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LIFE CYCLE ASSESSMENT OF THERMOELECTRIC COOLING TOTES:

FRIDGE AND FREEZER TOTES

Report # 216-001

Life cycle assessment of Phononic's thermoelectric cooling fridge and freezer totes according to ISO 14040 and ISO 14044

Prepared for:

Phononic

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This report was prepared by John Beath Environmental, LLC. The company was founded in 2015 to provide sustainability and environmental consulting services. With staff dispersed across the US, the company provides consulting services with a focus on a unique combination of the life cycle perspective and deep knowledge of process modeling and regulatory obligations.

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List of Abbreviations

AP	Acidification Potential
BOM	Bill of Materials
BWC	Blue Water Consumption
CO_2	Carbon Dioxide
EoL	End of Life
EP	Eutrophication Potential
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
GLO	Global
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JBE	John Beath Environmental, LLC
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MT	Metric Ton
MT.km	Metric Ton Kilometers
N	Nitrogen
PED	Primary Energy Demand
POTW	Publicly Owned Treatment Works
R134a	1,1,1,2-Tetrafluoroethane
R744	Carbon Dioxide (CO_2)
RoW	Rest of World
SO_2	Sulfur Dioxide
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
U.S.	United States
VOC	Volatile Organic Carbon

1 Goal of the Study

Phononic is a manufacturer of thermoelectric cooling products. They design and manufacture thermoelectric cooling chips which are used in their fridge and freezer totes for food and pharmaceutical industry storage. Phononic's totes do not use refrigerants as typical fridge and freezer reach-ins do, therefore Phononic wanted to understand the potential environmental impact of their products compared to cooling technologies that use refrigerants with mechanical refrigeration.

The comparative analysis in this report focuses on Phononic's offer of these totes as part of their omnichannel grocery solution for fulfilling online grocery orders. Grocery orders are packed into these totes, and then staged order by order until customers come to pick them up. These totes replace traditional reach-in refrigerators and freezers.

Phononic commissioned John Beath Environmental (JBE), LLC to conduct a cradle-to-grave life cycle assessment (LCA) of its thermoelectric fridge and freezer totes, alongside comparison cases using traditional and natural refrigerants for reach-in fridges and freezers. LCA is used to evaluate potential environmental impacts of a product over its life cycle. The study is conducted according to the requirements of ISO 14040:2006 (ISO, 2006a) and ISO 14044:2006 (ISO, 2006b).

The intended application for this study is to understand the potential environmental impacts of Phononic's thermoelectric cooling totes through an LCA, which enables Phononic to share its sustainability story. The primary audience for this study is internal stakeholders at Phononic and external stakeholders (e.g., Phononic's customers and investors).

To ensure the analysis' accuracy and quality, and to enable the comparative assessment results to be shared publicly with Phononic's stakeholders and customers, this study has undergone critical review by an independent review panel in accordance with ISO 14040:2006 and ISO 14044:2006. The critical review statement can be found in Annex B; review comments and responses are available upon request.

2 Scope of the Study

2.1 Product System

Phononic manufactures thermoelectric cooling totes, which are portable food storage totes with the capability to maintain cool and frozen temperatures for grocery products. The totes can be used along the entire cold chain from the retailer to the customer, ensuring product freshness. The fridge tote has the capability to maintain a refrigerated temperature for food, whereas the freezer tote has the capability to maintain a frozen temperature for food. This study is specifically focused on the use of the Phononic totes in-house at supermarket retailers for curbside pickup operations, replacing the reach-in freezers and refrigerators that are currently used to store grocery orders for curbside pickup. Typically, supermarket employees will collect grocery items from throughout the store either in a grocery cart, or directly into Phononic totes, putting together a curbside pickup order consisting of ambient, refrigerated and frozen products. Upon completion of the shopping, the order is transferred to the appropriate tote (fridge or freezer), where it waits for the customer to pick up their order. An order for an individual customer typically includes items stored in 2 fridge and 1 freezer totes. After the staff collects the order, these totes are stored together, by order, until the customer arrives to pick up their order. In the comparison scenario, the refrigerated and frozen portions of an order are kept in reach-in fridge or freezer units in the curbside order area. Phononic's totes may be used in place of reach-in units to store grocery orders in the curbside order area, enabling efficiencies by storing ambient, refrigerated, and frozen items in close proximity rather than in separate reach-ins and shelving. Totes used as described meet or exceed the same cooling performance requirements as the reach-ins that are currently used as the comparison case for the LCA.

