la reducción de las emisiones de carbono son temas cruciales para las empresas a nivel global. La evaluación de la huella de carbono se ha vuelto indispensable para gestionar los impactos ambientales e identificar áreas de mejora.

Esta tesis de máster evalúa la huella de carbono de Worldsensing y sus productos para el año 2023. El estudio incluye el cálculo de la huella de carbono de la organización para los Alcances 1, 2 y 3, que abarcan las emisiones directas, las emisiones indirectas de la energía comprada y otras emisiones indirectas, como los materiales de producción y los viajes de negocios. Además, se realiza una Evaluación del Ciclo de Vida (LCA) de un producto IoT, un registrador de datos inalámbrico, para examinar su impacto ambiental desde la extracción de materias primas hasta su disposición y reciclaje.

Los resultados muestran que la huella de carbono total de Worldsensing para 2023 fue de 1.896 toneladas de CO_2-eq, siendo las emisiones del Alcance 3, particularmente del transporte, los contribuyentes más significativos. La LCA de los dispositivos IoT (nodos y gateways) mostró una huella de carbono total de 450 toneladas de CO_2-eq, con emisiones sustanciales de la extracción de materias primas y el transporte.

Para mitigar los impactos ambientales, se recomienda reducir el número de envíos anuales, consolidar pedidos y utilizar transporte marítimo en lugar de aéreo siempre que sea posible. Además, se sugiere adoptar vehículos eléctricos o más eficientes y fomentar el uso del transporte público. Implementar estas estrategias es esencial para avanzar hacia operaciones más sostenibles y contribuir significativamente a la reducción de la huella de carbono de Worldsensing.

Adicionalmente, explorar tecnologías alternativas de recolección y almacenamiento de energía más allá del litio es crucial para minimizar los impactos ambientales.

Por último, es importante considerar el impacto ambiental y la cantidad de materiales utilizados en el diseño de nuevos productos. Aunque algunos materiales como el hierro se compran en grandes cantidades y tienen un impacto ambiental relativamente bajo, otros como el oro, a pesar de comprarse en cantidades menores, presentan un impacto ambiental significativamente mayor.

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List of abbreviations

CMT	Connectivity Management Tool
CNMC	Comisión Nacional de los Mercados y la Competencia
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
EMS	Environmental Management System
EU	European Union
GHG	Greenhouse Gas Emissions
IoT	Internet of Things
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
REACH	Registration, Evaluation, Authorization, and Restriction of Chemicals
RoHS	Restriction of Hazardous Substances
SME	Small and Medium-sized Enterprises

1. Introduction

Climate change and global warming are internationally recognized as pressing issues, primarily driven by greenhouse gas (GHG) emissions from industrial and anthropogenic activities. Restoring ecological balance requires urgent action to reduce these emissions.

The Paris Agreement aims to keep the rise in global average temperature well below 2 °C above pre industrial levels and to continue efforts to limit the temperature increase to 1.5 °C [1]. In alignment with this goal, the EU has set a target to reduce greenhouse gas emissions by at least 55% below 1990 levels by 2030, as part of the "European Green Deal" and the "Fit for 55" strategy, and to achieve climate neutrality by 2050 [2]. To achieve these ambitions, it is imperative to understand and manage the environmental impact of our activities, particularly those related to GHG emissions.

Against this backdrop, calculating carbon footprint has become an important tool for understanding and managing the environmental impact of business operations. By measuring GHG emissions throughout the lifecycle of a product or service, areas for improvement can be identified, and strategies can be developed to reduce climatic impacts. Companies anticipate facing an economy with CO_2 reduction obligations, where GHG emissions will be subject to taxes, restrictions, or regulations. In this context and starting in 2025, large companies affected by Law 11/2018 (Spanish legislation) will be required to report their greenhouse gas emissions and plans to reduce them, based on emissions made in 2024 [3].

The reduction of emissions and the analysis of the carbon footprint throughout the production and supply chain are crucial for sustainable development and are becoming increasingly pivotal issues for the business sector. Companies' sustainability objectives are mainly related to competitiveness, costs, regulatory risks, consumer perception, and market position.

This Master's thesis presents a calculation of the carbon footprints of both Worldsensing as an organisation (SME) and its products. The initial analysis focuses on calculating the carbon footprint for the year 2023 with a comprehensive examination of all emissions categories: Scopes 1, 2, and 3; this detailed analysis aims to uncover the direct emissions from sources owned or controlled by Wordsensing (Scope 1), the indirect emissions from the generation of purchased energy consumed by the company, such as electricity (Scope 2), and all other indirect emissions, including emissions from the production of materials, product usage , rented vehicles, outsourced services, waste management, and business travel (Scope 3) [4].

Corporate carbon accounting, which aims to calculate the carbon footprint of the organisation, contributes to transparency and ensures legal compliance.

The second analysis begins with a case study to illustrate the sustainability of a specific Internet of Things (IoT) product. Results can be easily extrapolated to the rest of the product portfolio.

Specifically, the examined product is a wireless data logger with a vibrating wire 5-channel. Worldsensing IoT products are suitable for the mining and construction industries, which contribute to reducing labour workloads by providing data on infrastructure conditions, essential for both preventing risks and assessing operational impacts [7]. However, it is essential to quantify their environmental impact to determine if they can be deployed worldwide in a sustainable approach.

As a methodology, Life Cycle Assessment (LCA) can be used to evaluate the environmental performance of electronic devices, such as the IoT node under analysis, throughout their entire life cycle, from the extraction of raw material to disposal and recycling. LCA not only quantifies a product's current impacts but also guides the (re-)design of products to make them more environmentally sustainable. In this work, we developed a toy model for the LCA of the selected product. evaluated the current situation, and proposed improvements to reduce the product's impact.

An important aspect of the product life cycle is the supply chain of raw materials "upstream" of the company's own manufacturing sites. While that process may be considered less controlled by the company, it is also a major factor in a product's overall environmental impact and in a company's sustainability efforts. This stage indicates whether our product complies with European Union RoHS (Restriction of Hazardous Substances) and REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) regulations.

The RoHS Directive restricts the use of six hazardous materials found in electrical and electronic products: lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE). Products containing any of these substances will not be placed on the European market if they exceed specified thresholds (up to 0.1% for each substance, except cadmium, which is restricted to 0.01%) [5].

The REACH regulation in the European Union requires manufacturers to ensure their products are safe and to provide detailed information on the substances they contain. This is to protect human health and the environment from any potential dangers. Therefore, products must comply with REACH regulations to ensure their safety and gain access to the market [6].

Worldsensing aims to make an inventory for its emissions to calculate the carbon footprint of its products and processes. This will ultimately allow it to analyse methods for reducing its overall emissions. Such an analysis enables Worldsensing to provide its clients with the product's carbon footprint, along with a detailed analysis demonstrating that Worldsensing products are optimal for preserving the environment and reducing carbon emissions. Actually, the products acquire data from infrastructure without the need to travel periodically to inspect them, thus minimising emissions for the clients.

This study demonstrates the difference in emissions before and after the implementation of Worldsensing's product in a standard infrastructure. It provides valuable insights to clients, showing the environmental benefits and emission reductions achieved with the product. Moreover, this analysis helps Worldsensing to provide delivery documentation in compliance with the aforementioned European environmental norms (REACH and RoHS).

2. Objectives

2.1. General Objective

The main objective of this study is to estimate the carbon footprints of Worldsensing as an organisation and its products, such as wireless data logger vibrating wire 5-channel, as shown in Figure 1. Additionally, the study aims to provide a comprehensive understanding of the environmental impact and potential strategies for reduction at company and product level.

2.2. Specific objectives

- To provide a methodology for estimating the carbon footprint generated by Worldsensing and its products.
- To quantify and analyse the carbon footprints of both Worldsensing as an organisation and its products.
- To estimate the emissions before and after using the Worldsensing product, highlighting the importance of the product in minimising the carbon footprint for its clients.
- To suggest strategies and proposals to decrease and mitigate the emissions.

Figure 1: Vibrating wire 5-channel (LS-G6-VW) [7].

3. Company Profile

Worldsensing, founded in 2008, collaborates with more than 270 engineering service providers worldwide to enhance geotechnical, geospatial, and structural monitoring in mining, construction, rail, and critical infrastructure management. With over 3,000 networks deployed globally and connecting over 65,000 sensors to the Internet of Things, the so-called Loadsensing product suite is the leader in the loT remote monitoring space. Loadsensing monitoring solution includes best-in-class edge devices, LoRa-based wireless connectivity, and a cloud-based management platform. The company also joins forces with key industry players to offer software applications and solutions that engineering service providers use to add value to end customers [8].

IoT remote monitoring solutions enable near real-time data acquisition of structural sensors, as well as remote network management. Normally, it does not require a cellular network to function, as it uses a specific communication protocol called LoRa to transmit data.

The data loggers are connected to existing sensors in the field, such as piezometers, to monitor risk points in real time, like water pressure in a tailing dam. In some cases, the data loggers are also a 2-in-1 device, i.e. a sensor, and a data transmitter.

These devices transmit monitoring data wirelessly to a gateway, which is usually connected to the internet. Additionally, the Connectivity Management Tool (CMT) software, an optional SaaS solution to manage the IoT network remotely, can be integrated with third-party data visualisation tools for an effective data processing of the acquired data [9].

The overall scenario of the monitoring solution is illustrated in Figure 2.

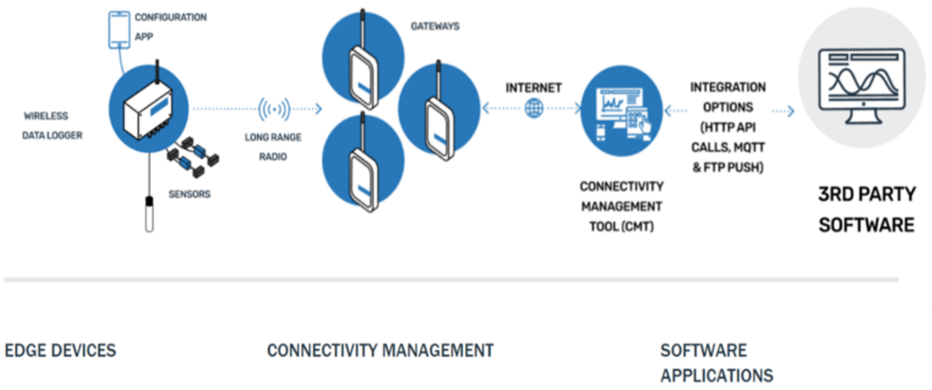

Figure 2: Functional Diagram of Worldsensing Monitoring Solution Architecture [9].

4. Calculation of the organisation Carbon footprint

The carbon footprint (CF) of Worldsensing refers to the total GHG emissions, specifically CO_2 emissions, associated with its operations, including both direct and indirect emissions.

In our study, we will focus solely on the Barcelona headquarters due to the limited data available from other offices. Actually,

1) The Worldsensing UK office is currently inactive.
2) The Worldsensing US office, founded in mid-2023, has only one employee working in a co-working space, while the rest of the employees, who are sales representatives, work from home. Their carbon footprint is mainly related to travel, which will be considered in our calculations.
3) The Worldsensing Poland office is in the process of liquidation and is scheduled to close by September.
4) The rest of the commercial offices indicated at the company website (such as Singapore) are not real offices but commercial PO boxes, so we will also exclude them from the study.
5) Finally, the laboratory at the University of Barcelona established in the frame of WS-UB Chair is very small, with only 2-3 employees using it occasionally to conduct tests and development experiments- Due to its small size, it is excluded from the calculation (Figure 3) [10].

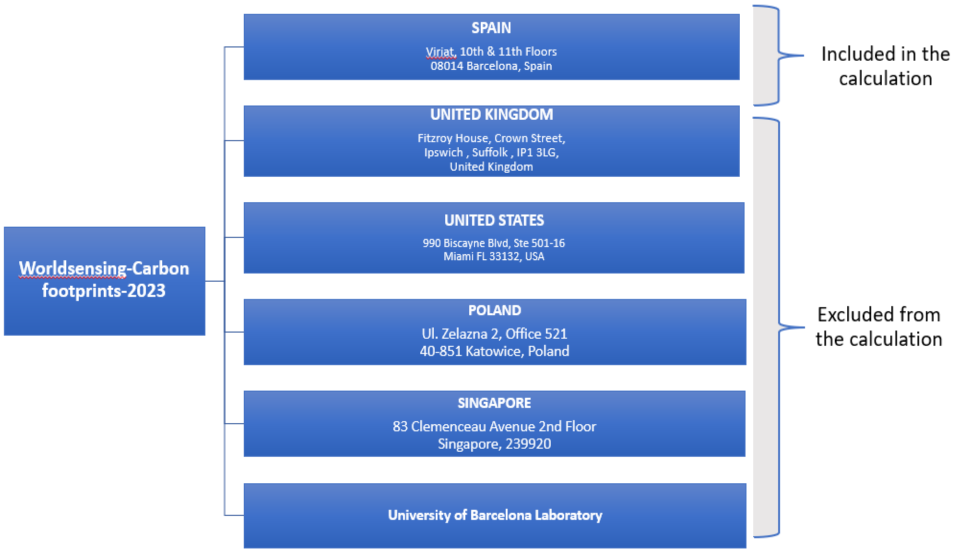

Figure 3:Extension Analysis of Worldsensing's 2023 Carbon Footprint Analysis: Included and Excluded Sites [10].

4.1. Methodology

Measurement and reporting of GHG emissions are the foundation for global warming countermeasures. Therefore, several international standards and guidelines have been established to guide companies seeking to measure their carbon footprint, reduce environmental loads, and build the foundation for a sustainable economy [11]. These standards include:

- GHG Protocol: This standard evaluates and reports GHG emissions by companies and organisations and defines the concepts of Scope 1, Scope 2, and Scope 3 (Figure 4) [11].
- ISO 14064: This international standard on measurement, reporting, and verification of GHG provides comprehensive guidelines for GHG measurement and reporting methods, data management, and verification processes. ISO 14064 comprises the following parts:
  - ISO 14064-1 (2018): Quantification and reporting of GHG - Provides methods for evaluating GHG emissions by companies at the organisational level [11].
  - ISO 14064-2 (2019): Quantification and reporting of GHG - Focuses on project-based efforts, providing methods for evaluating the effects of specific projects in reducing or removing GHG at the project level [11].
  - ISO 14064-3 (2019): Quantification and reporting of GHG - Provides methods for verification and validation of GHG statements and qualification of verifiers [11].

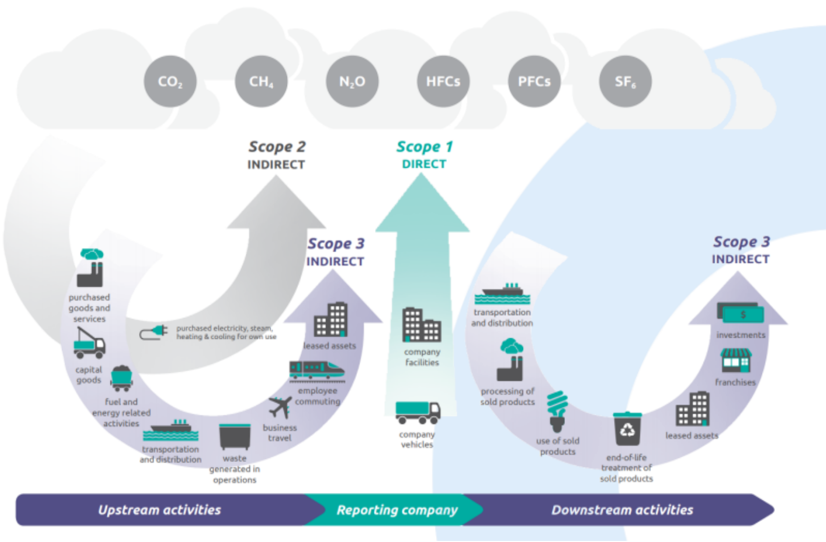

Figure 4: GHG Protocol Scopes and Emissions Flow (GHG Protocol 2013) [4].

The GHG Protocol categorises emissions into three scopes to segment the indirect and direct sources of emissions for businesses:

- Scope 1: Direct greenhouse gas emissions produced by the company. This includes all emissions originating from fuel combustion or the direct release of greenhouse gases linked to activities and sources under the company's control, such as process technologies and vehicles [4].
- Scope 2: Indirect greenhouse gas emissions associated with the purchase and delivery of electricity and energy services from third-party providers consumed by the company [4].
- Scope 3: All other indirect greenhouse gas emissions arising from the company's activities and throughout their value chain, including downstream emissions (waste stream and consumer emissions) for services and products and upstream emissions (supply chain). This scope generally accounts for the highest impact of greenhouse gases from a company, encompassing emissions from purchased operations, outsourced freight transportation, and distribution. Compliance with this scope requires cooperation along the entire value chain [4].

Table 3 in Annex 1 provides a description of available data in Scopes 1, 2, and 3 for the Worldsensing case. Scope 1 includes vehicle models and distance data; Scope 2 covers electricity consumption; Scope 3 encompasses transportation, materials, waste management, and contracted services.

4.2. Results and interpretation of the organization´s carbon footprint

4.2.1. Scope 1: Direct emissions from rented cars

This analysis focuses on the CO_2 emissions from rented cars used for business purposes. The data regarding the CO_2 emissions from these rented cars were obtained from reports provided by Worldsensing's travel booking software and travel agencies, including TravelPerk [55] and Captio [56]. For TravelPerk, the CO_2 emissions data were provided directly by the agency. For Captio, the available data included the distance traveled and the type of vehicle used (Table 4, Annex 1).

The results shown in the figure were obtained by multiplying the emission factors (g/km) (Table 5, Annex 1) by the distance traveled (km).

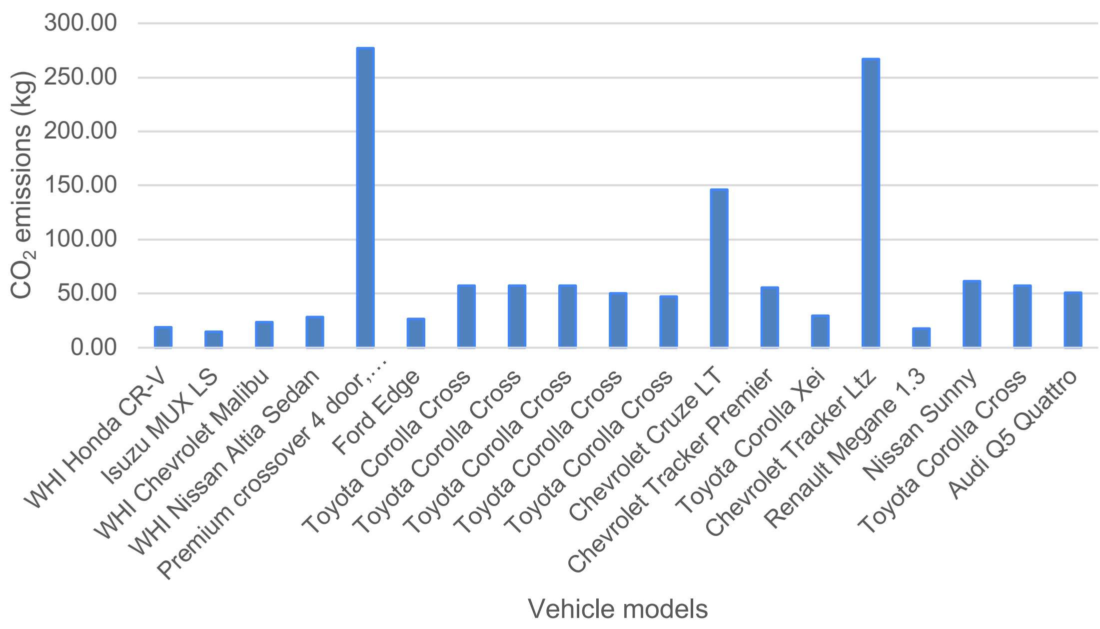

Figure 5: CO_2 emissions from rented cars (Source: software Captio).

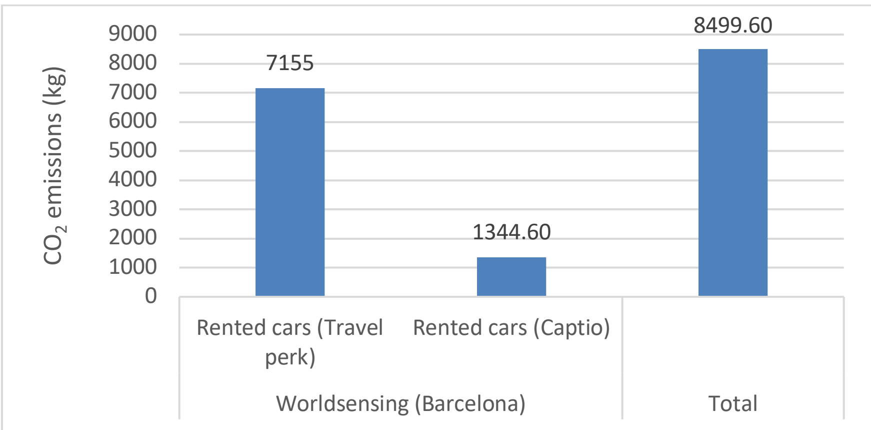

Figure 6: Total CO_2 emissions from rented cars (Source: TravelPerk and software Captio).