At the start of the day, Phononic's totes are turned on by docking them either onto powered racks or a portable grocery cart adapted to receive and power the totes. The freezer tote has a temperature default setpoint at -0.4°F/-18°C, and the fridge tote has a temperature default setpoint of 37.9°F/3.3°C. These temperatures are comparable to a typical reach-in freezer and fridge (Rossi, Favi, Germani, & Omicioli, 2021). Figure 1 shows an image of Phononic's thermoelectric cooling fridge and freezer totes. Figure 1 shows images and dimensions of Phononic's thermoelectric cooling fridge and freezer totes.

This cradle-to-grave study evaluates the potential environmental impacts of Phononic's thermoelectric cooling fridge and freezer totes, based on 2023 production and materials data. The assessment also studies four comparison products:

- Traditional refrigerant fridge reach-in
- Traditional refrigerant freezer reach-in
- Natural refrigerant fridge reach-in
- Natural refrigerant freezer reach-in

Figure 1: Phononic's thermoelectric cooling freezer tote (left) and fridge tote (right) with dimensions

2.2 Functional Unit

The functional unit of an LCA is the quantification of a product's performance characteristics and is the reference unit for which all results are presented. For this study, the analysis is conducted for **1 year of product use, equivalent to the grocery product volume contained in a typical reach-in fridge/freezer. The grocery product volume for all cases is 0.65m^3**.

One year of product use was chosen for the functional unit of the study. This is due to the anticipation of (and result of) the use phase being the most dominant life cycle stage, and therefore one year would allow the most straightforward comparison of the product systems in the study.

For Phononic's fridge and freezer totes, the hours of operation are assumed to be 12 hours per day. This was chosen by Phononic as a conservative estimate, as the totes only have to be turned on to cool or freeze items when needed, and are not anticipated to be used to store food items overnight and when the stores are closed. It was assumed by Phononic that all comparison case reach-ins were turned on for 24 hours per day (i.e. they are never turned off, even if they do not contain any food items).

The systems are equivalent in this study as the Phononic products and the comparison case products all fulfill the same role. Phononic's fridge and freezer tote carry food items in a cold or frozen temperature environment, allowing supermarket workers to house items inside the totes, waiting for orders to be completed and the food be transferred to the customer at the store. The comparison case fridges and freezers are reach-in units, which also store food items at cold or frozen temperatures, allowing supermarket workers to house items inside the fridge and/or freezer, waiting for orders to be completed and the food transferred to the customer at the store.

2.3 System Boundaries

An LCA's system boundary defines which unit processes are considered in the modelled system. Unit processes are one or several operations in a manufacturing system. This analysis adopts a cradle-to-grave perspective. The intent of this study is to capture all known and material product-specific impacts from raw material extraction to end of life (EoL). In accordance with the goal and scope of the study, Table 1 and Figure 2 detail the system boundary components included in the study and those that are excluded. Excluded aspects are commonly outside the scope of product-level LCA studies and are expected to have small to negligible impact when normalized to the study functional unit.

Table 1: Components included in and excluded from the system boundary

Included	Excluded
• Raw materials extraction and processing • Shipment of materials to manufacturing location • Product manufacturing • Manufacturing emissions • Use phase utilities and refrigerant usage and emissions (where relevant to comparison cases) • Product EoL pathways	• Manufacturing equipment maintenance • Capital equipment, infrastructure[1], and maintenance • Human labor and employee commute • Transportation to and from customers

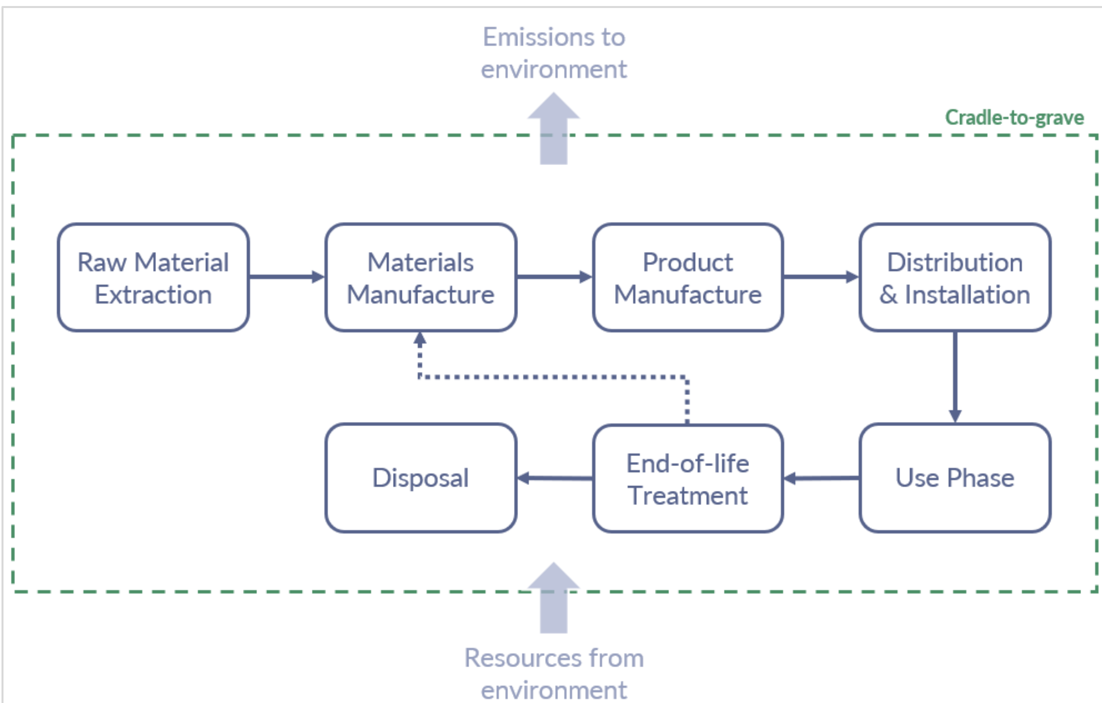

Figure 2: System boundary for the LCA study

2.3.1 Time Coverage

This study represents the 2022-2024 calendar years.

The Bill of Materials (BOM) represents locked designs for Gen 2 units. The manufacturing is completed or planned for 2024. The manufacturing data provided was from the calendar year January 1st 2022 through December 31st 2022. The 2022 data was based on production of chips at Phononic's Durham, North Carolina facility. The tote manufacturing facility data is based on historic actual data provided by the

[1] Although infrastructure and capital equipment are excluded from the foreground system primary data, ecoinvent datasets may include infrastructure as the study was modelled in an ecoinvent system process database.

manufacturing facility in Thailand for the 2022 calendar year, accounting for the share of the facility that would be dedicated to Phononic tote production.

Phononic's totes are innovative new products that began with a prototype product (Gen 1), which was tested with customers in a 2023 product trial. Gen 2 is the focus of the study and is based on the Gen 1 products. Gen 2 is in the early stages of production. The energy model is based primarily on a customer trial of the Gen 1 prototype units that ran from April 18th 2023 through May 18th 2023, in which 18 refrigerator totes and 10 freezer totes were operated. Using data collected every 30 minutes from these totes, an average energy consumption per hour of refrigerator and freezer tote operation was calculated. These values were used as the unit value for energy consumption per hour by a single refrigerator and freezer tote, in the final designs for Gen 2 units being manufactured in 2024. Given the energy model was based on the Gen 1 prototype, Phononic expects the Gen 2 totes will operate in a more efficient manner.

The comparison cases are representative of 2021 calendar year materials and manufacturing data, and 2023 use phase data.

2.3.2 Technology Coverage

This study represents the manufacturing of existing technologies by Phononic using the 202 bill of materials and 2022 manufacturing data with a retrospective energy model. The energy model is based on the first generation (Gen 1) of Phononic's totes, and the manufacturing estimates are based on the second generation (Gen 2).