The total CO_2 emissions from rented cars amounted to 8499.60 kg. Of these, 7155 kg were from cars rented via Travel Perk, and 1344.60 kg were from cars rented via Captio, both of which are travel platforms used by Worldsensing (Figure 6).

These results indicate that the majority of CO_2 emissions from rented cars stem from bookings made through TravelPerk, suggesting that optimizing travel bookings by selecting high-efficiency vehicles, such as hybrids or electric cars, for rentals through this platform could significantly reduce the Scope 1 carbon footprint. These types of vehicles have significantly lower CO_2 emissions compared to traditional gasoline or diesel cars, making them a sustainable choice for business travel.

4.2.2. Scope 2: Indirect emissions from imported energy

Scope 2 emissions encompass the indirect GHG emissions resulting from the consumption of purchased electricity. For Worldsensing, these emissions predominantly arise from the electricity used in headquarter offices. To quantify these emissions, we collected the monthly electricity bills for floors 10 and 11 for the year 2023. The emission factor used for these calculations was obtained from the Comisión Nacional de los Mercados y la Competencia (CNMC) 2023 report [57].

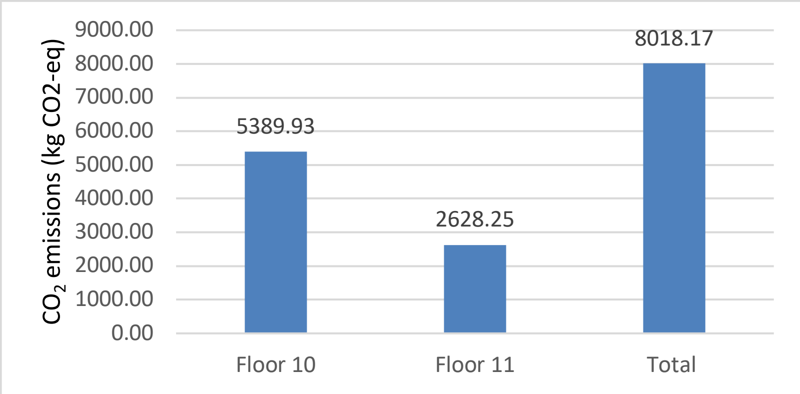

Figure 7: CO_2 emissions from electricity consumption in Worldsensing headquarters.

To calculate the CO_2 emissions, the total electricity consumption for each floor was multiplied by the emission factor of 167 g CO_2/kWh. As illustrated in Figure 7, floor 10 produced 5,389.93 kg of CO_2-eq, while floor 11 produced 2,628.25 kg of CO_2-eq. The combined total emissions for both floors amounted to 8,018.17 kg of CO_2-eq. This data highlights the significant contribution of electricity consumption to the overall carbon footprint and underscores the importance of energy efficiency initiatives. Specifically, it is crucial for Worldsensing to select energy packages with a higher percentage of renewable energy compared to other sources, thereby significantly reducing indirect emissions and improving overall sustainability.

4.2.3. Scope 3: Other indirect emissions

4.2.3.1. Indirect Emissions from Transport

Indirect emissions from transport are a significant part of Scope 3 emissions. These include emissions resulting from downstream transport and distribution of goods, upstream transport of purchased goods and services, employee commuting and remote work, and business travel. Although these emissions occur outside the direct control of Worldsensing, they are essential to its operations [12].

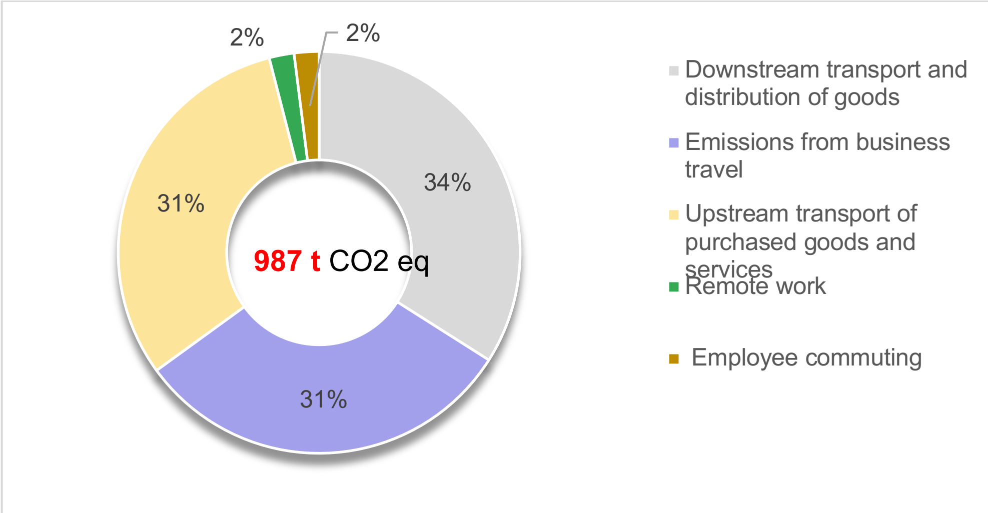

Figure 8:Distribution of Worldsensing's Scope 3 emissions for 2023 [12].

Figure 8 illustrates the distribution of Worldsensing's Scope 3 emissions for 2023, highlighting the contributions from downstream transport, upstream transport, business travel, remote work, and employee commuting. The total emissions amount to 987 t CO2-eq [12].

a. Indirect emissions from downstream transport

To perform this analysis, Worldsensing provided data on the shipment of each product, including net weight, EMS, customer name, and destination country. The distances between origins and destinations were calculated to determine the ton-kilometers for each shipment. This calculation considered the transport of final products (sensors and accessories), antennas, packaging, and batteries. The transport routes included the journey from the manufacturer to the warehouse, and from the warehouse to the final client. The mode of transport was estimated based on shipment data. Emission coefficients from Ecoinvent [58] were used for these calculations [12].

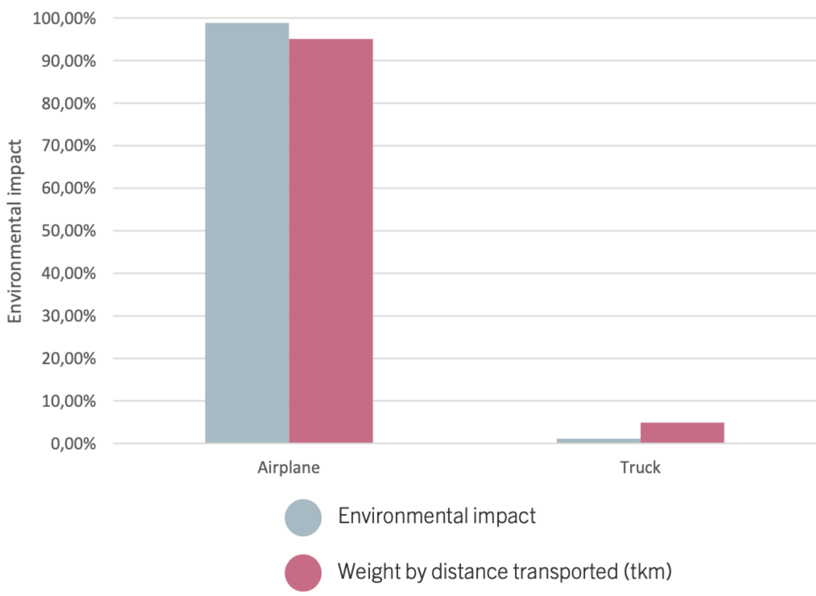

Figure 9:Impact of Worldsensing's 2023 CF for downstream transport and distribution of goods [12].

Downstream transport and distribution of goods contributed 34% of the total CO_2-eq, amounting to 335.58 t CO_2-eq (Figure 8). The main contributor of CO_2 emissions in the downstream transport subcategory is transport by airplane, which accounts for 99% of the emissions. The remaining 1% is derived from downstream transport by truck (Figure 9) [12].

b. Emissions from business travel

Emissions from business travel include those from personal cars, flights, hotel stays, rail, and public transport. It is important to note that emissions from rented cars are excluded here as they are accounted for in Scope 1. Emissions data were directly obtained from Worldsensing's travel booking software and travel agencies (TravelPerk, Captio, and BCM) [12].

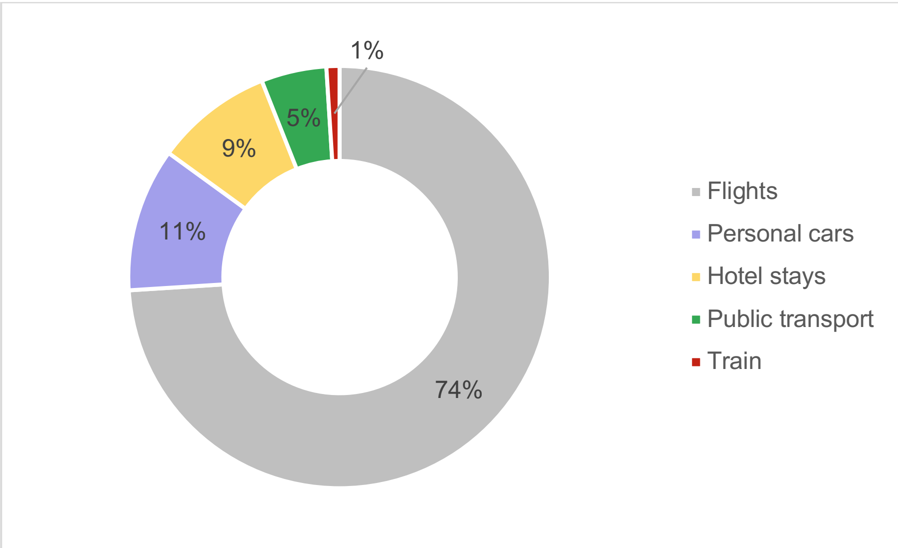

Figure 10: Distribution of Worldsensing's 2023 carbon footprint from business travel [12].

Business travel contributed 31% of the total CO_2-eq, amounting to 305.97 t CO_2-eq. The majority of this subcategory's impact is associated with flights taken for business travel purposes, which account for 74% of the emissions. Personal cars contribute 11%, hotel stays 9%, public transport 5%, and train use 1% (Figure10) [12].

c. Upstream transport of purchased goods and services

The upstream transportation of raw materials and packaging was calculated by considering the respective weights and routes from suppliers to the manufacturer (DigiProces). Product shipment data was used to determine the number of units sold and the corresponding weight of raw materials transported. Travel-related emissions were directly provided by suppliers. Emission factors from Ecoinvent v3.9 were applied to ensure accurate calculations [12].

Upstream transport of purchased goods and services also contributed 31% of the total CO_2-eq, amounting to 305.97 t CO_2-eq (Figure 8). The majority of the impact in this subcategory is from the transportation of electronic parts by airplane, which accounts for 79% of the emissions. The remaining 21% is from the upstream transport of aluminum body/casings, with 19% from airplane transport and 2% from truck transport. Packaging-related upstream transport has a minimal impact, representing 0.02% of the emissions (Figure 11, Table 6 in Annex 1) [12].

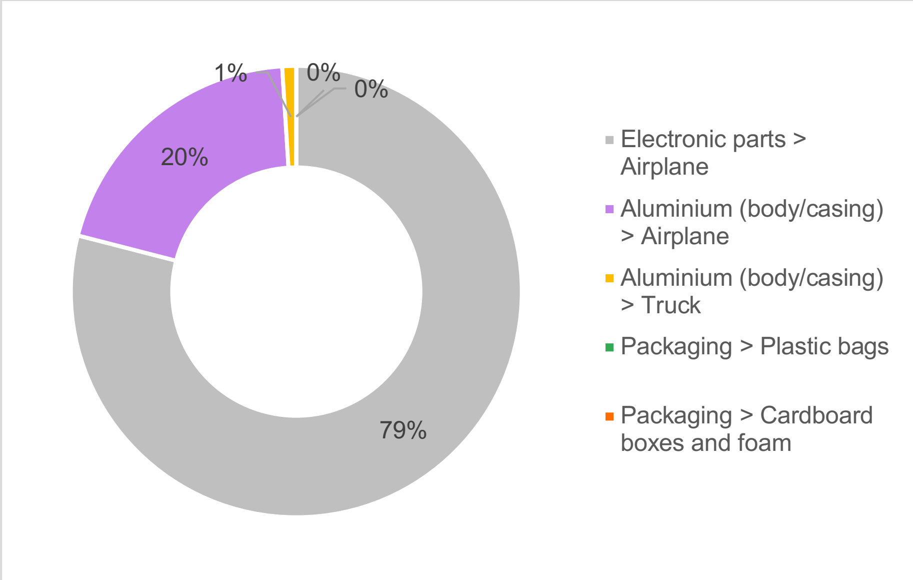

Figure 11: Impact of Worldsensing's 2023 CF for upstream transport of purchased goods and services [12].

4.2.3.2. Indirect emissions of products used by the organization.

Indirect emissions from the products used by the organization are a substantial part of Worldsensing's overall carbon footprint. These emissions arise from various stages, including the production and transportation of raw materials, emissions from production processes, and other related activities [12].

Figure 12 illustrates the distribution of these emissions, highlighting the significant contributions from different sources. Raw materials for production are the largest contributors to the carbon footprint, accounting for 91% of the emissions. This is due to the high environmental impact of materials such as aluminium, gold, chromium, and silicon, which are essential components in Worldsensing's products (Figure 13). The emission factors used for these calculations were derived from Ecoinvent v3.9 [12].

Emissions from DigiProces' production processes contribute 4.5% to the total emissions. These emissions include the consumption of water, diesel, electricity, and the disposal of both dangerous and non-dangerous waste associated with Worldsensing's activities [12].

Contracted services, particularly the use of Google Cloud services for company operations and cloud-services offering, rank third in terms of impact, accounting for 1.8% of the emissions. Other minor contributors include raw materials for packaging, emissions from upstream suppliers' production processes, WTT (Well-to-Tank) emissions of consumed energy, management and disposal of waste generated, and consumables used by the organization [12].

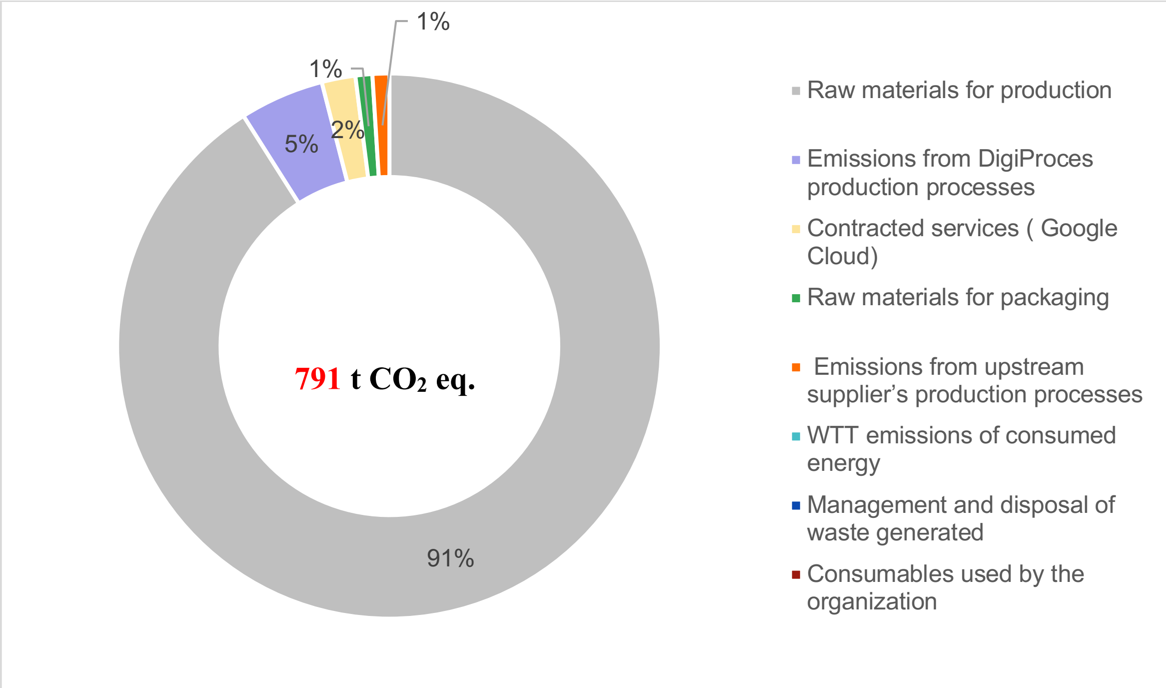

Figure 12: Distribution of Worldsensing's 2023 Carbon Footprint for indirect emissions of products [12].

Figure 13 illustrates the relationship between the environmental impact and the purchased quantity of various raw materials used by Worldsensing. Aluminium has the highest environmental impact at 26% and is the second most purchased material at 20%. Gold, despite a minimal purchase quantity (0.008%), has a significant impact of 24%. Iron, the most purchased material (42%), shows a lower impact at 4%. Chromium and silicon also have notable impacts of 17% and 16%, respectively [12].

The data shows that although some materials like iron have a high purchase quantity, their environmental impact is relatively low. Conversely, materials like gold, despite being purchased in smaller quantities, exhibit a significantly higher environmental impact (Figure 13). This highlights the need for careful consideration of both the environmental impact and the quantity of raw materials used in the design process of new products, to improve sustainability and reduce overall environmental impact [12].

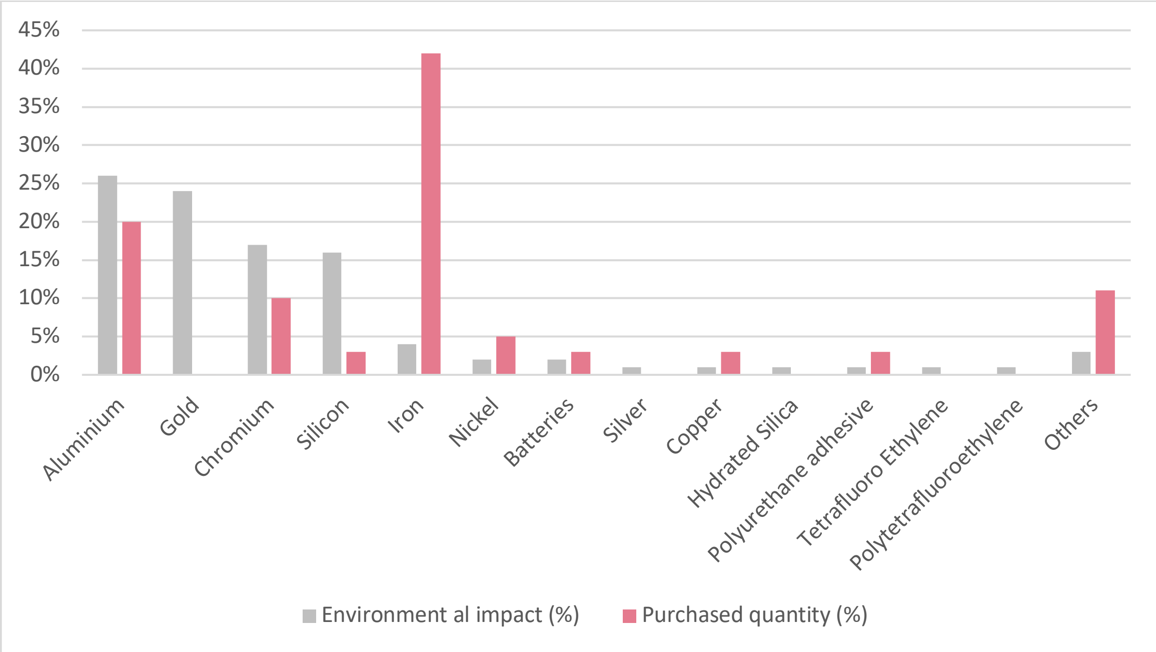

Figure 13: Environmental impact vs. Purchased quantity of raw materials used by Worldsensing in 2023[12].

4.2.3.3. Use and End-of-Life Emissions

Figure 14 illustrates the impact of use and end-of-life emissions: 50% of the impact in this category results from the electricity consumption of Gateway devices during their use phase. This electrical consumption is accompanied by emissions from the Google Cloud service used specifically during the product use phase, accounting for an additional 6% of the impact. On the other hand, the waste treatment of the metallic components of the product contributes 43% of the emissions generated. The subsequent waste treatment methods, including cardboard box packaging, foam packaging, plastic bags, and other materials, contribute a very small proportion to the overall carbon footprint [12].

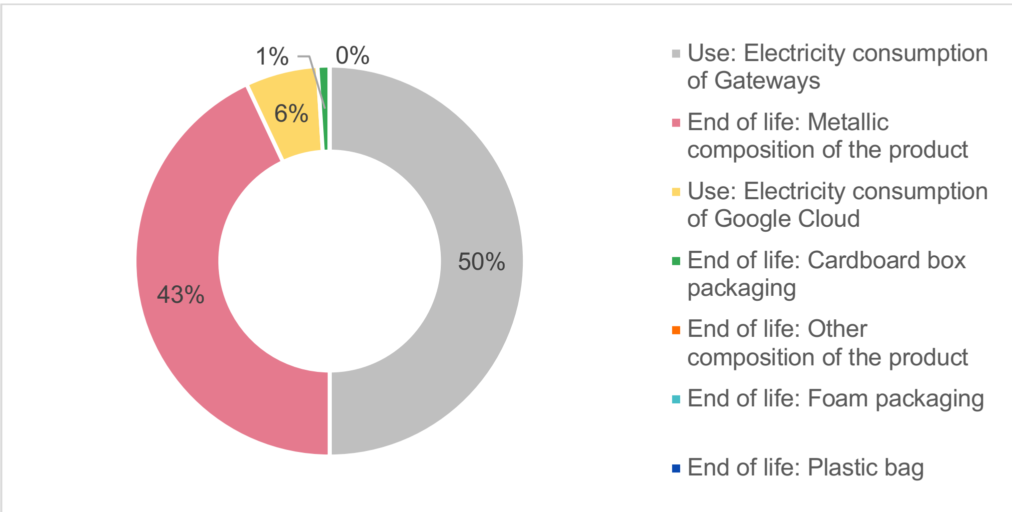

Figure 14: Impact of Worldsensing's 2023 CF for use and end-of-life emissions [12].

5. Calculation of product Carbon footprints

5.1. Methodology

5.1.1. LCA Standard

In light of the growing demand for environment and resource conservation, two types of International Organization for Standardization (ISO) 14000 standards have been established; (i) product-oriented and (ii) management-oriented [13].

The ISO 14000 product-oriented standards comprise Environmental Labels and Declarations, Life Cycle Assessment (LCA), and Eco-design. LCA is most widely recognized for quantifying the environmental impacts of a product over its entire lifecycle. There are four phases in an LCA: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation (ISO 14040, 1997) (Figure 15) [13].

The ISO 14040 standard is an overarching guideline that encompasses all four phases of LCA. There are three more standards supplementing ISO 14040: ISO 14041 addresses goal and scope definition and life cycle inventory methods, ISO 14042 deals with life cycle impact assessment methods, and ISO 14043 life cycle interpretation methods [13].

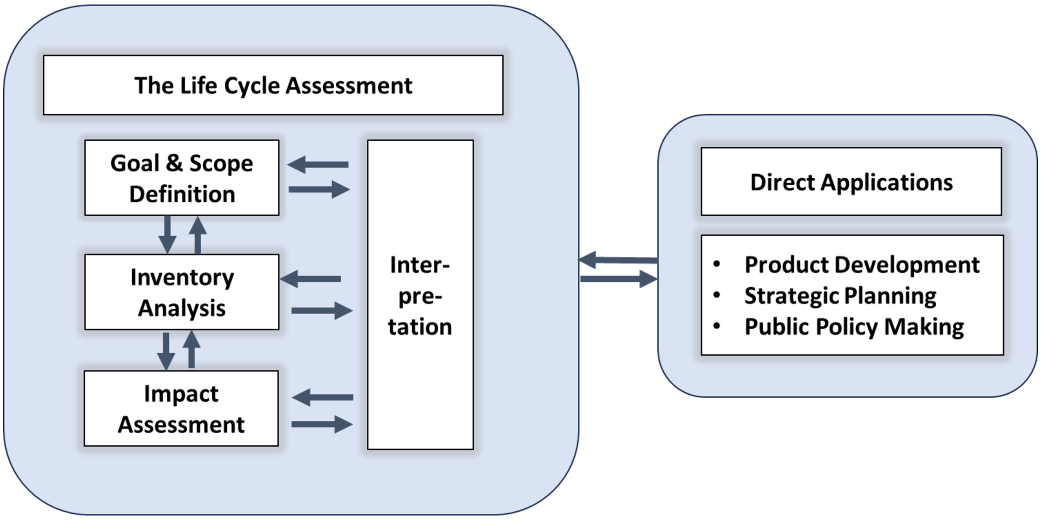

Figure 15: Phases of an LCA Analysis (ISO 14040, 1997) [13].

5.1.2. Goal and Scope definition

5.1.2.1. Function of the product system

Here and as mentioned earlier, we have chosen the Vibrating wire 5-channel data logger as the target product for the LCA study because it is the most representative one within the company's product range. It is a key component in their wireless monitoring systems used in various infrastructure projects globally. The 5-channel data logger is used in several scenarios, such as when a borehole contains many sensors of piezometers to monitor pore water pressure through vibrating wire piezometers. It is also used to measure vertical deformation at various depths with a multi-point borehole extensometer (MPBX) connected to the Vibrating Wire 5-channel data logger, enabling the monitoring of ground movements between depths (Figure 16) [7].

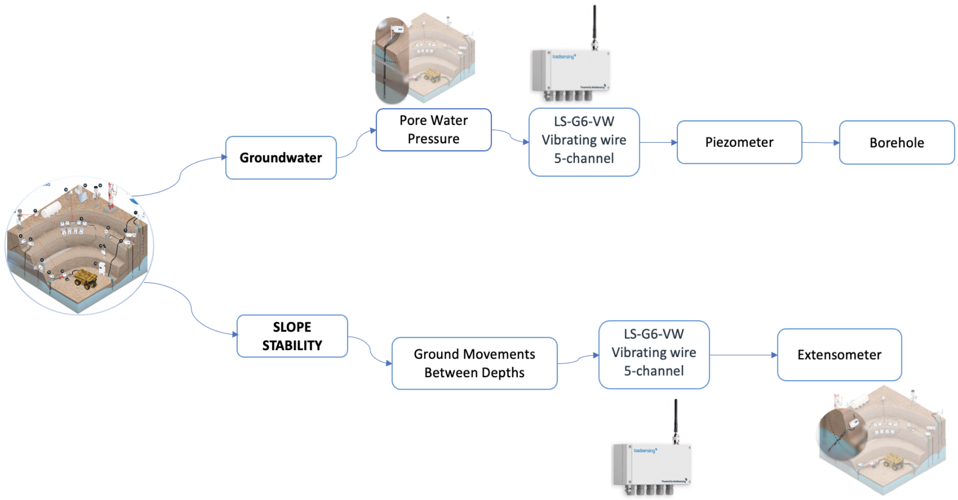

Figure 16: Applications of Worldsensing LS-G6-VW vibrating wire 5-channel [7].

The product reference code is LS-G6-VW; this device is used as a wireless data logger with five external channels (connections). To use this edge device, the users need to install a gateway device to receive the data and send it to the Internet.

In the calculation of the carbon footprint, multiple factors have been considered to ensure the accuracy of the results. These factors include the number of products sold to each country and the number of shipments made during 2023, reflecting customer demand. Some assumptions made to create a model are the following:

1) The number of gateways is calculated as one per ten target devices, and if the number was a decimal, it is rounded up to the nearest integer (Figure 17).
2) Since it is difficult to determine where the devices are finally installed, the number of deployment locations in each country is calculated as one per 50 target devices.
3) Each device contains four batteries, and the data sampling rate is set to once an hour. Thus, the lifespan of the edge device is roughly 11.4 years based on the technical specifications [14]. Thereby, the simulation period was also decided as 11.4 years. Therefore, the simulation period was also set to 11.4 years. The impact category evaluated in this study is 'Global warming (kg CO_2-eq)'.

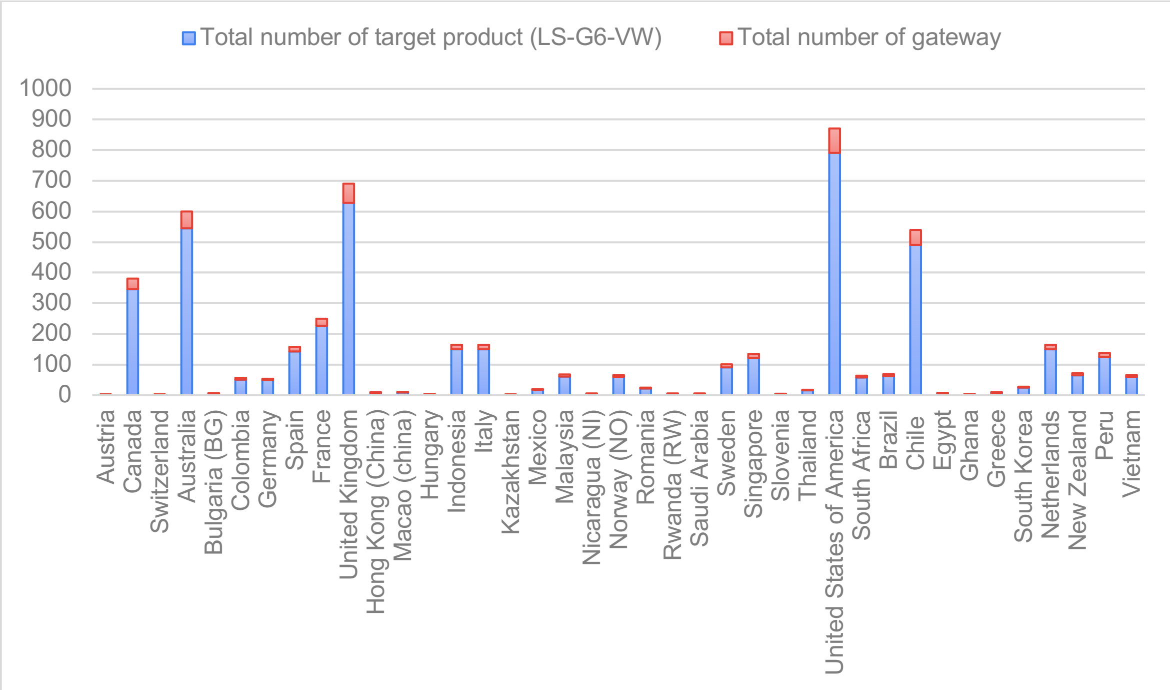

Figure 17: Number of Edge Devices and Gateways per Country Considered in the Study.

5.1.2.2. System boundaries

Here, we evaluated the five phases of the entire life cycle of the IoT devices (nodes and gateways), from raw material extraction to final disposal (Figure 18). It is noteworthy to mention that at the disposal and manufacturing stages, we depended on estimated data to calculate the carbon footprints, as these phases are not directly controlled by Worldsensing.

Providing precise data is challenging because the 'Manufacturing/Assembly' phase is outsourced to an external EMS provider, DigiProces located in the Barcelona area [59]. Additionally, the data regarding the Disposal/Recycling phase is directly unavailable since it is not controlled by Worldsensing.

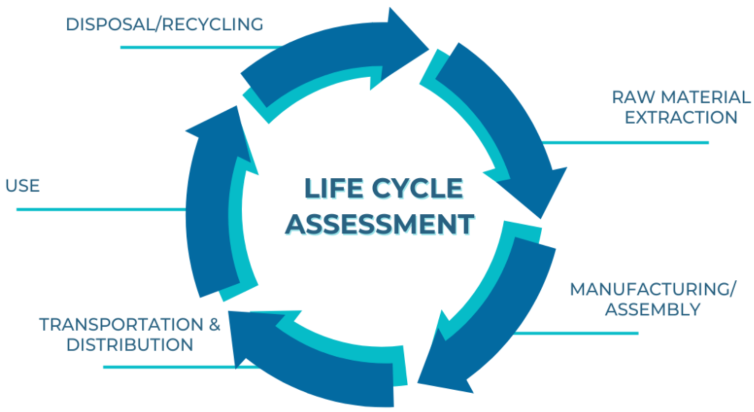

Figure 18: Steps of the entire life cycle of the IoT devices [15].

Table 1: Conditions of the LCA target device.

Factor	Figure
Period (sold in)	2023
Target Customers installed edge devices	152
Number of gateways	1 per 10 edge devices
Lifespan of battery [years]	11.4 [14]

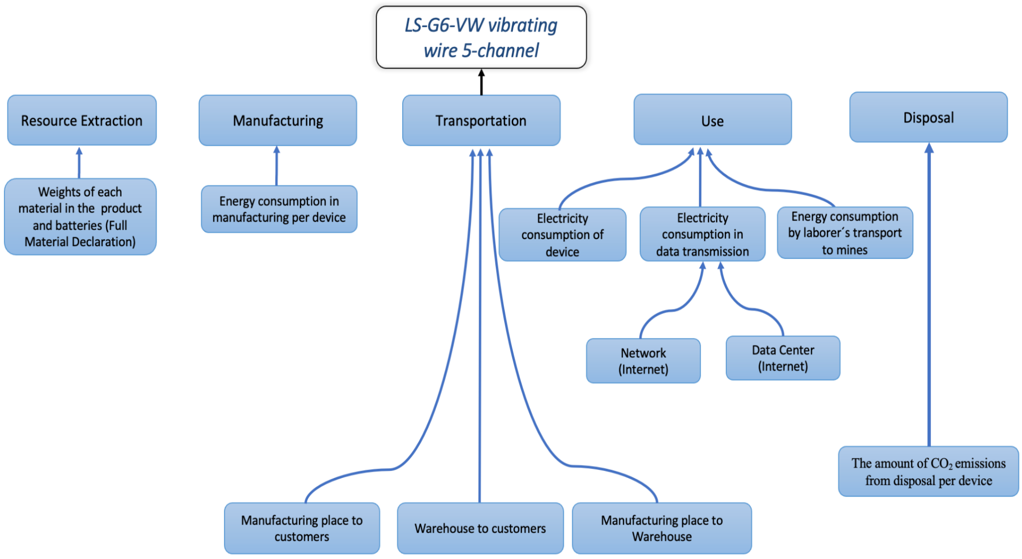

Figure 19: Components Making Up Each Phase in the Life Cycle Assessment (LCA).

5.1.3. Life Cycle Inventory Analysis

Life cycle inventory analysis (LCI) is a thorough procedure for accounting for the environmental impact during the product's life cycle. Inventory Analysis is a systematic, objective, and stepwise procedure for quantifying energy and raw materials requirement, atmospheric emissions, solid wastes, and other releases throughout the entire life cycle of a product. LCI involves data collection and calculation to quantify the inputs and outputs of a product system [13].

In this context, all inputs and outputs of a unit process and a product system are related to the main output of the unit process and the final product of the product system, respectively. Inputs include raw materials and energy, while outputs consist of carbon dioxide emission and lithium depletion. Figure 20 illustrates the general procedures for the implementation of LCI (ISO 14041, 1998).

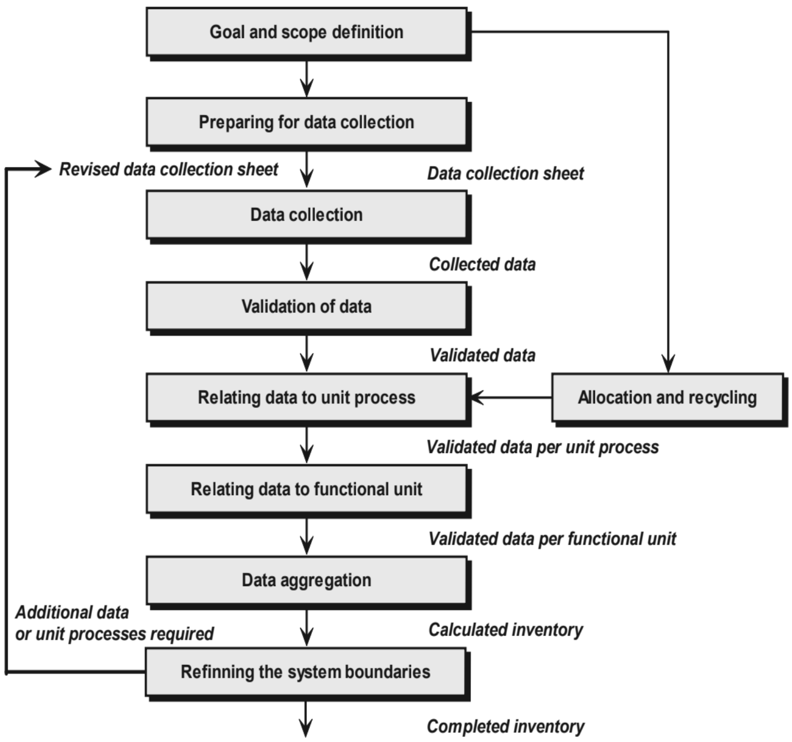

Figure 20: Operational procedure for LCI (ISO 14041, 1998) [13].

5.1.3.1. Used data

To improve environmental performance and sustainable manufacturing practices, it is crucial to evaluate the carbon footprints associated with the extraction and processing of raw materials.

During my internship at Worldsensing, we conducted a comprehensive analysis to obtain a full material declaration of Worldsensing's products, including those destined for the target product (LS-G6-VW). For simplicity, we identified a list of the 20 materials in the target product ranked by weight, constituting 97.25% of the mass total (Figure 30, Annex 2).

The target product includes up to 4 batteries from the Saft company. Due to limited information, we estimated the battery materials based on the battery's data sheets [16].

Figure 21 shows the percentage of materials in the vibrating wire 5-channel data logger, including the 4 batteries.

Additionally, we considered that the raw materials used to produce a node (LS-G6-VW) are similar to those used in the gateway. This similarity is due to both the node and the gateway sharing fundamental electronic components. These components include a box, chips, antennas, connectors, and power management systems such as voltage regulators. Furthermore, their weights are also approximately similar: the gateway weighs about 1400 g, while the node weighs approximately 1494 g.

The data on the material carbon dioxide emission factors are illustrated in Table 8, Annex 2.

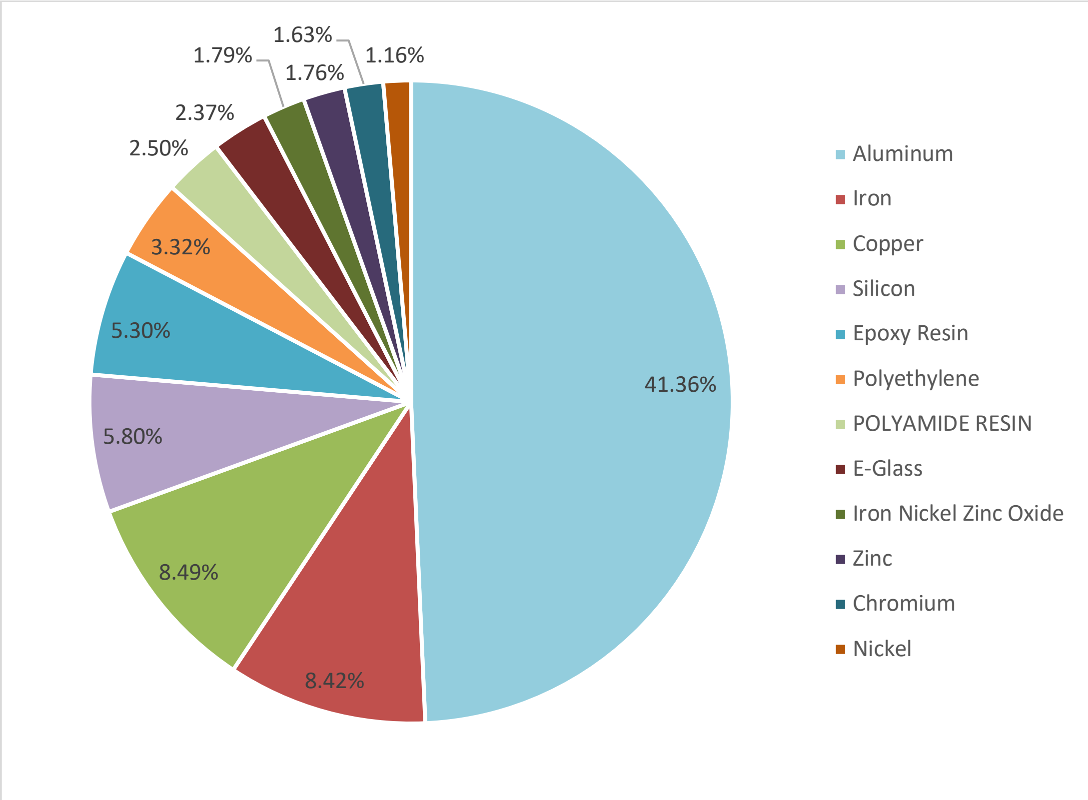

Figure 21: Percentage of each Substance in the vibrating wire 5-channel, Including 4 Batteries.

In the Manufacturing/Assembly phase, we estimated the electrical consumption required to produce a node (LS-G6-VW) to be 13 kWh per unit [17]. We assumed the same consumption applies to the production of one gateway due to the shared critical components and similar weights mentioned previously.

The data on electricity carbon dioxide emission factors for each country and emission factors by mode of transport are presented in Table 9 and Table 10 (Annex 2).

In the Distribution and Transportation phase, the type of transport used, and the number of shipments varied by country, as detailed in Table 11 (Annex 2). Figures 31 and 32 (Annex 2) illustrate the distances traveled from Worldsensing's warehouse or manufacturing facility to the customers' final locations, both in total and per edge device. Notably, the warehouse operations are managed by a Third-Party Logistics (3PL) provider, Naeko Logistics, located in the Barcelona area [60].

In the Use phase, local employees need to visit the device deployment spots regularly. To account for CO_2 emission during the transport, we create a toy model to make a first analysis. To do this, the conditions shown in Table 2 were established. Consequently, the number of deployment spots regularly visited by laborers was calculated, as shown in Figure 22. In short, the total travel time to deployment locations over 11.4 years is 595 trips before installing edge devices, and 43 trips after installation.

Significant technical data utilized in our analysis is summarized in Table 12 in Annex 2.