2.3.3 Geographic Coverage

This study represents manufacturing of Phononic's thermoelectric cooling chips in the United States, and the manufacturing of their totes in Thailand. The study also represents the global manufacturing of the comparison case reach-ins for both the traditional refrigerant cases and the natural refrigerant cases.

2.4 Cut-off Criteria

No cut-off criteria are defined for this analysis. All available energy and material flow data are included in accordance with the system boundary. Proxy data are used as needed in the model to capture all considered life cycle impacts.

2.5 Allocation Procedures

2.5.1 Co-product Allocation

A process, sub-system or system may produce co-products in excess of the necessary reference flow or intermediate product. Such co-products leave the system to be used in other systems yet should carry a portion of the burden of their production system. To allocate burden in a meaningful way between co-products, several procedures are possible, including system expansion, mass allocation, allocation by heating value, and economic allocation.

The manufacturing processes under study produce no co-products. As such, no allocation procedure is necessary for co-products.

2.5.2 End-of-life Allocation

At EoL, all products under study are disposed of in various waste streams including ferrous metal waste to recycling, non-ferrous waste to recycling, and general waste to landfill. The mass of waste to each stream is allocated based on the mass of material types in the input to manufacture the chips and totes, and comparative reach-ins. All waste treatment at EoL is allocated to either the totes or the comparison case reach-ins. At EoL, metals were modelled with the cut-off approach. No credit (avoided burden) was taken for materials sent into a recycling stream.

Background data for the study uses a cut-off approach for end-of-life allocation.

2.6 LCIA Methodology

The impact assessment categories and other metrics considered to be of high relevance to the goals of this project are shown in Table 2 below. The impact categories are calculated using globally accepted methods: Intergovernmental Panel on Climate Change (IPCC) and the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (US EPA, 2011). TRACI v2.1 is an impact assessment method focused on North America, and was chosen as it is the most applicable to the U.S. region where the chips are manufactured and the totes products are currently sold. This study intends to quantify the total global warming potential (GWP, total), acidification potential (AP), eutrophication potential (EP), non-renewable primary energy demand (PED, fossil), and blue water consumption (BWC) of the products under study.

GWP, total and PED, fossil are chosen because of their relevance to energy efficiency and climate change, both of which are of high public and political interest. The GWP impact category is assessed based on the current IPCC characterization factors from the 6th Assessment Report (IPCC, 2021) for a 100-year timeframe.

AP and EP are chosen because they are connected to air, water, and soil quality, and capture the environmental burden associated with metals and heavy industrial processes required to manufacture such materials. BWC is chosen because of its relevancy to political and commercial matters. This study does not investigate regional water scarcity impacts.

Table 2: Environmental indicators chosen for the comparative assessment

Indicator	Units	Description
GWP, total	kg CO_2eq	Global warming potential, 100-year time horizon, including impacts from fossil sources, land use and land use change, and biogenic methane. A measure of how much solar radiation a greenhouse gas emitted to the atmosphere will absorb over a given timeframe. Emissions with larger GWPs contribute more to climate change.
EP	kg N-eq	The enrichment potential of the freshwater ecosystem due to the emission of nitrogen or phosphorous-containing compounds.
AP	kg SO_2-eq	The potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulfur oxides.
BWC	m^3	Water extraction from the environment (resource) and water released back to water bodies (emission).
PED, fossil	MJ	Primary energy demand, fossil. This is a measure of the total energy demand of a process or system. In this case, energy demand only from fossil sources is accounted for.

Although the comparison case products used two refrigerants; R134a (1,1,1,2-Tetrafluoroethane) and R744 (carbon dioxide), neither of these refrigerants have characterization factors in the TRACI 2.1 ozone depletion method. Additionally, Phononic's fridge and freezer totes do not use refrigerants to keep items cool and frozen. Therefore, the exclusion of ozone depletion from the study is justified.

This study does not address other environmental indicators or impact categories, nor does it consider social impacts, land use, biodiversity, human health or ecotoxicity, or local impacts such as noise.

The LCI unit processes were modelled using either primary data from Phononic or secondary data from published, peer-reviewed LCA studies for the comparison cases. This data was then entered into openLCA v2.0.4, where the chosen impact methods were run with characterization factors from IPCC AR6 and TRACI v2.1. This generated LCIA results as described herein.

2.7 Data Quality Requirements

The key requirement for data quality is that data be as accurate and representative as possible. Data quality evaluations are described in section 3.3, which includes an evaluation of data quality specific to this study. The requirements are based on the ISO 14044:2006 standard. To fulfill these requirements and to ensure reliable results, primary data in combination with representative, secondary literature, and consistent background life cycle inventory (LCI) information from ecoinvent version 3.9.1 (Wernet, et al., 2016) are used.

2.8 Type of Document

This report intends to conform with the requirements of ISO 14044:2006. As such, this document aims to report the results and conclusions of the LCA completely and accurately, without bias to the intended audience. The results, data, methods, assumptions, and limitations are presented in a transparent manner with intention to provide sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent to the LCA. The report aims to be used in a manner consistent with the goals of the study.

2.9 Critical Review

An external review of this report was conducted by a panel comprised of Thomas Gloria of Industrial Ecology Consultants, Terrie Boguski of Harmony Environmental, and Angela Fisher of Aspire Sustainability. The external review process was conducted to ensure consistency between the completed LCA and the requirements of the ISO 14044:2006.

The critical review statement is included in Annex B. Reviewer comments and JBE responses can be made available upon request.

3 Life Cycle Inventory Analysis

3.1 Data Collection and Modeling

Primary data on product materials, manufacturing, inbound transportation, and energy use for Phononic's fridge and freezer tote were provided by Phononic via a customized spreadsheet template. Other data, such as EoL pathways and the comparison case materials and manufacturing data, were obtained from secondary sources.

Secondary data on product materials, manufacturing, inbound transportation, refrigerant charge, refrigerant leakage, and EoL for the comparison reach-ins were gathered from peer-reviewed published LCAs. Energy requirements for the use of comparison reach-ins were provided by Phononic based on a customized energy model.

Once data were consolidated, they were entered into a software model developed in openLCA v2.0.4 (openLCA, 2023). The following sections provide details on primary and secondary data used to model product environmental performance. Secondary datasets were taken from ecoinvent v3.9.1 and are detailed in Section 3.2 and Annex A: Background Data.

3.1.1 Manufacturing Process – Phononic Products

The chips are made from a combination of metals, plastics, and heat exchangers. The chips are then transported to Thailand where they are used in combination with electrical components and other materials to make the totes. The chips used for the fridge and freezer totes are similar, however are used in varying numbers to achieve the cooling and freezing properties required. One fridge tote uses one chip, and one freezer tote uses six chips. Materials and manufacturing data for the chips are provided in

Table 3 and
Table 4 respectively. Materials and manufacturing data for the totes are provided in
Table 5 and Table 6.

The chips are manufactured consistent with industry standards and methodology, including bonding pairs of n-type and p-type semiconductor material to ceramic headers, in an electrically serial but thermally parallel manner. The chips are soldered to a printed circuit board that is then encapsulated between two heat exchangers within the tote. The totes are then assembled, and foam is injected into voids in the tote walls and lid to provide thermal insulation. The chips cool on one side causing the heat exchanger to cool the inside of the tote chamber. The opposite side of the chip rejects heat through the hot side heat exchanger (located outside the tote chamber). The chips are only active when the tote is on DC power, however has a small coin battery to keep IOT (internet) communication, but the unit does not actively cool when off power. Each tote is tested before being packed and shipped.

Electricity grids used to model the manufacture of Phononic's chips and totes were representative of the areas of manufacture. Phononic's chips are manufactured in Durham, NC, USA, which was modelled using the US-SERC grid (Table 23). Phononic's totes are manufactured in Thailand, which was modelled using the TH grid, as well as an electricity production via photovoltaics dataset, as representative of the facilities' electricity (

Table 24).