Table 2: Local employees regular transportation.

Factor	Figure
Frequency of transport	Before installing; once a week After installing; once every 6 months (Maintenance)
Average distance for 1 way [km]	50
Period [year]	11.4[14]
Type of transport	Car(petrol)
CO2 equivalent of Average car(petrol) in 2023 [g/km]	163.9[54]

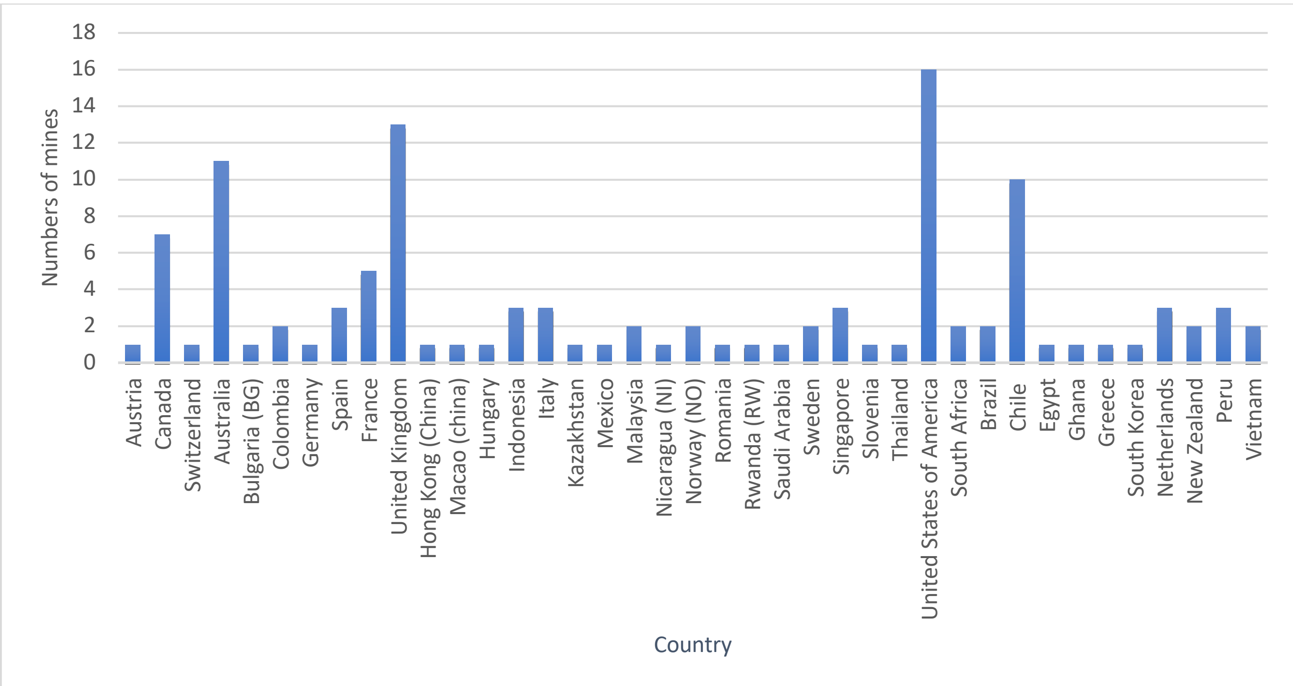

Figure 22: Number of deployment spots associated with IoT nodes installed in each country.

Determining the exact CO_2 emissions in the disposal phase of electronic devices, such as nodes and gateways, is complex due to variability in disposal methods, recycling processes, transportation, and final material treatment. Factors such as specific disposal practices, recycling efficiency, and transportation distances can significantly influence the final emissions. Additionally, it is unclear whether customers recycle the devices or simply discard them. Due to this complexity and the lack of scenario-specific data, we have estimated the CO_2 emissions for a node (LS-G6-VW) to be approximately 3.5 kg CO_2-eq. This estimate also applies to gateways.

5.1.3.2. Theoretical Model

To calculate the carbon dioxide emissions at each stage of the life cycle of nodes and gateways, we employed the following equations.

A. CO_2 emission in raw material phase

To determine the total environmental impact, we calculate the emissions per unit and then multiply by the number of gateways or nodes produced in 2023, providing the aggregate emissions for the year. The carbon dioxide emissions in the raw material phase per gateway and per node are calculated according to Equation (1):

$$E_r = \sum W * Cm \quad (1)$$

where:

- E_r: CO_2 emission of the material [kg CO_2-eq]
- C_m: CO_2 emission factor per unit of material [kg CO_2-eq/kg]
- W: weight of the material [kg]

B. CO_2 emissions in the manufacturing phase

All nodes are manufactured and assembled in Spain by DigiProces. The carbon intensity or emission factor of electricity in Spain is 174 g CO_2/kWh in 2023. To calculate the total environmental impact, we multiply the emissions per unit by the number of gateways or nodes manufactured in 2023:

$$E_m = C_i * P_p \quad (2)$$

where:

- E_m : CO_2 emission from manufacturing phase of the device [kg CO_2-eq]
- C_i: Carbon intensity of electricity [g CO_2-eq/kwh]
- P_p: Electricity consumption to produce one device [kWh]

C. CO_2 emission in transportation /distribution phase

We consider two different scenarios for the transportation and distribution phase. In the first, products are transported from the manufacturing plant to the warehouse, and then from the warehouse to the customer. In the second scenario, products are shipped directly from the manufacturing plant to the customer, bypassing the warehouse, with transportation handled by Worldsensing. During 2023, some shipments followed the second scenario to countries like Australia, Bulgaria, Canada (two shipments each), and Spain and Italy (one shipment each).

1. Manufacturing to warehouse

$$E_{mw} = L_{mw} * C_e * W * N \quad (3)$$

where:

- E_{mw}: Transport CO_2 emission from manufacturing to warehouse [kg CO_2-eq]
- L_{mw}: Transportation distance from manufacturing to warehouse [km]
- C_e: CO_2 emission factor[kg-CO2/t-km]
- W: Weight of devices[t]
- N: Number of devices

2. Warehouse to customers

$$E_{wc} = L_{wc} * C_e * W * N \quad (4)$$

Where:

- E_{wc}: Transport CO_2 emission from warehouse to customers [kg CO_2-eq]
- L_{wc}: Transportation distance from warehouse to customers [km]
- W: Weight of devices[t]
- N: Number of devices

3. Manufacturing to Customers

$$E_{mc} = L_{mc} * Ce * W * N \quad (5)$$

Where:

- E_{mc}: Transport CO2 emission from manufacturing to customers [kg CO2-eq]
- L_{mc}: Transportation distance from manufacturing to customers[km]
- C_e: CO2 emission factor[kg-CO2/t-km]
- W: Weight of devices[t]
- N: Number of devices

D. CO_2 emission in Use phase

1. Electricity consumption of gateway

To calculate electricity consumption per gateway for the entire lifespan, the data transmission rate through the gateway must be calculated in advance, as the power consumption per gateway is based on the frequency of data transmission:

$$R_t = \frac{Rd + Ru}{2} * C_c * f \quad (6)$$

Where:

- R_t: Average data transmission rate through gateways [MB/h]
- R_d: Data transmission download rate [Mbps]
- R_u: Data transmission upload rate [Mbps]
- C_c: Mbps to MB/s converter [MB/Mbps]
- f: Data transmission hourly frequency [s/h]

Both the data transmission download rate and upload rate are referenced based on the data in Table 12 in Annex 2. In this analysis, the data sampling rate is decided to be once per hour, which means that the data transmission frequency through the gateway, *f*, is once per hour. Using the above consumption data from Equation (4), the power consumption per gateway is calculated as follows:

$$E_g = C_i * Pe * R_t * P \quad (7)$$

Where:

- Eg: CO_2 emission from power consumption of gateway for 11.4 years [kg CO_2-eq]
- C_i: Carbon intensity of electricity [g CO_2-eq]
- P_e: Electricity consumption rate of edge device [kWh/GB]
- P: Target period [day]

2. Electricity consumption for the internet to the Cloud.

The following electricity consumption was calculated for the edge and core network during the target period according to Equation (7) in (6) as follows.

$$E_i = C_i * P_i * R_t * P \ (8)$$

Where:

- E_i: Electricity consumption for the Internet for 11.4 years [kg CO_2-eq]
- P_i: Electricity consumption rate in using core network [kWh/GB]

3. Electricity consumption for Data Center

Similarly, the following electricity consumption was calculated for the data center during the target period according to Equation (8) in (6):

$$E_d = C_i * Pd * R_t * P, \ (9)$$

Where:

- E_d: Electricity consumption for data center for 11.4 years [kg CO_2-eq]
- P_d: Electricity consumption rate in using data center [kWh/GB]

4. CO_2 emission from local employees' transport

During the "use phase," local employees are required to monitor the data remotely, but they also need to visit the deployment spots for maintenance checks, which occur every six months. This additional transport should also be considered in our LCA analysis:

$$E_t = L_t * 2 * C * T * N_l \ (10)$$

Where:

- E_t: CO_2 emission from Laborers regular transport [kg CO_2-eq]

- L_t: Distance to deployment's location [km]
- C: CO_2 equivalent of Average car [g/km]
- T: Times going to the location for 11.4 years
- N_l: Numbers of locations

The value of C is taken from Table 2 and N_l from Figure 22.

E. Life cycle impact assessment

Life cycle impact assessment (LCIA) evaluates the significance of potential environmental impacts of a product system based on life cycle inventory (LCI) results. LCIA comprises several elements: classification, characterization, normalization, and weighting. Classification and characterization are mandatory, while normalization and weighting are optional (ISO 14042, 2000). Figure 23 illustrates these elements and their interrelationships. This assessment allows for consistent evaluation of various environmental impacts, such as CO_2 and methane emissions, to provide a comprehensive understanding of the environmental footprint of a product system.

In this study, we focus on the "Global warming" and "Abiotic and biotic resource depletion" categories. For "Global warming," only CO_2 emissions are considered, while for "Abiotic and biotic resource depletion," the evaluation is based on lithium usage due to its significant contribution from IoT device batteries. The lithium impact is converted to "kg Cu-eq/kg" using a factor where 1 kg of lithium equals 4.86 kg of copper, as referenced in Table 13.2 from the ReCiPe 2016 report. This conversion allows for a more standardized assessment of resource depletion impacts. The environmental impacts of "Abiotic and biotic resource depletion" were calculated using the following equation:

$$D_l = N * W_l * S \quad (11)$$

Where:

- D_l; Lithium resource depletion [kg Cu-eq]
- W_l; Weight of Lithium per device[g]
- S; Standard Operating Procedures (SOPs) factor [kg Cu-eq/kg]

The value of **S** is referenced from Table 12 in Annex 2.

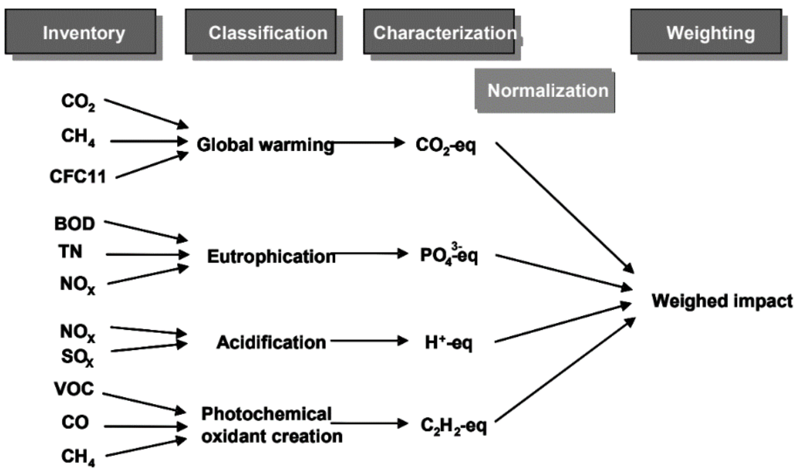

Figure 23: Elements and relationship among the elements of LCIA.

5.2. Result

This section presents the results obtained after calculations using equations 1 to 10. These results offer a detailed view of the environmental impact across different phases of the life cycle of the nodes and gateways.

5.2.1. Total carbon dioxide emissions

The total CO_2 emissions for each phase are illustrated in the following graphs, providing a clear and understandable visualization of the results.

5.2.1.1. Raw material phase

To calculate the carbon footprint of the raw materials used in packaging as well as those necessary to manufacture the nodes and gateways, we employed Equation 1. For packaging, we utilized three materials: foam PE (Polyethylene) with 40% recycled content, cardboard, and plastic Linear Low-Density Polyethylene (LLDPE). The CO_2 emissions from the packaging materials are approximately 0.20 kg CO2 per device.

Figure 24 demonstrates that the CO_2 emissions from the raw materials used in the manufacturing of nodes (LS-G6-VW) and gateways are significantly higher compared to the emissions from the raw materials used for packaging. The high CO_2 emissions from nodes are primarily due to the larger number of nodes produced in 2023, with approximately 4563 nodes compared to 475 gateways Additionally, materials such as aluminum have the highest environmental impact, contributing significantly to the total CO_2 emissions due to their high emission factors and substantial usage in the manufacturing process (Figure 33, Annex 3).

The raw materials used in manufacturing nodes account for 58.40 tonnes CO2-eq, while those used for gateways contribute 6.08 tonnes CO2-eq. In contrast, the emissions from the raw materials used for packaging are much lower, totaling 0.097 tonnes CO2-eq for the packaging of gateways and 0.93 tonnes CO2-eq for the packaging of nodes.

Moreover, detailed results of total CO2 emissions from manufacturing and packaging raw materials by country are presented in Figure 34 (Annex 3), highlighting the geographical distribution of these emissions.

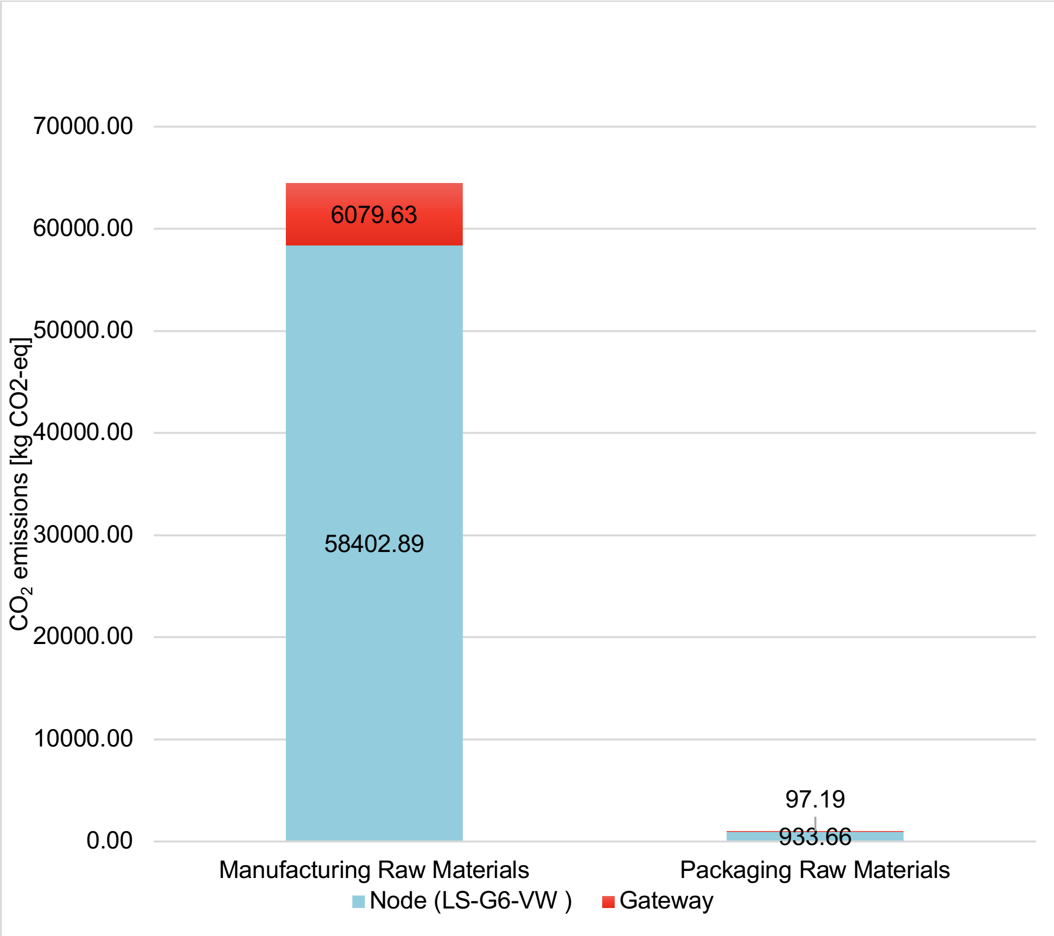

Figure 24: Global warming CO_2 emissions in the raw materials phase.

5.2.1.2. Manufacturing phase

To calculate the carbon footprint of the manufacturing and assembly phase, we employed Equation 2.

Figure 25 shows the CO_2 emissions from the nodes (LS-G6-VW) and the gateways during the manufacturing and assembly phase. The nodes contribute 10.32 tonnes CO_2-eq, while the gateways contribute 1.07 tonnes CO_2-eq. These values are influenced by the carbon intensity of electricity in Spain, which is 174 g CO_2/kWh in 2023. A lower carbon intensity would lead to reduced emissions, demonstrating the significance of energy sources on the overall carbon footprint.

Detailed results of total CO_2 emissions from the manufacturing and assembly phase by country are presented in Figure 35 (Annex 3).

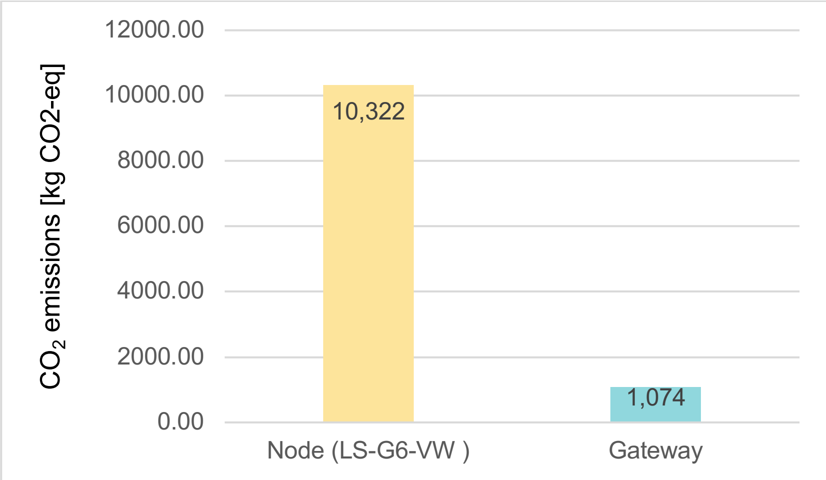

Figure 25: Global warming CO_2 emissions in manufacturing/assembly phase.

5.2.1.3. Transportation/Distribution phase

a. Manufacturing to Warehouse

Worldsensing outsources the manufacturing and transportation phases to DigiProces and Naeko Logistics, respectively. After manufacturing, Naeko Logistics uses trucks to pick up the products and transport them to the warehouse. Using Equation 3, the total CO_2 emissions in this phase were calculated to be 0.047 tonnes CO_2-eq.

b. Warehouse to Customers

Similarly, we calculate the CO_2 emissions for the transportation/distribution phase from the warehouse in Barcelona to customers, either by truck or airplane. Figure 26 illustrates the total CO_2 emissions in the transportation/distribution phase. Compared to the first transport in Spain (manufacturing to warehouse), the second transport (warehouse to final customers) has a significantly higher impact on total CO_2 emissions.

Figure 36 in Annex 3 shows the variation in emissions across different countries. Each country has different customer locations and shipment methods, contributing to the variability in CO_2 emissions. The total CO_2 emissions from the warehouse to customers are 202.50 tonnes. In this phase, shipments to Africa, America, Asia, Oceania, and non-European Union countries are exclusively by air, while shipments to EU countries are made by road or air (Table 11, Annex 2). Figure 36 in Annex 3 also highlights that the more air shipments are used, the more CO_2 is emitted. Both the type of transport and the distance traveled by air, along with the number of shipments, have a significant impact on CO_2 emissions. Additionally, the emission factor of airplanes is much higher than that of other types of transport.