The manufacturing data provided by Phononic was based on a year of operation. The number of chips manufactured during this time period was also provided. Chip production is representative for average chip manufacturing at the Durham, NC facility and was calculated based on the number of chips produced at the facility on a per unit basis. As the chip manufacturing stage is a low contributor to overall footprint of the fridge and freezer totes, this assumption is justified. The difference in mass of the fridge and freezer chips was accounted for in raw materials and transportation stages, and is reflected in Table 3 and Table 5. Table 4 contains manufacturing data for one average thermoelectric chip, and so one of this unit process is used for the fridge tote, and six for the freezer tote manufacture as they have one and six chips, respectively, without recharging.

Table 3: LCI data for one of Phononic's thermoelectric fridge and freezer chips

Material	Units	Fridge Chip	Freezer Chip	Inbound Transportation Distance [km]
Inputs				
Bismuth telluride	kg	3.25E-04	1.72E-03	34,000 ship, 4,000 truck
Gold	kg	1.00E-06	1.00E-06	34,000 ship, 4,000 truck
Polyphenylene sulfide	kg	7.50E-03	1.32E-02	34,000 ship, 4,000 truck
Copper	kg	7.84E-02	2.23E-01	34,000 ship, 4,000 truck
Printed circuit board	kg	5.00E-06	7.10E-03	34,000 ship, 4,000 truck
Solder	kg	1.00E-06	1.00E-06	4,000 truck
Solder paste	kg	1.00E-06	1.00E-06	4,000 truck
Sealant	kg	1.00E-02	1.50E-02	4,000 truck
Thermal Grease	kg	6.00E-04	6.00E-04	4,000 truck
Nickel plating	kg	1.00E-05	1.00E-05	34,000 ship, 4,000 truck
Reject heat exchanger copper	kg	5.73E-01	8.30E-01	34,000 ship, 4,000 truck
Reject heat exchanger aluminum	kg	1.01E-01	1.47E-01	34,000 ship, 4,000 truck
Outputs				
Thermoelectric solid state cooling chip [1 item]	kg	7.71E-01	1.24E+00	N/A

Table 4: Phononic manufacturing unit process for one average thermoelectric chip

Material	Units	Quantity	Outbound Transportation Distance [km]
Inputs			
Purchased electricity	kWh	3.01E+00	N/A
Natural gas	MJ	2.06E+00	N/A
Municipal water	m^3	9.34E-02	N/A
Outputs			
Thermoelectric cooling chip	Item	1.00E+00	N/A
Non-hazardous waste to landfill	MT	1.13E-05	50 truck
Hazardous waste to recycling	MT	4.73E-06	50 truck
Wastewater to POTW	m^3	9.34E-02	N/A
Particulate matter	MT	5.29E-07	N/A

Material	Units	Quantity	Outbound Transportation Distance [km]
Volatile organic carbon	MT	4.34E-07	N/A
Sulfuric acid	MT	1.08E-06	N/A
Hydrochloric acid	MT	4.34E-08	N/A
Nitric acid	MT	6.68E-07	N/A

Table 5: LCI data for one of Phononic's thermoelectric fridge and freezer totes, from BOM

Material	Units	Fridge Tote	Freezer Tote	Inbound Transportation Distance [km]
Inputs				
Thermoelectric solid state cooling chips	kg	7.71E-01	7.43E+00	20,765 ship, 100 truck
Steel	kg	3.00E-01	3.00E-01	250 truck
Aluminum	kg	2.19E+00	2.19E+00	250 truck
Acrylonitrile butadiene styrene	kg	3.50E+00	3.50E+00	400 truck
Insulation	kg	1.30E+00	1.30E+00	500 truck
Batteries (lithium ion)	kg	1.00E-02	1.00E-02	3,000 ship, 20 truck
Motors (12V DC fan motors)	kg	3.00E-01	3.00E-01	3,000 ship, 20 truck
Copper	kg	9.20E-01	9.20E-01	250 truck
Outputs				
Thermoelectric solid state cooling tote [1 item, unscaled]	kg	9.29E+00	1.59E+01	N/A

Table 6: Phononic thermoelectric fridge and freezer tote manufacturing unit process

Material	Units	Quantity	Outbound Transportation Distance [km]
Inputs			
Purchased electricity	kWh	1.66E+01	N/A
Electricity generated on-site (solar)	kWh	5.08E-01	N/A
Diesel	m3	2.37E-04	N/A
Municipal water	m3	1.03E-01	N/A
Outputs			
Thermoelectric cooling tote	Item	1.00E+00	N/A
Non-hazardous waste to recycling	MT	2.52E-04	50 truck
Hazardous waste to recycling	MT	1.60E-05	50 truck
Water discharged to river or lake	m3	8.21E-02	N/A

Water inputs and outputs for the tote manufacturing are based upon water meter readings for water entering the facility, and information from Phononic that 80% of water input leaves the facility with the remaining 20% consumed during manufacturing.