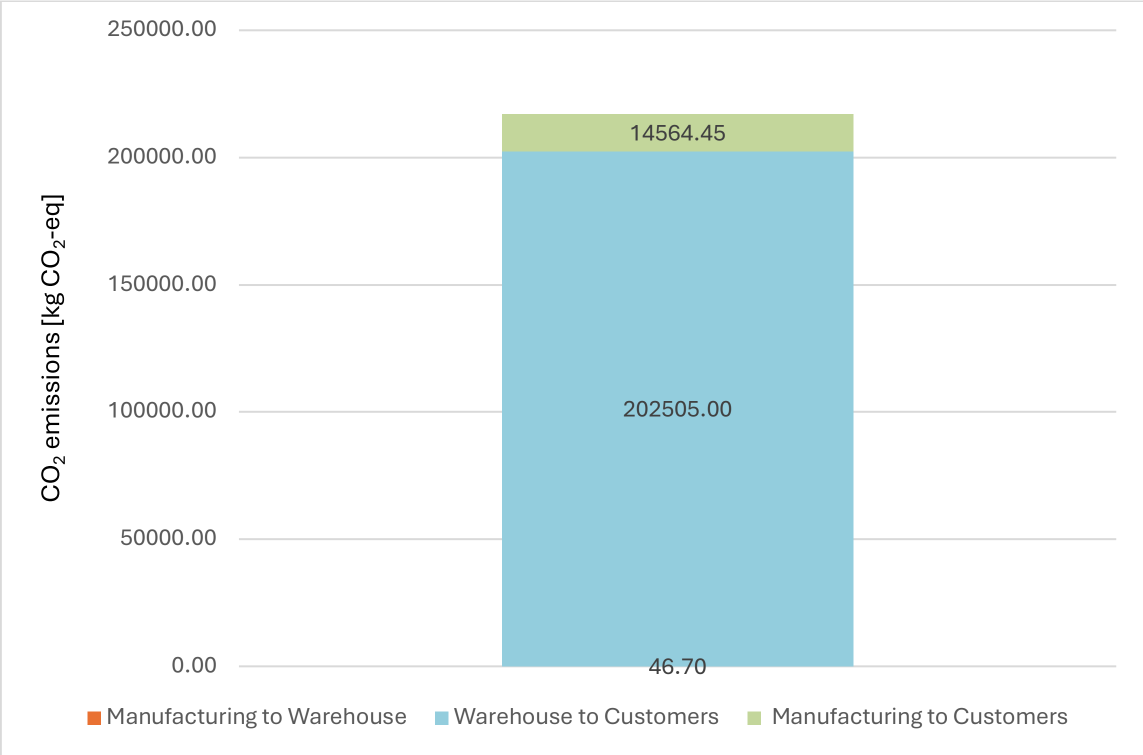

Figure 26: Global warming CO_2 emissions in the transportation/distribution phase.

c. **Manufacturing to customers**

Almost all products are shipped from the manufacturing plant to the warehouse and then from the warehouse to the customers. However, in some exceptional cases, shipments are made directly from the manufacturing plant to the customers, handled by Worldsensing instead of Naeko Logistics. During 2023, these direct shipments included two shipments to Australia, Bulgaria, and Canada (all by air), one shipment to Spain (by road), and one shipment to Italy (by air).

The results in Figure 26 and Figure 36 in Annex 3 show the impact of these direct shipments on total CO_2 emissions. In this phase, the total CO_2 emissions from manufacturing to customers are 14.56 tonnes. Although these exceptional cases reduce the use of trucks between the manufacturing plant and the warehouse, the significant impact persists due to the greater environmental impact of air shipping.

5.2.1.4. Use phase

a. **Total CO_2 emission of electricity consumption by devices**

While the target edge devices (LS-G6-VW) are operated by batteries, the gateways consume electricity. Additionally, electricity is used for transmitting data from gateways to the Internet and for operating the data center (cloud infrastructure). The results of this electricity consumption evaluated using equations (6) to (9) are illustrated in Figure 37, Annex 3.

The number of gateways, and consequently the number of edge devices, along with the CO_2 emission factor of electricity, have a significant impact on the total CO_2 emissions. The CO_2 emission factor is directly related to the type of energy resources used to generate electricity. Energy sources such as fossil fuels (coal, natural oil) result in increased CO_2 emissions. In contrast, switching to low-carbon electricity generated by renewable sources can significantly reduce emissions.

For example, Figure 37 in Annex 3 illustrates that the US emits more CO_2 due to the large number of devices used and the significant emission factor. In contrast, Italy emits half the CO_2 compared to Indonesia, even though both countries use a similar number of devices. Furthermore, Norway, Switzerland, and Sweden emit minimal CO_2 by utilizing low-carbon energy resources.

b. Total CO_2 emission by laborer's regular transport to deployment locations

The installation of the target devices not only contributes to reducing the burden of regular worker transportation but also significantly reduces carbon dioxide emissions. Due to the operation of the edge devices, the frequency of transportation is reduced to approximately once every six months (as shown in Table 2), leading to a drastic decrease in CO_2 emissions associated with this activity, as illustrated in Figure 38 (Annex 3). To demonstrate the impact of this CO_2 reduction resulting from the solutions' installation, we subtract the CO_2 emissions after installation from the emissions before installation, with the results shown in Figure 39, Annex 3. The reduction impacts are based on the number of deployment spots in each country.

c. Total CO_2 emission in Use phase

Figure 27 shows the total CO_2 emissions from laborers' regular transport to deployment locations, both before and after the installation of edge devices. Before installing the edge devices, the CO_2 emissions were 1,121.49 tonnes CO_2-eq. After installation, the CO_2 emissions were significantly reduced to 43.35 tonnes CO_2-eq from employees' local transport, 69.97 tonnes CO_2-eq from gateways, 10.11 tonnes CO2-eq from data transmission in the network, and 15.03 tonnes CO_2-eq from data transmission in the data center. By comparing these situations, it is evident that the total CO_2 emissions have decreased by approximately 983.04 tonnes CO_2-eq.

Furthermore, Figures 40 and 41 in Annex 3 illustrate CO_2 emissions by country during the Use Phase, combining data from Figures 37 and 38 (Annex 3). Specifically, Figure 40 (Annex 3) presents the total CO_2 emissions before installing the solution, while Figure 41 (Annex 3) depicts the total CO_2 emissions after installing the solution. By comparing Figures 40 and 41, it is evident that the installation of the solution (including the target products and gateways) results in a drastic reduction of carbon dioxide emissions, lowering them to less than one-sixth of the original levels.

This significant reduction is crucial as it allows Worldsensing to offer its customers sustainable and eco-friendly products, helping them achieve their environmental goals. Although the installation of the solutions introduces new CO_2 emissions through electricity usage, this impact is relatively minor compared to the substantial reduction in CO_2 emissions from laborers' regular transport.

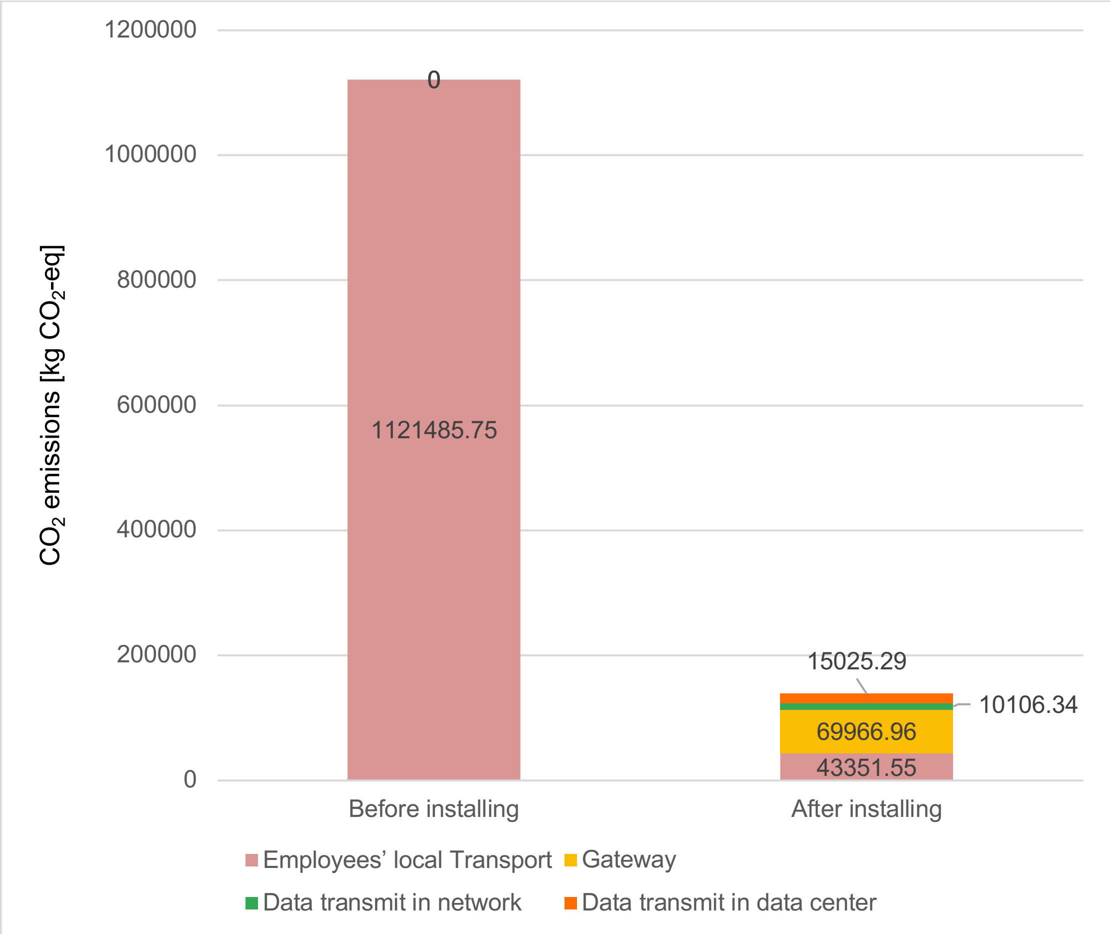

Figure 27: Total CO2 emissions in the use phase before and after installing edge devices.

5.2.1.5. Disposal phase

Figure 28 illustrates the total CO_2 emissions in the disposal phase, amounting to 17.63 tonnes CO_2-eq, distributed between 15.97 tonnes CO_2-eq for nodes and 1.66 tonnes CO_2-eq for gateways. The number of gateways and nodes significantly impacts the total CO_2 emissions. Additionally, Figure 42 in Annex 3 presents the CO_2 emissions across different countries, showing the distribution of these emissions between nodes and gateways in each region. These simulations are fundamental for obtaining an overview of the environmental impact at the end-of-life stage of the devices and are essential for understanding the magnitude of the impact at this stage of the product life cycle.

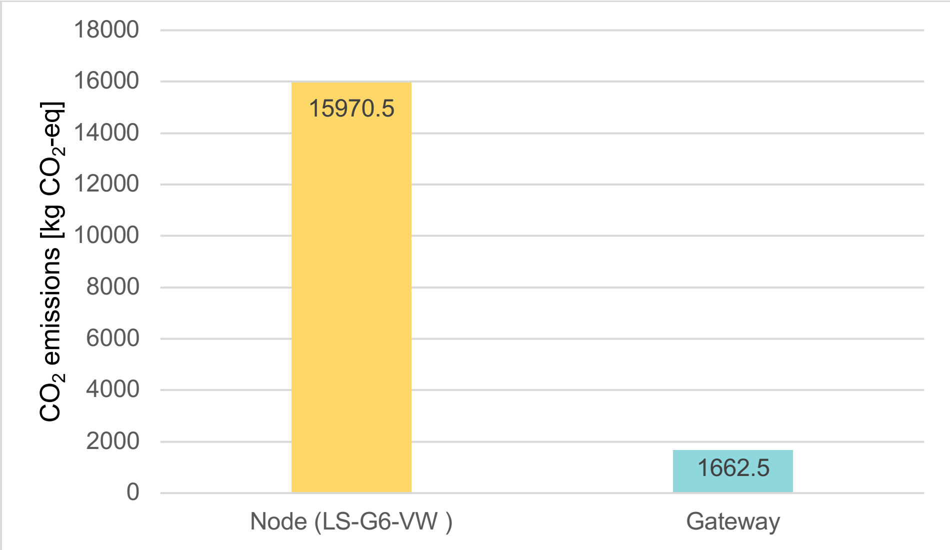

Figure 28: Total CO2 emissions in disposal phase.

5.2.1.6. Summary of the Life Cycle Analysis phases

In this section, the total CO_2 emissions from all phases of the life cycle, including the impact of laborers' transport reduction, are evaluated. The results are summarized in Figure 43 in Annex 3 and Figure 29.

Figure 29 demonstrates the total CO_2 emissions across the entire life cycle of all devices. The LCA of Worldsensing's IoT devices (nodes and gateways) for 2023 revealed a total carbon footprint of 450 tonnes CO_2eq. The largest contributor to the carbon footprint is the Transportation/Distribution Phase, accounting for 217.116 tonnes CO_2-eq, followed by the Use Phase, which contributes 138.450 tonnes CO_2-eq. The Raw Material Phase adds 65.513 tonnes CO_2-eq, while the Manufacturing/Assembly Phase contributes 11.396 tonnes CO_2eq. The Disposal Phase has the smallest impact, with 17.633 tonnes CO_2-eq.

This comprehensive assessment highlights the significant emissions associated with each phase, emphasizing the need for targeted strategies to reduce the overall environmental impact of Worldsensing's products.

Figure 43 in Annex 3 shows CO_2 emissions for each country across all life cycle phases, highlighting regional differences in environmental impact. Notably, the US has a negative balance of -18,348.23 kg CO_2-eq compared to other countries due to the large number of shipments to the US, significant travel distances involved, and the higher emission factor of the electricity used.

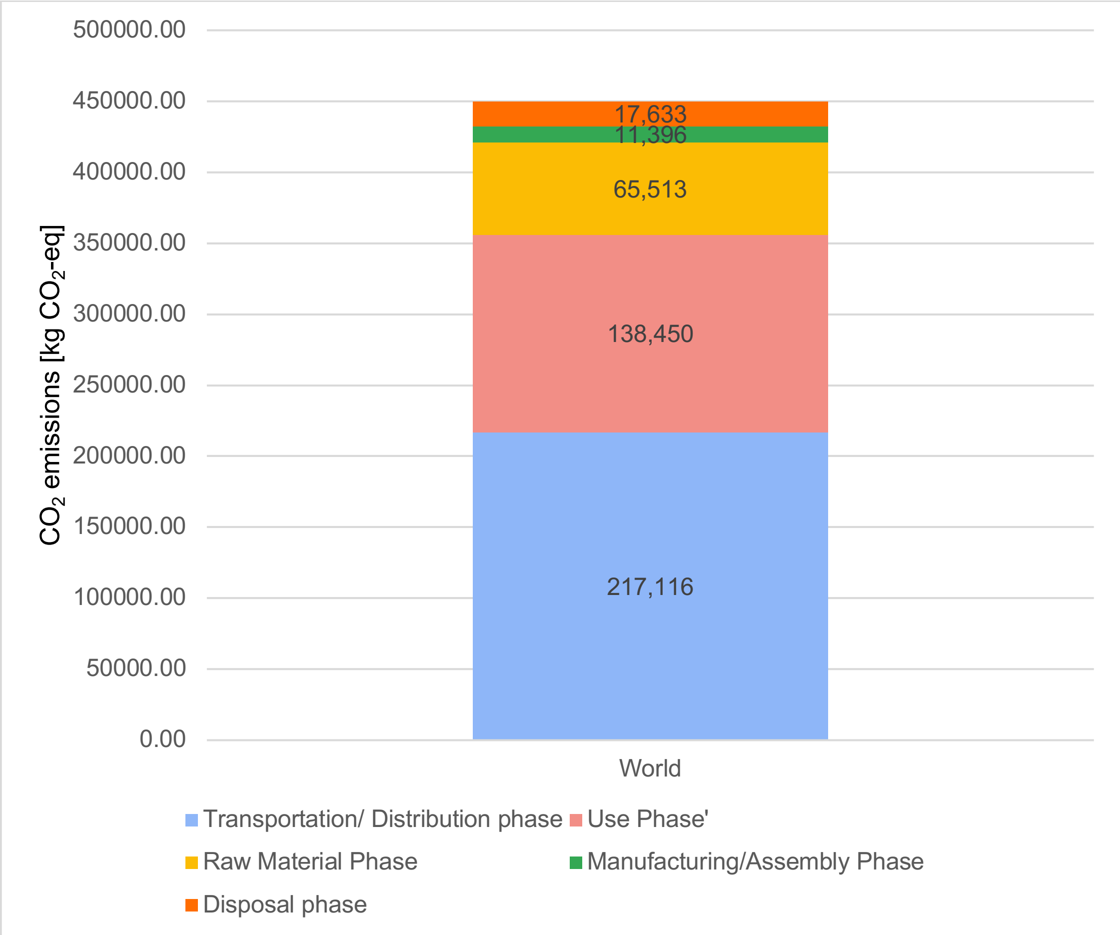

Figure 29: Total CO_2 emissions across the entire Life Cycle of all devices.

5.2.2. Depletion of Lithium

The target node is powered by four lithium batteries. The extraction of lithium has notable environmental impacts, which can be quantified using the unit "kg Cu-eq" (kilograms of copper equivalent). According to Table 12 in Annex 2, each edge device contains 1.7 grams of lithium. By multiplying this amount by the number of edge devices used in each country and applying the conversion factor to copper, the total lithium consumption equates to approximately 150.8 kilograms of copper globally. To mitigate the environmental impact of lithium usage, it is essential to encourage our stakeholders to recycle the lithium within the nodes. Additionally, it is the responsibility of Worldsensing to explore alternatives such as energy harvesting and storage technologies beyond lithium to further reduce environmental impacts [22].

6. Discussion

The analysis of CO_2 emissions from different phases of the product life cycle across various countries reveals that the overall impact is positive in most regions, with significant reductions in CO_2 emissions observed. However, in the United States, the net total emissions show a negative impact. This suggests a need to closely examine and improve working conditions, logistics, and operational strategies in the U.S. Optimizing shipping methods, increasing energy efficiency, and adopting more sustainable practices are crucial to reduce the negative impact in the U.S. and achieve the positive results seen in other countries.

7. Conclusion and recommendations

This study shows that the carbon footprint of Worldsensing in 2023 totaled 1896 t CO_2-eq, or 68 kg CO_2eq per unit of shipped product. Scopes 1 and 2 constitute a minimal part of the carbon footprint, each contributing 1% to the total impact. The majority of Worldsensing's impact is attributed to Scope 3, with indirect emissions from transport representing 52% of the emitted CO_2eq. This significant impact is largely due to transportation emissions, which are almost equally distributed between downstream transportation, upstream transportation, and business travel. In each of these subcategories, most transportation occurs by airplane [12].

Indirect emissions from products used significantly contribute to Worldsensing's carbon footprint, representing 42% of the total. The raw materials for production are almost entirely responsible for this impact. Aluminium, gold, chromium, silicon, and iron are the top five contributors to the carbon footprint, considering both quantity consumed and environmental impact, while the most purchased materials are iron, aluminium, chromium, nickel, and copper [12].

The use and end-of-life phases of the product, which comprise the electricity consumption of the gateways during their use phase and the waste treatment of the metallic components of the products at the end of their lifespan, also contribute significantly to the overall carbon footprint [12].

The Life Cycle Assessment (LCA) of Worldsensing's IoT devices (nodes and gateways) for 2023 revealed a total carbon footprint of 450 tonnes CO_2-eq by applying a simplified model to reflect the reality of Worldsensing's carbon footprint. Significant emissions arose from raw materials, with nodes contributing 58.40 tonnes CO_2eq and gateways 6.08 tonnes CO_2eq. In the manufacturing phase, nodes contributed 10.32 tonnes CO_2eq and gateways 1.07 tonnes CO_2eq, influenced by Spain's electricity carbon intensity. The transportation phase was a major contributor to the total carbon footprint, with the second transport phase from the warehouse to customers being the most impactful, contributing 202.50 tonnes CO_2eq, primarily due to air transport.

During the use phase, Worldsensing's solutions significantly reduced CO_2 emissions associated with the regular transport of laborers to deployment locations. Before installation, emissions were 1,121.49 tonnes CO_2eq, which dropped to 43.35 tonnes CO_2eq from local transport, 69.97 tonnes CO_2eq from gateways, 10.11 tonnes CO_2eq from network data transmission, and 15.03 tonnes CO_2eq from data center transmission, achieving a total reduction of 983.04 tonnes CO_2eq.

In the disposal phase, emissions totaled 17.63 tonnes CO_2-eq, with nodes contributing 15.97 tonnes CO_2-eq and gateways 1.66 tonnes CO_2-eq. The study emphasizes the need for sustainable practices, optimizing shipments, improving logistics, and adopting low-carbon technologies to reduce CO_2 emissions.

To further reduce environmental impacts, several strategies are recommended. First, the operations department, in collaboration with Naeko Logistics, should aim to reduce the number of shipments annually, not only to the USA but also to other countries, particularly those with long distances. Efficiently managing customer requests and consolidating orders into fewer shipments can significantly lower emissions. When time constraints allow, using ships instead of airplanes for distribution can further reduce the carbon footprint due to the lower emissions of maritime transport. Additionally, for cars used in business travel and laborer transport, adopting electric vehicles or more fuel-efficient cars can help minimize CO_2 emissions. Encouraging the use of public transport for business travel whenever possible can also contribute to reducing emissions.

Implementing a carbon footprint reduction plan with well-defined actions and impact estimation, defining Green Purchasing Criteria, reducing the use of highly impactful raw materials, and finding substitutes for high-impact materials are also crucial. Furthermore, sourcing suppliers with a similar environmental business mentality and obtaining a 100% renewable electricity consumption certificate can significantly enhance sustainability and reduce the overall carbon footprint of Worldsensing's operations.

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Annex 1: Data Used for Organisation Carbon Footprint Calculation.

Table 3: Components in each Scope for Worldsensing's Carbon Footprint Calculation.

	Stage	Description of Data Available
Scope 1	Internal vehicle fleet	Model and Distance Travelled by Each Car
Scope 2	Electricity consumption	Monthly electricity bills for headquarter offices (two floors).
Scope 3	Downstream transportation and distribution of goods	Number of IoT nodes sent in 2023 per country, by model, and by means of transportation.
	Business travel	Emissions from personal cars, flights, hotel stays, rail, and public transport, obtained from travel booking software and agencies (Travel Perk, Captio, and BCM).
	Upstream transportation	Distances between suppliers and the manufacturer (DigiProces), including weights and types of raw materials transported.
	Employee commuting and remote working	Data from employee surveys on commuting modes and distances, remote working frequency.
	Raw materials for production	Full material declaration for each product
	Raw materials for packaging	Types and Quantities of Materials Used in Packaging.
	Waste generation and management	Quantities of non-hazardous and hazardous waste generated.
	Upstream production process	Emission report from the warehouse provider (NAEKO)
	Contracted services for SaaS services	CO_2 emissions report for the contracted Google Cloud Service.
	Use of products sold by the organisation	Carbon footprint linked to the clients' consumption.

Table 4: Distances traveled by various vehicle models.

Vehicle description	Distance (km)
WHI Honda CR-V	116
Isuzu MUX LS	59
WHI Chevrolet Malibu	131
WHI Nissan Altia Sedan	162
Premium crossover 4 door, standard SUV	1845
Ford Edge	180
Toyota Corolla Cross	493
Toyota Corolla Cross	493
Toyota Corolla Cross	493
Toyota Corolla Cross	431
Toyota Corolla Cross	405
Chevrolet Cruze LT	1178
Chevrolet Tracker Premier	301
Toyota Corolla Xei	285
Chevrolet Tracker Ltz	1411
Renault Megane 1.3	141
Nissan Sunny	493
Toyota Corolla Cross	493
Audi Q5 Quattro	257

Table 5: CO_2 emission factors for rented vehicles.

Vehicle model	CO_2 emission factor (g/km)
WHI Honda CR-V	161[23]
Isuzu MUX LS	252[24]
WHI Chevrolet Malibu	181[25]
WHI Nissan Altia Sedan	175[26]
Premium crossover 4 door, standard SUV	150[23]
Ford Edge	149[27]
Toyota Corolla Cross	116.7[23]
Toyota Corolla Cross	116.7[23]
Toyota Corolla Cross	116.7[23]
Toyota Corolla Cross	116.7[23]
Toyota Corolla Cross	116.7[23]
Chevrolet Cruze LT	124[28]
Chevrolet Tracker Premier	185[29]
Toyota Corolla Xei	103.7[23]
Chevrolet Tracker Ltz	189[30]
Renault Megane 1.3	124[23]
Nissan Sunny	125[23]
Toyota Corolla Cross	116.7[23]

Audi Q5 Quattro	197[23]

Table 6 : Upstream transport of purchased goods and services [12].

Component	Weight (tn)	Distance in one trip (km)	Environmental impact
Electronic parts > Airplane	33.7	8438*	78,67%
Aluminium body/casing > Airplane	8.5	8381**	19,84%
Aluminium body/casing > Truck		2794**	1,47%
Packaging > Plastic bags	0.1	1543	0,01%
Packaging > Cardboard boxes and foam	6.6	19	0,01%
Total	48.9	21175	100%

*Electronic parts route: India – Germany – Zaragoza, Spain – Barcelona.

** Aluminium body/casing route: China – Barcelona, Spain.

Annex 2: Data used for product carbon footprint calculation.

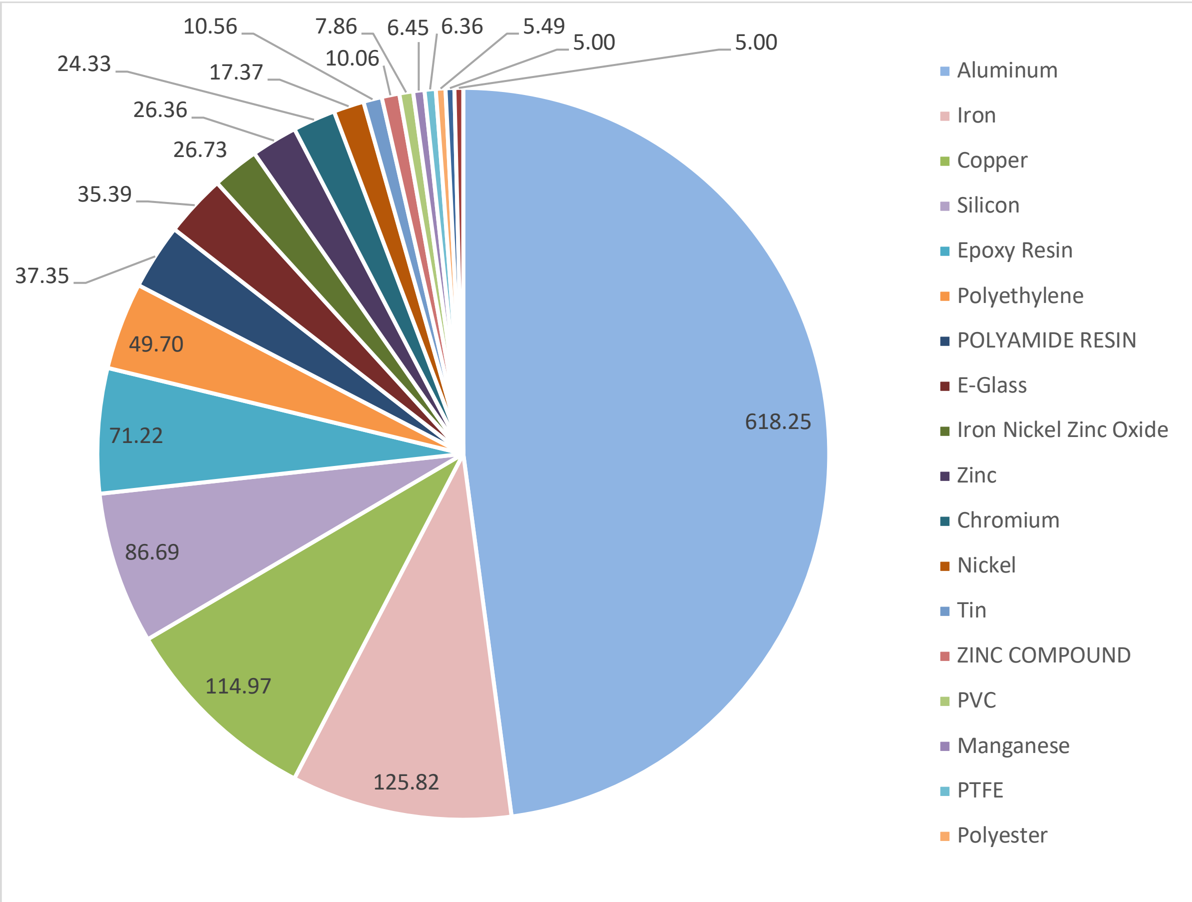

Figure 30: Weight in gram of the Top 20 Substances in a Product, excluding 4 batteries.

Table 7: Weights in grams of substances in the Vibrating Wire 5-Channel Data Logger, including 4 batteries.

Substance name	CAS #	Substance Weight	Rate of each substance in a product (wt.%)
Aluminum	7429-90-5	618.25	41.36%
Iron	7439-89-6	125.82	8.42%
Copper	7440-50-8	126.97	8.49%
Silicon	7440-21-3	86.69	5.80%
Epoxy Resin	Proprietary	79.22	5.30%
Polyethylene	9002-88-4	49.70	3.32%
POLYAMIDE RESIN	63428-84-2	37.35	2.50%
E-Glass	14808-60-7	35.39	2.37%
Iron Nickel Zinc Oxide	12645-50-0	26.73	1.79%
Zinc	7440-66-6	26.36	1.76%
Chromium	7440-47-3	24.33	1.63%

Nickel	7440-02-0	17.37	1.16%
Tin	7440-31-5	10.56	0.71%
ZINC COMPOUND	7440-66-6	10.06	0.67%
PVC	9002-86-2	7.86	0.53%
Manganese	7439-96-5	6.45	0.43%
PTFE	9002-84-0	6.36	0.43%
Polyester	113669-97-9	5.49	0.37%
Neoprene	184963-09-5	5.00	0.33%
Polyolefin	308070-21-5	5.00	0.33%
Lithium (metal)	7439-93-2	6.80	0.45%
Thionyl chloride (SOCl2)	Proprietary	80.00	5.35%
304 Stainless steel (for the container)	Proprietary	81.20	5.43%
Glass (in sealants)	65997-17-3	8.00	0.54%
Metal (in sealants, e.g., Kovar)	Proprietary	8.00	0.54%
Total		1494.97	100%

Table 8: Carbon dioxide emission factors [kg CO_2e/kg].

Substance name	Emission factors [kg CO_2e/kg]
Aluminum	15.1[31]
Iron	1.91 [32]
Copper	3.524[33]
Silicon	5[34]
Epoxy Resin	6.8[35]
Polyethylene	2.10[36]
Polyamide Resin	9.04[37]
E-Glass	1.42[35]
Iron Nickel Zinc Oxide	3.46[38]
Zinc	5.18[39]
Chromium	2.54[40]
Nickel	13[41]
Tin	12.1[42]
Zinc Compound	6.5
PVC	3.41[43]
Manganese	6.0[44]

PTFE	14.4[45]
Polyester	12.7[46]
Neoprene	6.49[47]
Polyolefin	2.7[48]
Lithium (metal)	10[49]
Thionyl chloride (SOCl2)	0.44
304 Stainless steel (for the container)	1.91[50]
Glass (in sealants)	1.42[51]
Metal (in sealants, e.g., Kovar)	7.4

Table 9: Electricity carbon dioxide emission factors in each target country [g CO_2/ kWh] [52].

Country	CO_2 emission factor in 2023
Austria	111
Canada	170
Switzerland	35
Australia	549
Bulgaria (BG)	335
Colombia	260
Germany	381
Spain	174
France	56
United Kingdom	238
Hong Kong (China)	610
Macao (China)	492
Hungary	204
Indonesia (2022)	676
Italy	331
Kazakhstan	821
Mexico	507
Malaysia (2022)	606
Nicaragua (NI) (2022)	265
Norway (NO)	30
Romania	241
Rwanda (RW) (2022)	316
Saudi Arabia (2022)	707

Sweden	41
Singapore	471
Slovenia	231
Thailand	550
United States of America	390
South Africa	708
Brazil	98
Chile	291
Egypt	570
Ghana (2022)	484
Greece	337
South Korea	431
Netherlands	268
New Zealand	113
Peru	266
Vietnam	475

Table 10: CO_2 emission factors by mode of transport [g CO2/ ton-km] [53].

Mode	CO_2 emission factors
Air	435
Road	80
Rail	35
Shipping	5

Table 11: Types of transport and number of shipments by country.

Country	Number of shipments	Transport mode	Transport (%)
Austria	1	Road	100%
Australia	2	Air	100%
Bulgaria	2	Air	100%
Canada	5	Air	100%
Switzerland	1	Air	100%
Colombia	3	Air	100%
Germany	4	Road	80%
	1	Air	20%
France	7	Road	100%

Hong Kong (China)	3	Air	100%
Macao (China)	1	Air	100%
Hungary	1	Road	100%
Indonesia	2	Air	100%
Italy	3	Road	75%
	1	Air	25%
Kazakhstan	1	Air	100%
Malaysia	3	Air	100%
Mexico	2	Air	100%
Nicaragua	1	Air	100%
Norway	1	Air	100%
Romania	2	Road	100%
Rwanda	1	Air	100%
Saudi Arabia	4	Air	100%
Singapore	2	Air	100%
Slovenia	1	Road	100%
South Africa	4	Air	100%
Spain	24	Road	100%
Sweden	3	Road	27%
	8	Air	73%
Switzerland	1	Air	100%
Thailand	1	Air	100%
United Kingdom	13	Air	68%
	6	Road	32%
United States of America	26	Air	100%
Brazil	3	Air	100%
Chile	16	Air	100%
Egypt	1	Air	100%
Ghana	1	Air	100%
Greece	1	Road	100%
South Korea	2	Air	100%
Netherlands	3	Air	100%
New Zealand	3	Air	100%
Peru	6	Air	100%

Vietnam	3	Air	100%

Table12: Technical data of edge device and gateway.

Factor	Value
Weight of Node including a battery[g]	1494.97[14]
Lifespan of battery in an edge device [years]	11.4[14]
Number of batteries in each device	4[14]
Data transmission rate (LTE FDD: - Max (DL)) [Mbps]	150 [14]
Data transmission rate (LTE FDD: - Max (UL)) [Mbps]	50 [14]
Weight of gateway[g]	1400 [18]
Lifespan of gateway [years]	11.4
Mean power consumption of Gateway[W]	4.5 [18]
Continuous current of battery[mA]	1300[16]]
Nominal voltage of a battery (at 1mA + 20°C) [V]	3.6[16]
Li metal content [g/node]	1.7[16]
Midpoint characterization factors SOPs for Hierarchist perspectives [kg Cu-eq/kg]	4.86[21]
Electricity consumption for the core network[kWh/GB]	0.052 [19]
Electricity consumption for data center[kWh/GB]	0.077[20]

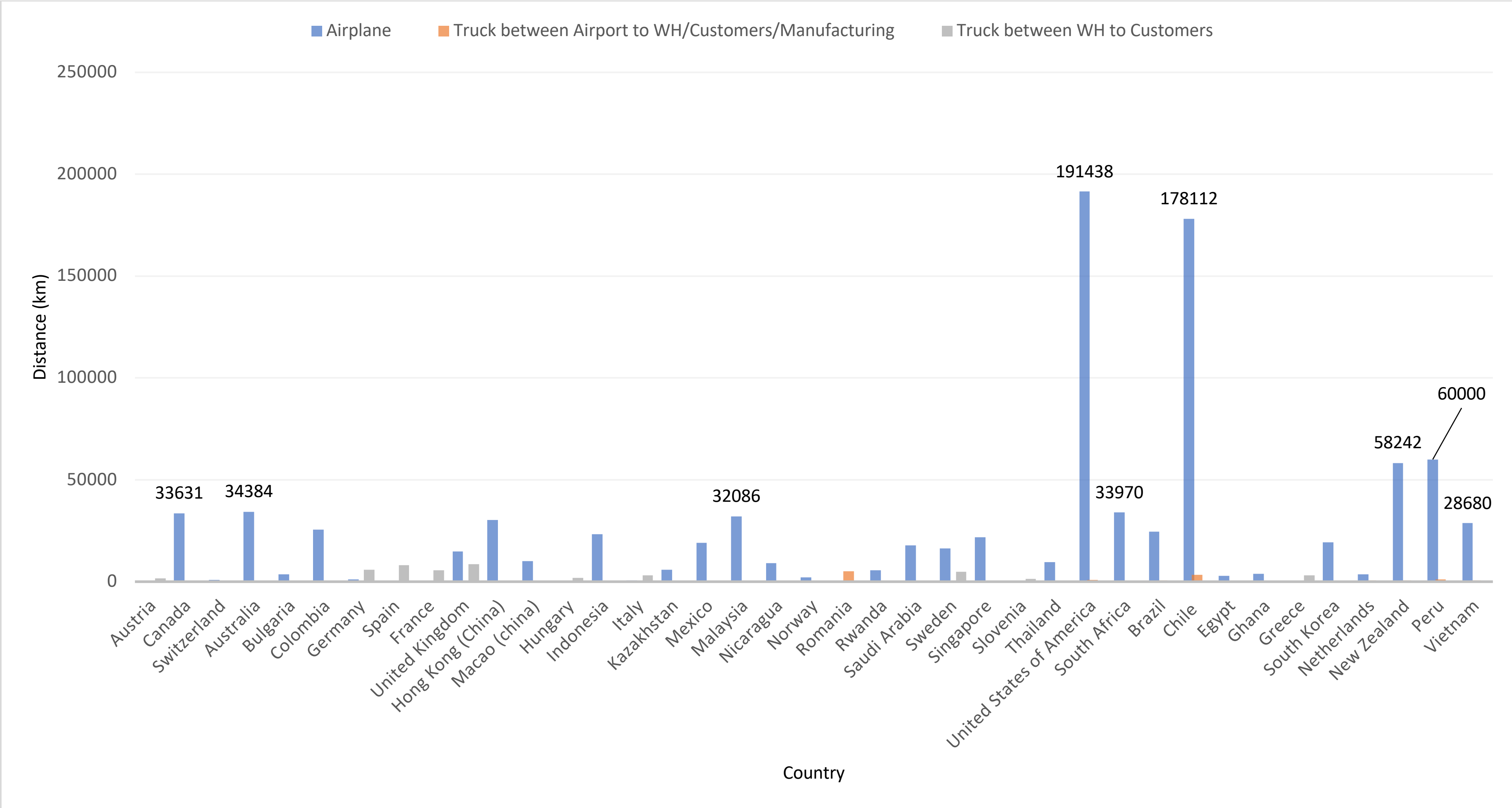

Figure 31: Distance traveled by different modes of transport by country in 2023.

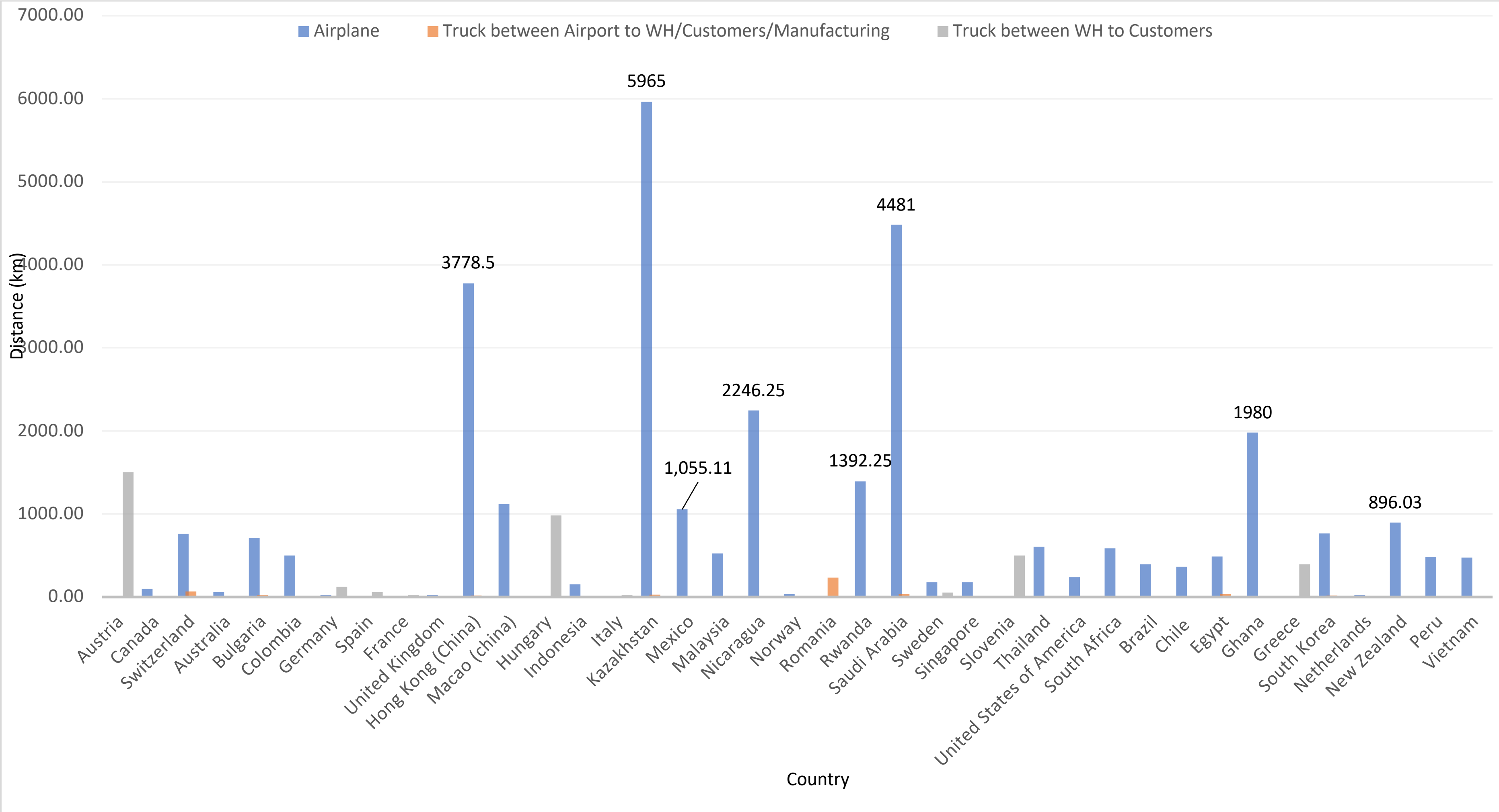

Figure 32: Transport distance and type by country per target product in 2023.

Annex 3: LCA results of all devices in each country.