3.1.2 Manufacturing Process – Comparison Cases

The comparison cases were developed using secondary data from two peer-reviewed published LCAs. (Rossi, Favi, Germani, & Omicioli, 2021) provided the BOM for a reach-in refrigerator with traditional refrigerant (1,1,1,2-Tetrafluoroethane/R134a) and a reach-in refrigerator with natural refrigerant (CO_2/R744) The paper also provided the lifetime of the equipment (10 years). JBE scaled the equipment from the BOM using the ratio of the capacity of the Rossi paper's fridge (3m^3) to the capacity of the equivalent reach-in for this study (0.65m^3). It was assumed that the BOM for the traditional refrigerant fridge and natural refrigerant fridge would be the same for the traditional refrigerant freezer and the natural refrigerant freezer respectively.

Table 7 provides detail on all materials in the BOM for the comparison reach-ins, which have been scaled from the actual BOM quantities provided in the Rossi paper, using the ratio of the Rossi size (3m^3 to the size of Phononic's totes (0.65m^3), giving a scale value of 4.65. Therefore, all items in the BOM were divided by this value.

The 0.65m^3 volume capacity for the reach-ins was provided by Phononic using a specification from Hussmann (Hussmann, 2022). This reach-in was considered to be representative of Phononic's competitor products. The peer-reviewed published LCA (Rossi, Favi, Germani, & Omicioli, 2021) was used however to model the reach-ins, as it contained more complete data. The used LCA does, however, have a capacity of almost 5-times that of the actual competitors. It may be the case that scaling of materials does not occur linearly in reality, although it has been modelled in this way. The modeling of the comparison cases is likely to represent an underestimate of the actual materials required for the comparison cases, and thus a conservative impact on the comparison cases results compared to Phononic's results.

Electricity grids used to model the manufacture of the reach-ins was assumed by JBE as the location of manufacture was unknown but considered to be wide ranging. Therefore, in order to be representative of the areas of manufacture, a global dataset was used for the electricity (Table 25). As the manufacturing stage for the reach-ins is a small contributor to overall footprint, this is a reasonable assumption.

There is no waste data included in the bill of materials for the comparison cases as this data was not supplied in the referenced literature. This is a conservative assumption as it would increase raw material impacts and add waste processing impacts to the comparison case product systems if manufacturing scrap and other wastes were considered.

Table 7: Comparison reach-ins BOM, scaled from actual size

Material	Units	Traditional Fridge/Freezer	Natural Fridge/Freezer	Inbound Transportation Distance [km]
Inputs				
Compressor	MT	1.84E-02	2.91E-03	500 truck
Oil charge	MT	4.91E-04	1.10E-04	500 truck
Crankcase heater	MT	3.01E-05	0.00E+00	500 truck
Vibration dampers	MT	1.70E-04	0.00E+00	500 truck
Muffler	MT	2.71E-04	0.00E+00	500 truck
Condenser	MT	2.44E-03	0.00E+00	500 truck
Motor fans	MT	2.58E-03	2.67E-03	500 truck
Liquid receiver	MT	9.79E-04	1.72E-03	500 truck
Drier filter	MT	1.87E-04	8.91E-05	500 truck
Liquid indicator	MT	4.30E-05	1.29E-05	500 truck