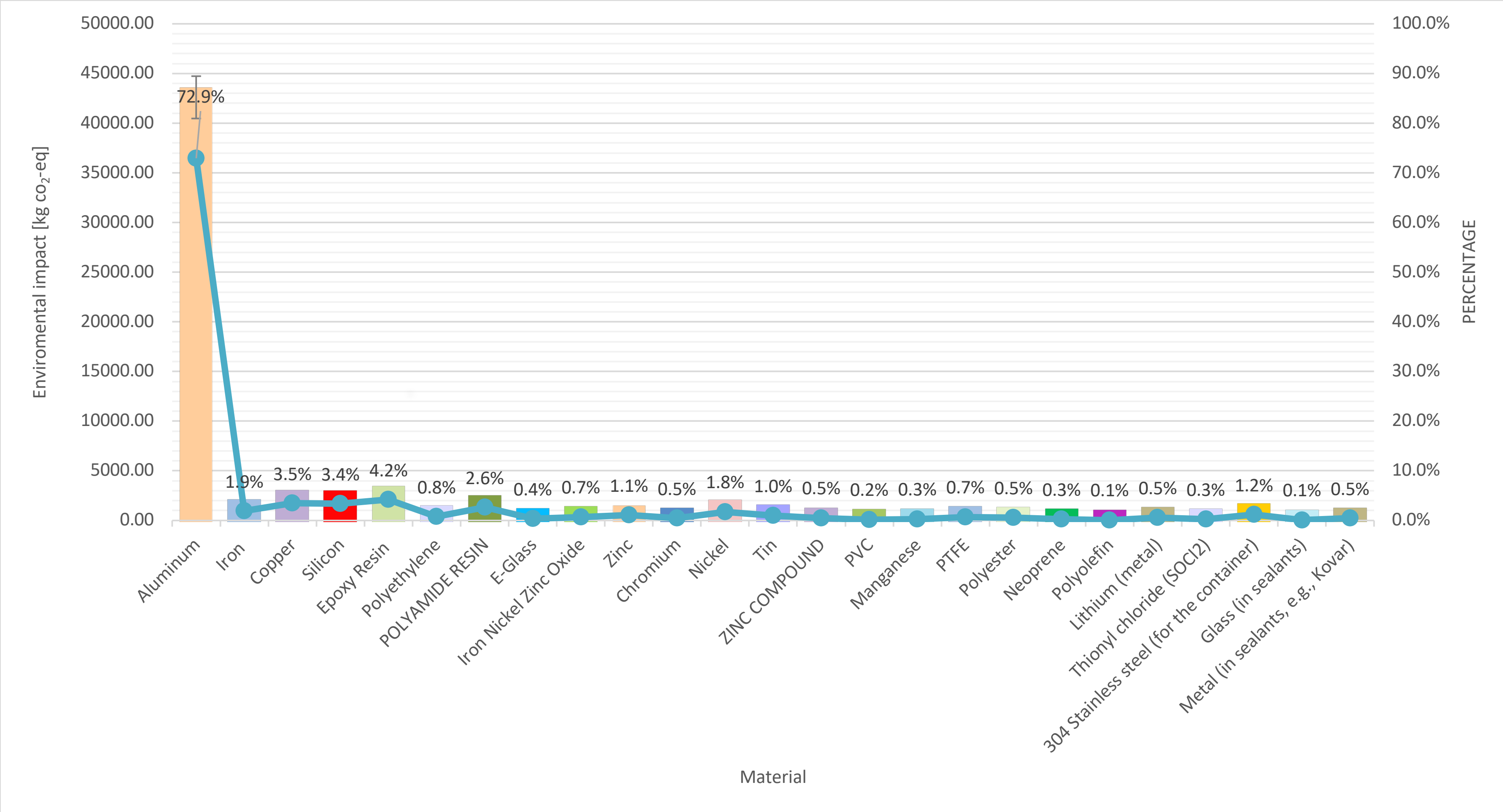

Figure 33: Global Warming Impact of Raw Materials Used in LS-G6-VW Nodes (2023).

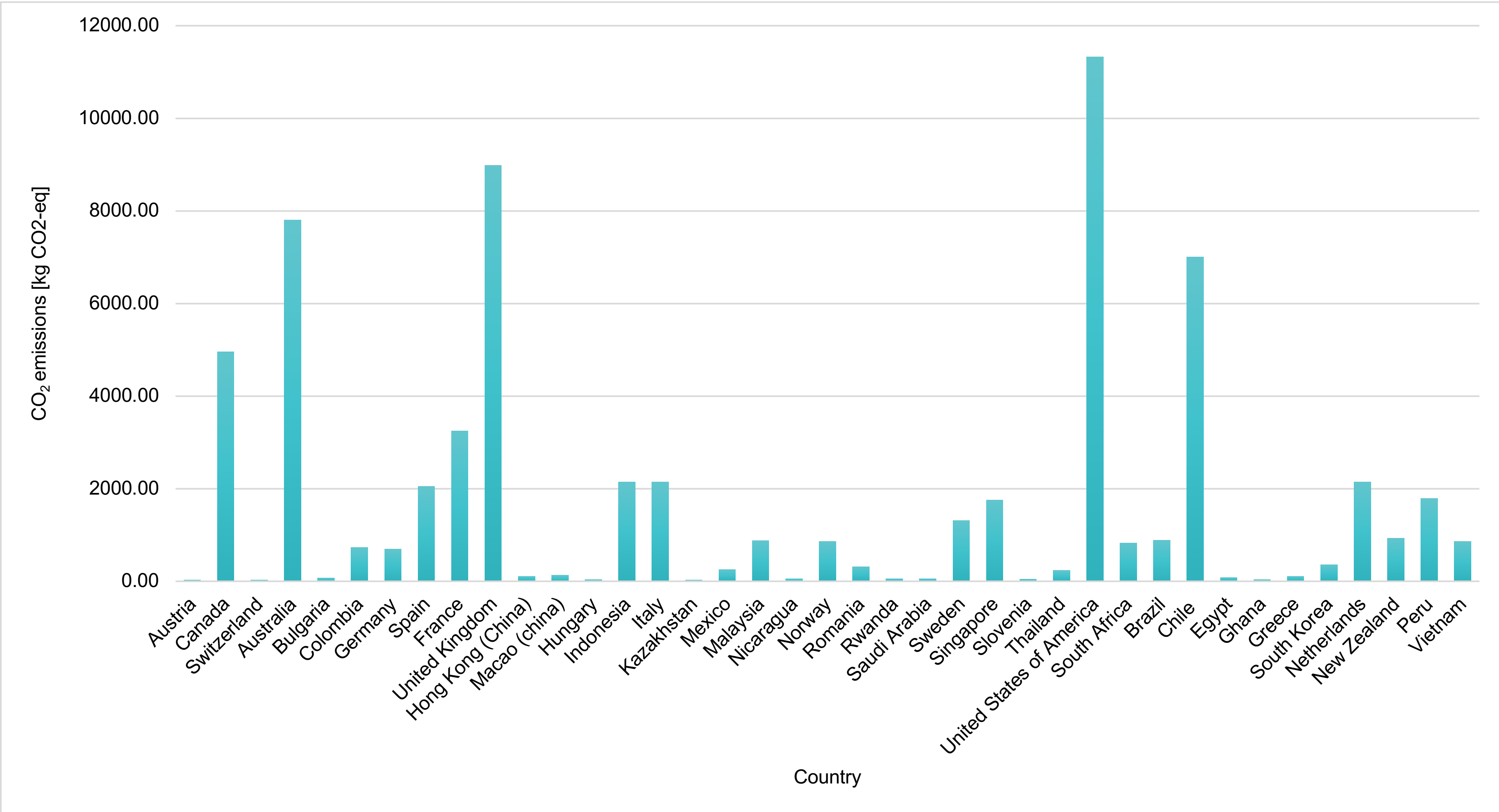

Figure 34: Total CO_2 emissions from manufacturing and packaging raw materials by country in 2023.

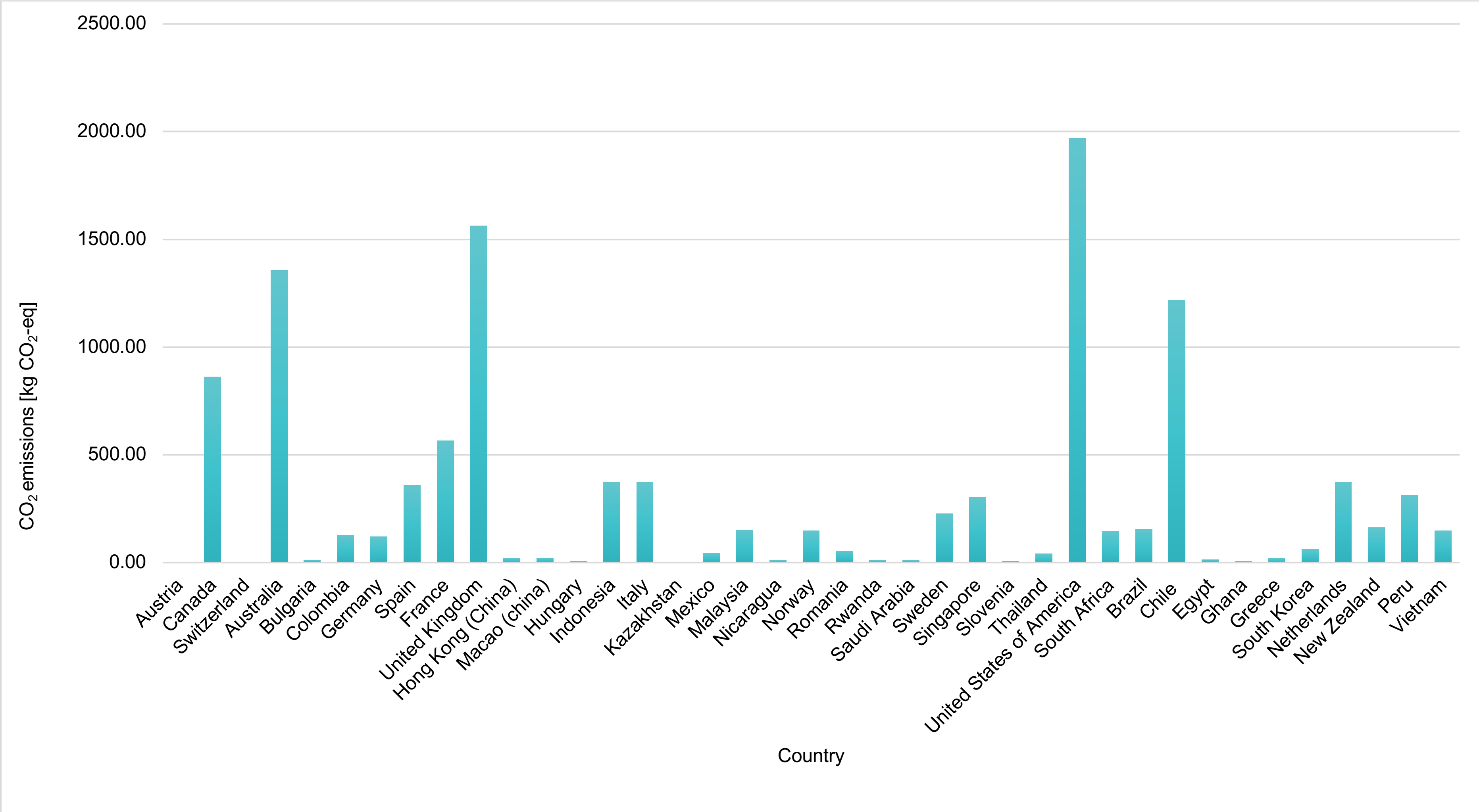

Figure 35: Total CO_2 emissions manufacturing and assembly phase by country in 2023.

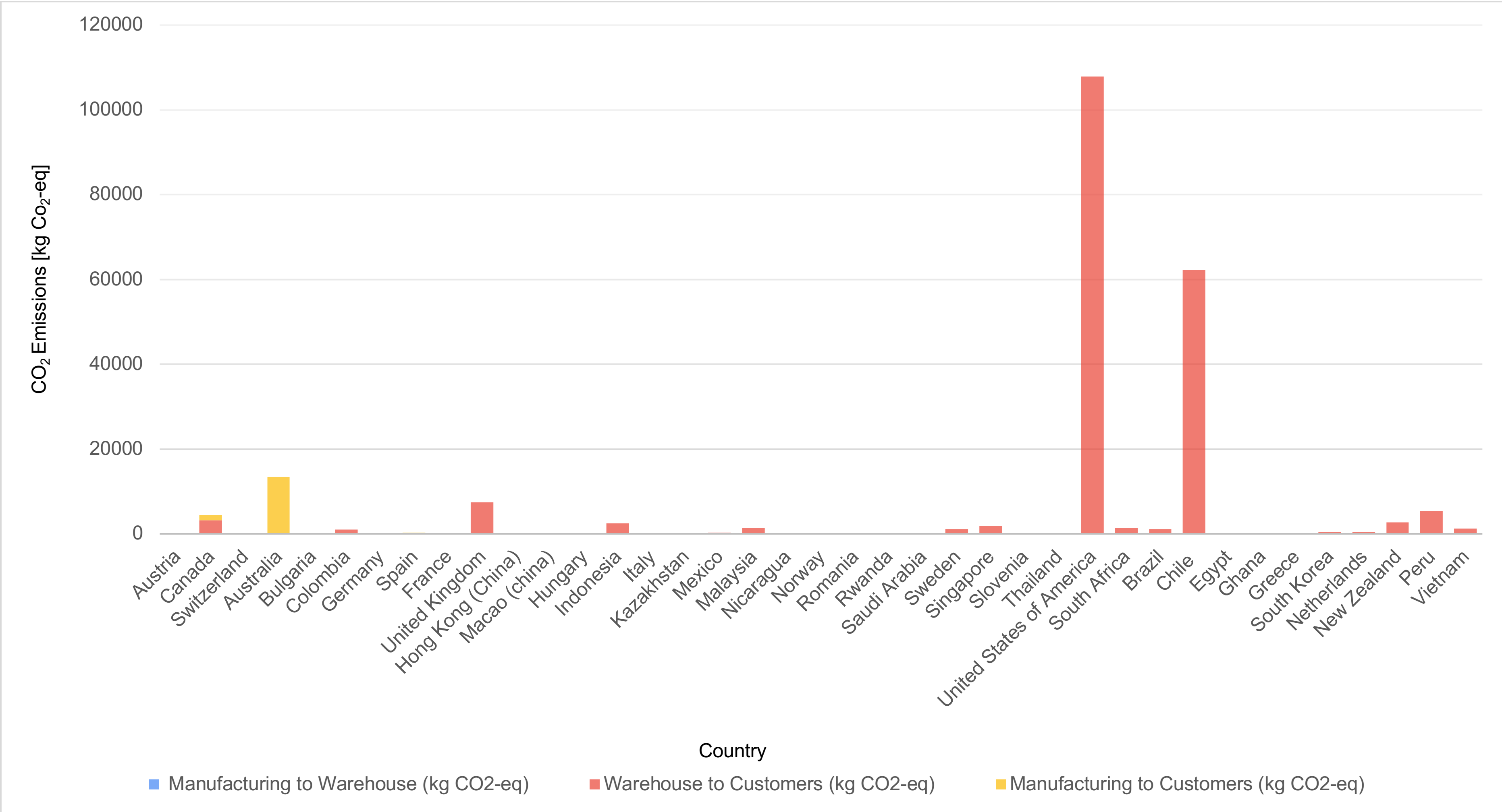

Figure 36: Global CO_2 Emissions from different transportation phases by country.

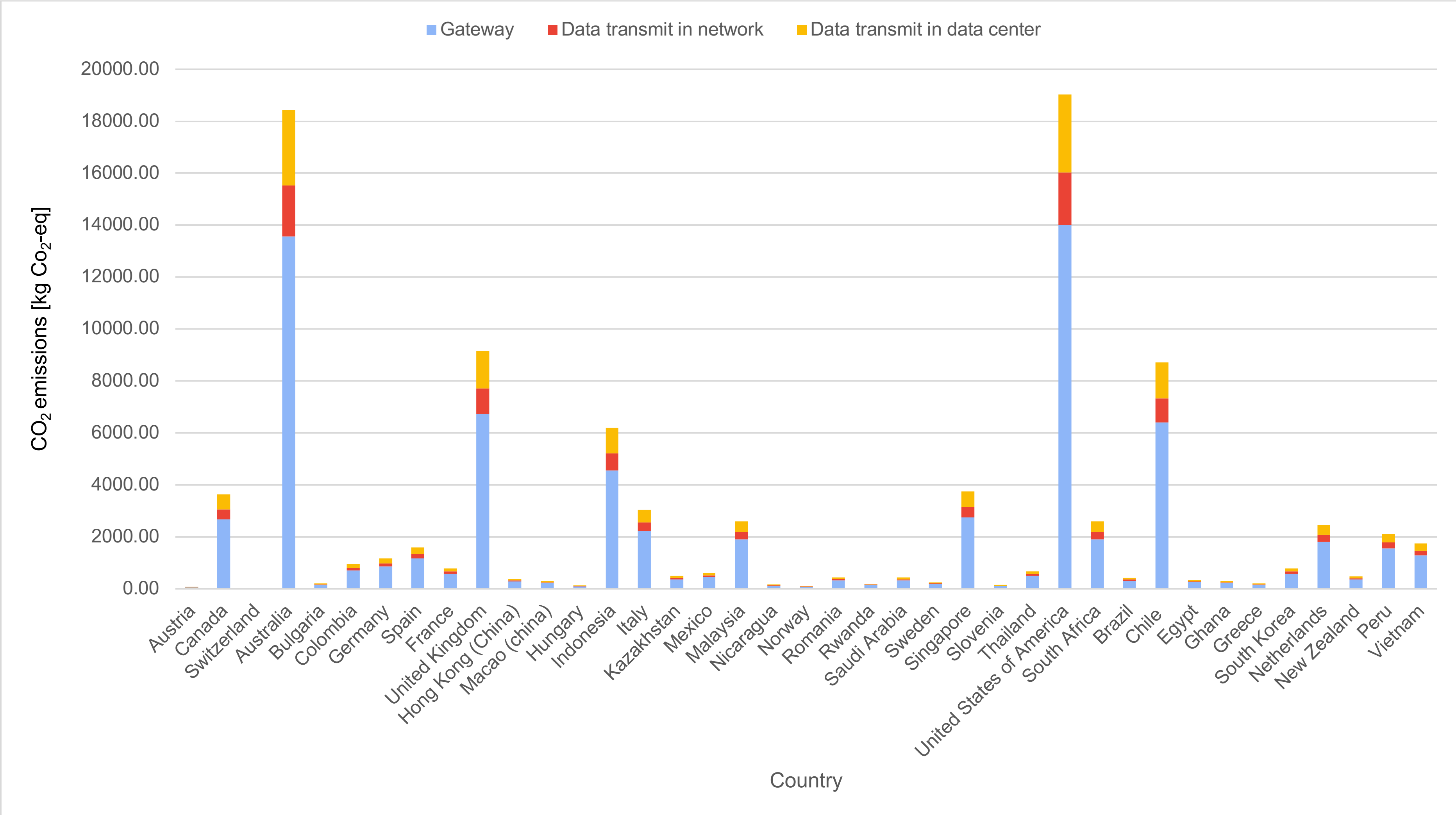

Figure 37: Total CO_2 emissions from electricity consumption in the use phase.

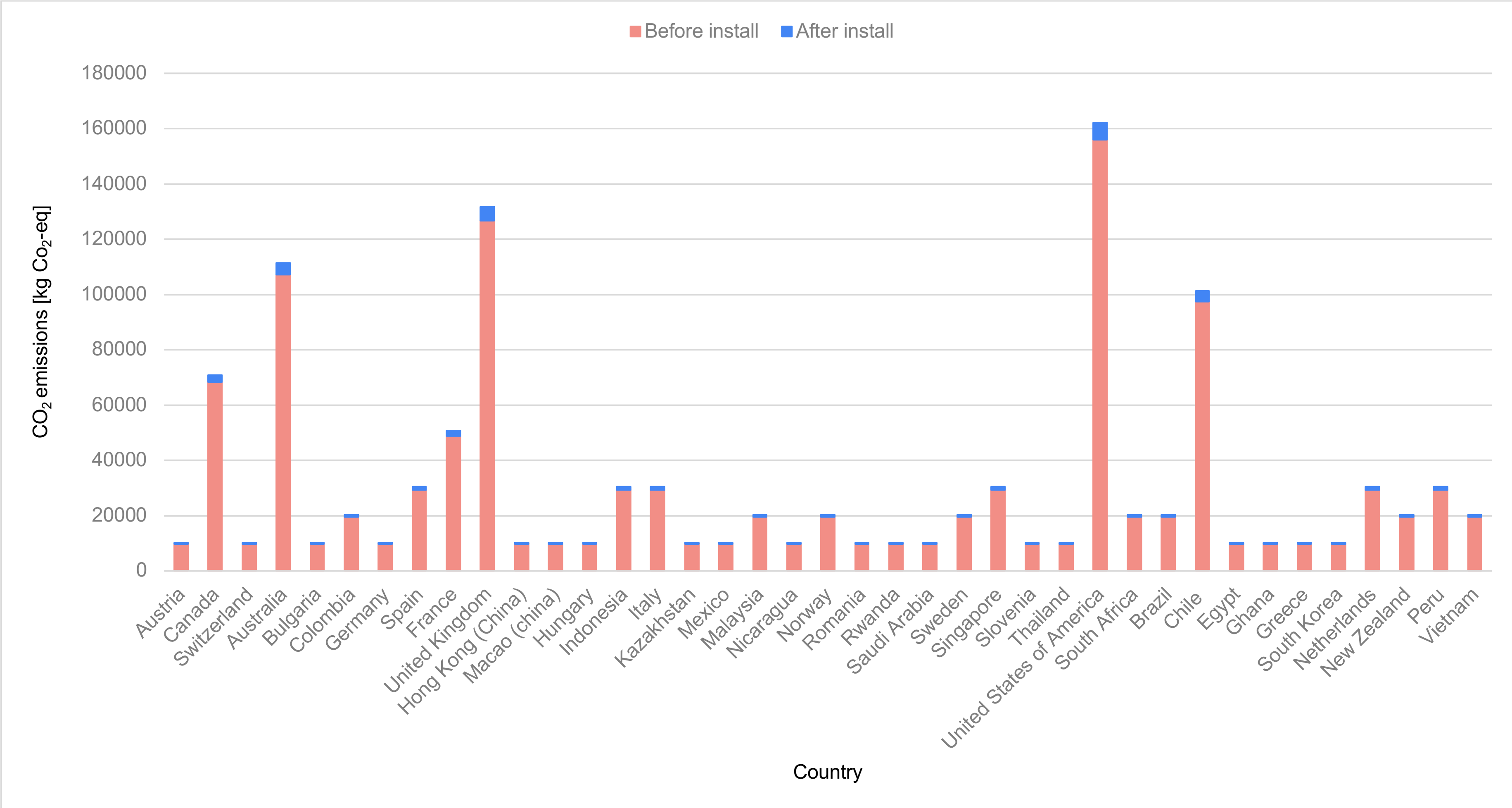

Figure 38: Total CO_2 emissions by country from laborers' regular transport to deployment locations before and after installation.

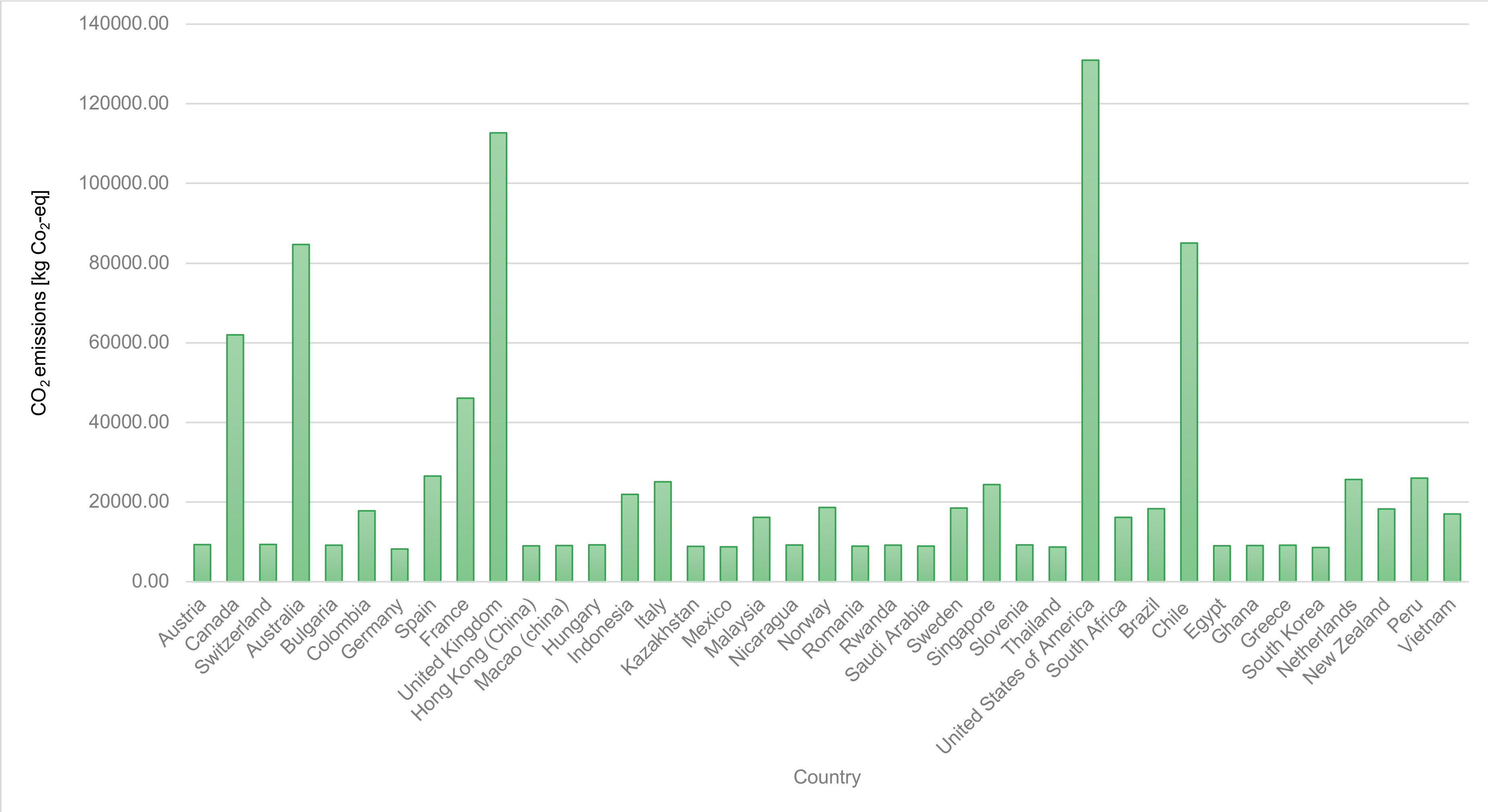

Figure 39: Total CO_2 emissions reduction by edge devices.

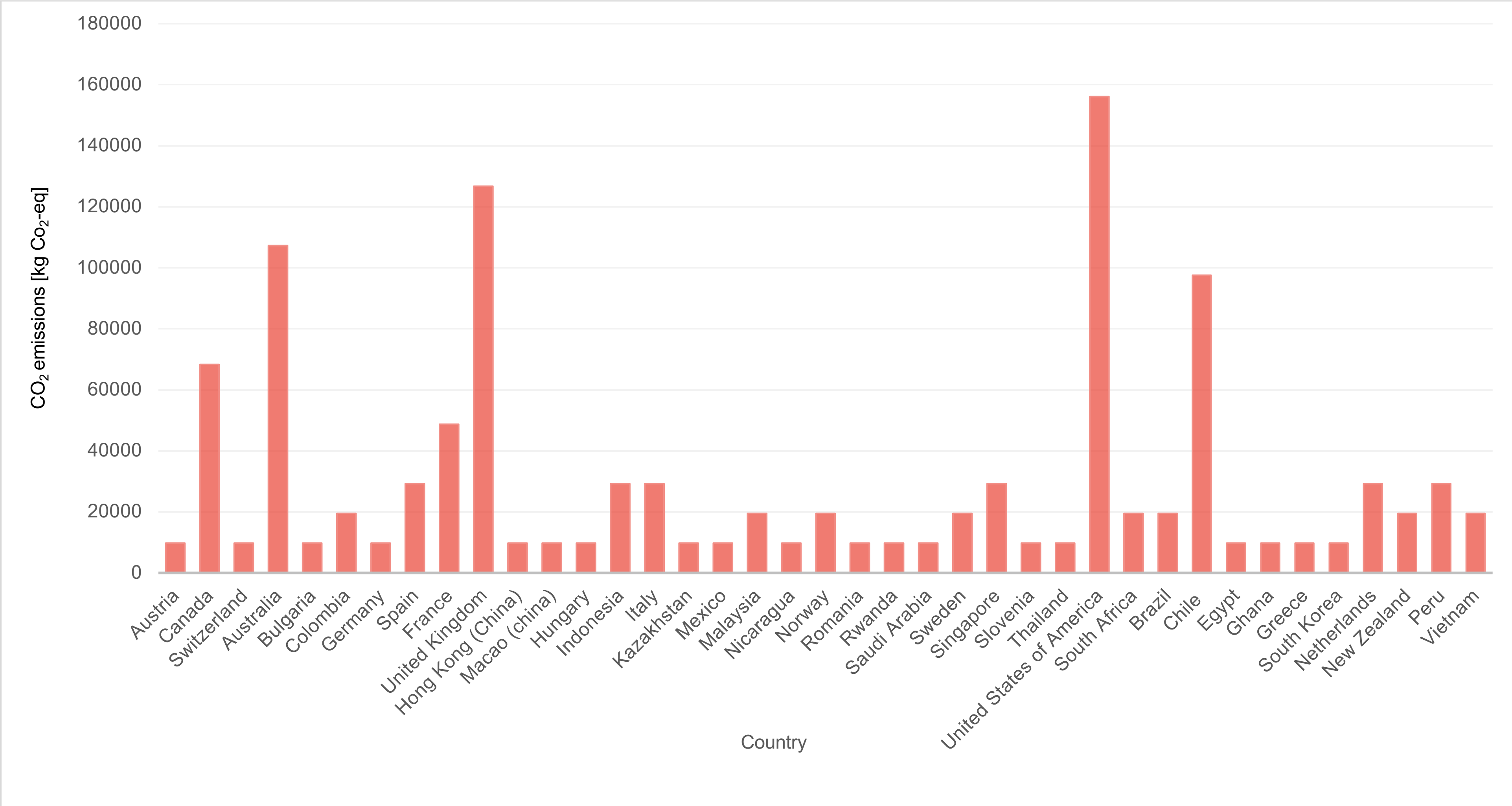

Figure 40: Total CO_2 emissions in the use phase before installing the solution by country.

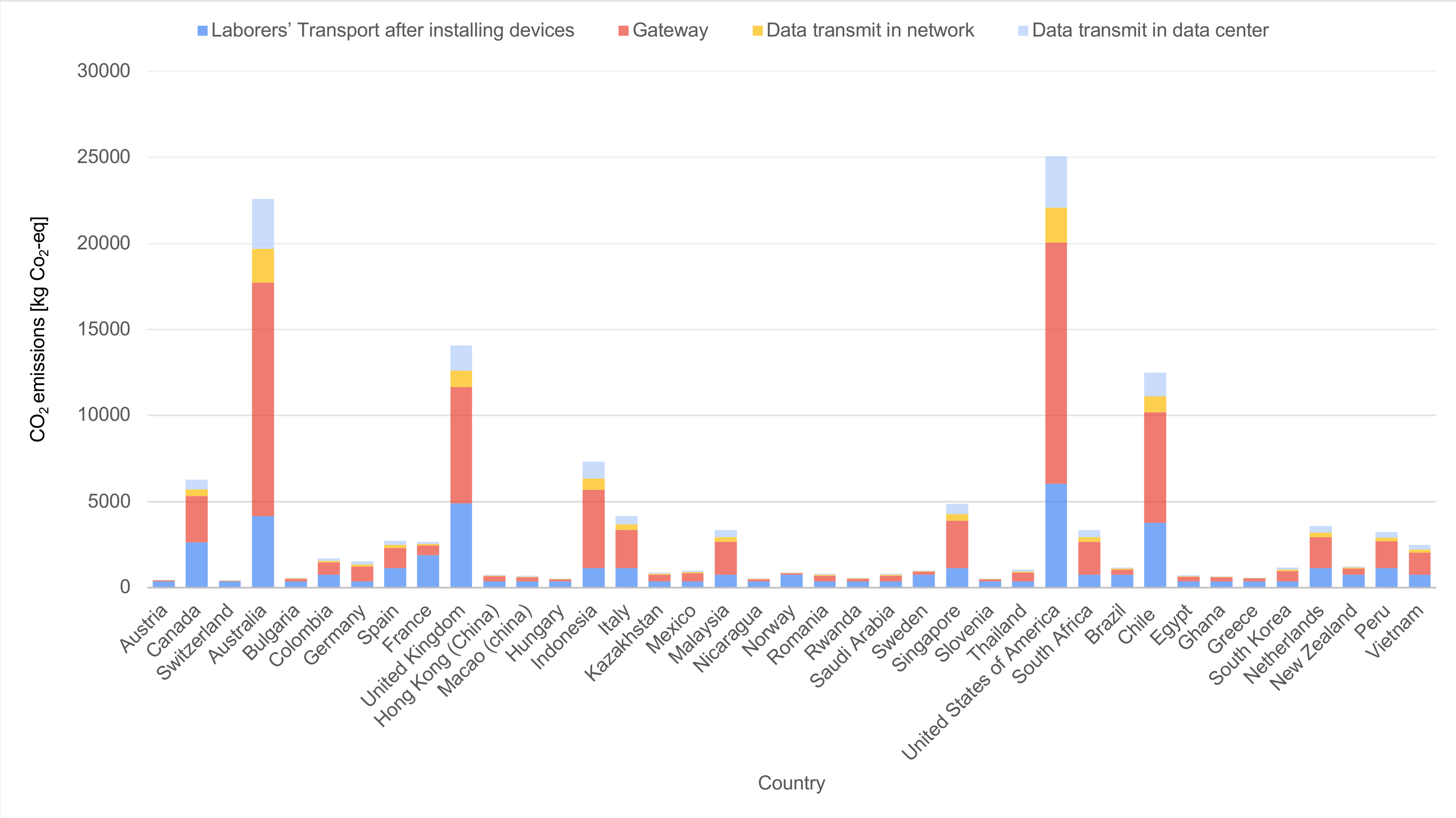

Figure 41: Total CO_2 emissions in the use phase after installing the solution by country.

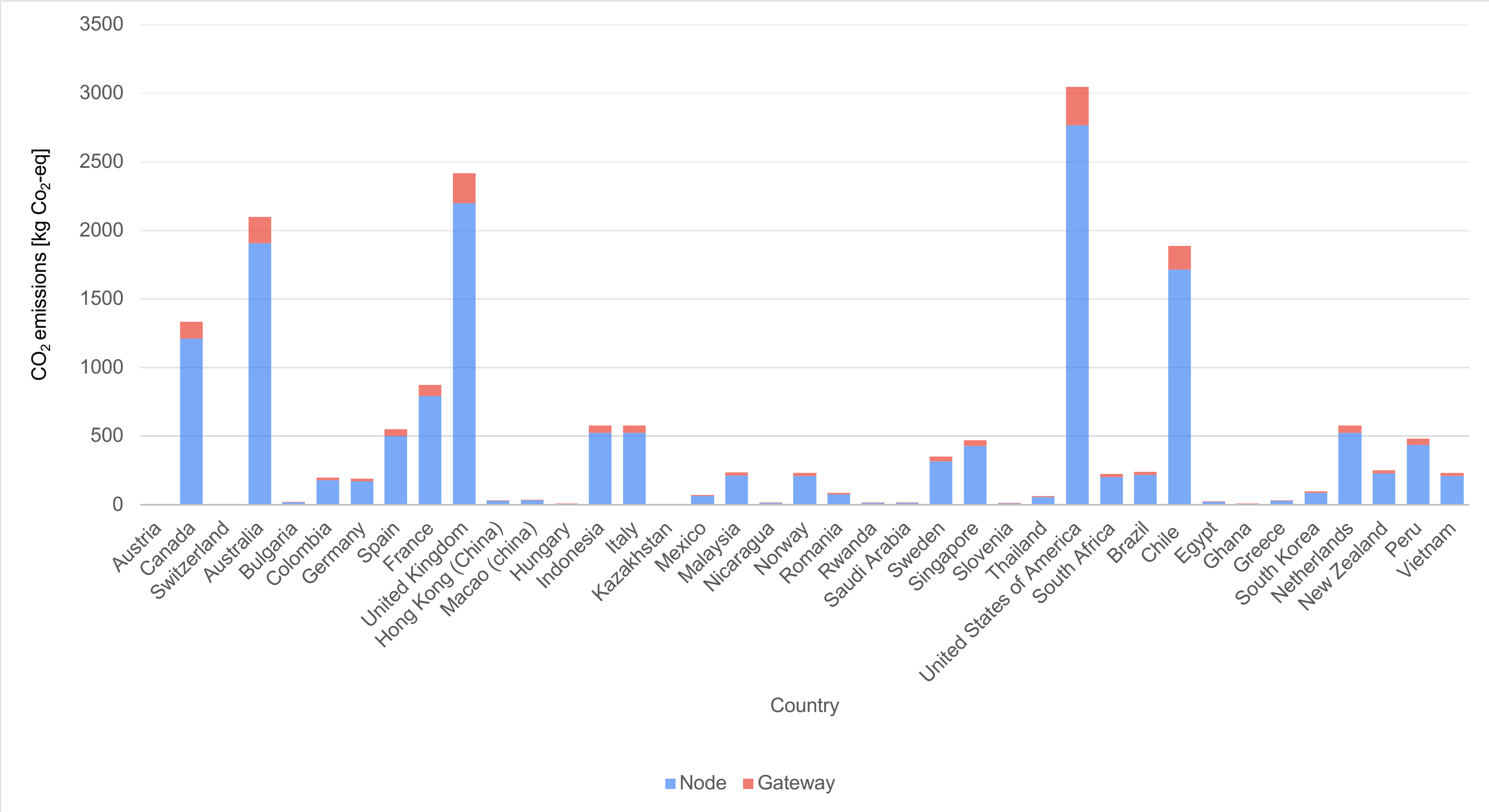

Figure 42: Total CO_2 emissions in the disposal phase for nodes and gateways by country.

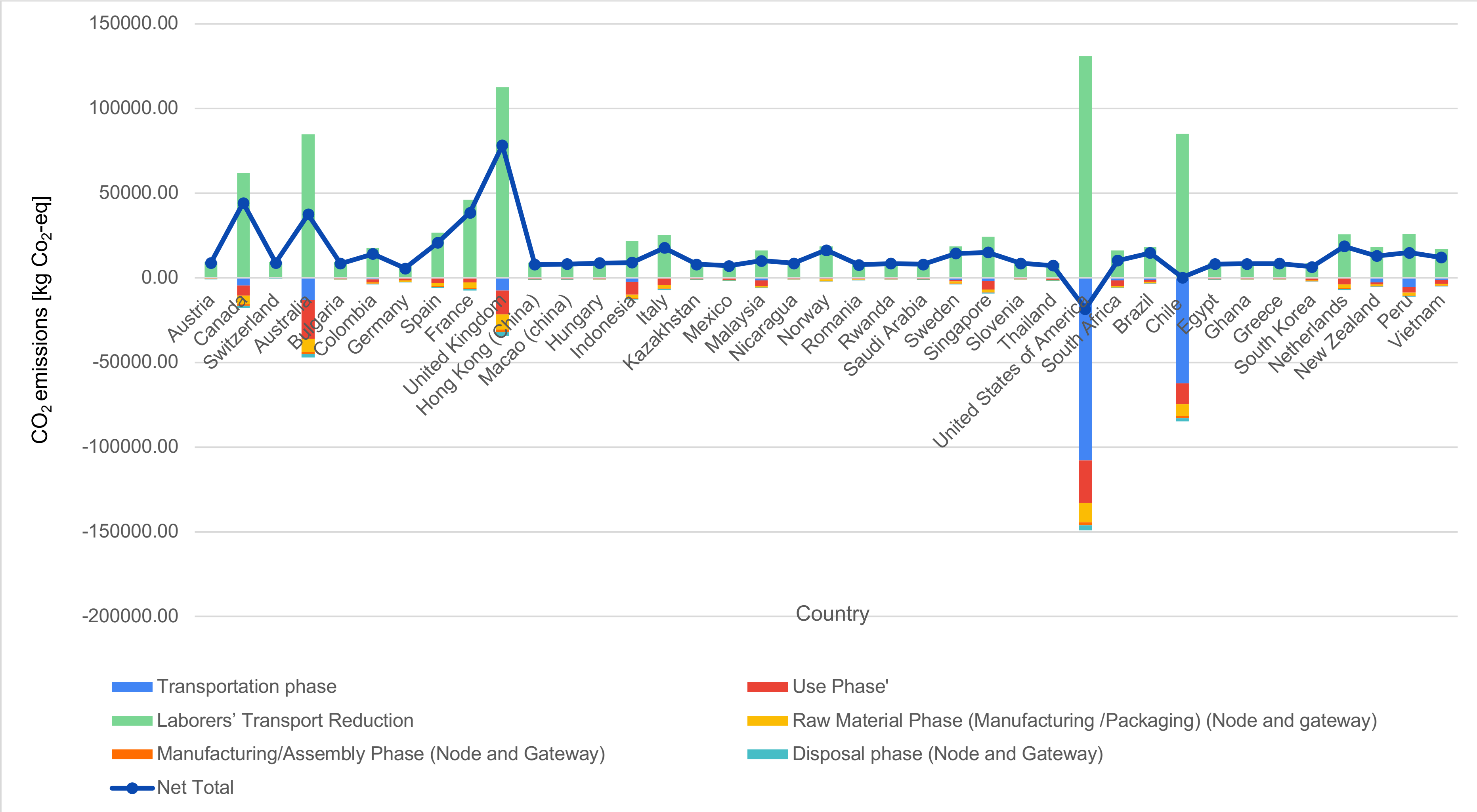

Figure 43: Total CO_2 emissions across the entire life cycle of all devices by country, including the impact of laborers' transport reduction.