Material	Units	Traditional Fridge/Freezer	Natural Fridge/Freezer	Inbound Transportation Distance [km]
Electrical panel	MT	1.80E-03	1.42E-03	500 truck
Shut-off valves and solenoid/electronic valve	MT	3.44E-04	2.99E-04	500 truck
Pressure switches, pressure probe, and gomax	MT	6.89E-05	1.08E-04	500 truck
Anti-condensation	MT	2.80E-05	2.80E-05	500 truck
Structure	MT	2.74E-02	2.08E-02	500 truck
Acoustic insulation	MT	2.47E-03	1.08E-03	500 truck
Pipes	MT	2.24E-04	5.10E-04	500 truck
Hardware, collars, and fittings	MT	1.83E-04	3.29E-04	500 truck
Inverter	MT	0.00E+00	8.61E-04	500 truck
Gas Cooler	MT	0.00E+00	4.51E-03	500 truck
Plate Heat Exchanger	MT	0.00E+00	8.13E-04	500 truck
Nitrogen	MT	8.07E-06	8.07E-06	500 truck
Supplied oil	MT	2.45E-04	6.13E-05	500 truck
R134a system charge	MT	4.62E-03	0.00E+00	500 truck
R744 system charge	MT	0.00E+00	3.58E-03	500 truck
Cable	MT	1.08E-04	5.38E-04	500 truck
Alloy for Brazing	MT	8.61E-06	5.38E-05	500 truck
Outputs				
Fridge/Freezer [1 item]	MT	6.31E-02	4.25E-02	N/A

(Lewandowska, Kurczewski, Joachimiak-Lechman, & Zablocki, 2021) provided the manufacturing requirements to build the traditional refrigerant and the natural refrigerant fridges. It was assumed that the manufacturing requirements for the traditional refrigerant fridge and the natural refrigerant fridge were the same as the traditional refrigerant freezer and the natural refrigerant freezer respectively. JBE scaled the manufacturing requirements to the size of the comparison reach-in capacity. Table 8 provides detail on the manufacturing requirements for the comparison case reach-ins.

Table 8: Comparison reach-ins manufacturing requirements

Material	Units	Traditional Fridge/Freezer	Natural Fridge/Freezer	Inbound Transportation Distance [km]
Inputs				
Compressed Air	m3	2.06E+01	1.39E+01	N/A
Metal Working	kg	2.97E-08	2.00E-08	N/A
Metal Working Energy	kg	2.97E-08	2.00E-08	N/A
Electricity	kWh	1.18E+01	7.98E+00	N/A
Natural Gas	MJ	1.14E+01	7.67E+00	N/A
Steam	kg	8.40E+00	5.67E+00	N/A
Difluoroethane	kg	2.58E-02	1.74E-02	N/A
Outputs				
Fridge/Freezer	Item	1	1	N/A
Wastewater	m3	5.94E-02	4.01E-02	N/A

3.1.3 Reference Flows

To generate equivalent comparison cases for an equivalent functional unit for all products, JBE calculated the number of Phononic totes and comparison reach-ins required to satisfy the functional unit. The scaling is done based on the equipment lifetime and the number of equipment pieces required to satisfy the functional unit.
Table 9 provides detail on the scaling for the Phononic and comparison cases.

Table 9: Equipment required to satisfy the functional unit

Product	Reach-in Equivalent [ea]	Equipment Lifetime [years]	Equipment/Year [ea]
Phononic fridge tote	4	5	0.8
Phononic freezer tote	4	5	0.8
Traditional refrigerant fridge reach-in	1	10	0.1
Traditional refrigerant freezer reach-in	1	10	0.1
Natural refrigerant fridge reach-in	1	10	0.1
Natural refrigerant freezer reach-in	1	10	0.1

Reach-in equivalence was provided by Phononic and is understood to be determined based on grocery packing capacity and efficiency of the tote and typical reach-ins. This is based on the number of totes needed versus reach-ins to fulfill the same number of orders. Typical use of a reach-in does not entail filling 100% of the interior volume with groceries, but rather organizing groceries inside in such a way that makes the product accessible to the user. When comparing the use of Phononic's totes to reach-ins, it should be noted that a whole unit must be used, regardless of its filled proportion. Therefore, the number of reach-ins must be sized for peak capacity demands, and they must remain powered 24/7 regardless of the amount of groceries they contain. Thus, a reach-in will be fully powered whether it is filled to capacity, holding a small order, or empty. In contrast, while a grocer may size the number of Phononic totes used for peak capacity demands, the totes do not need to be powered on when they are not in use or being pre-cooled for use.
Equipment/Year denotes number of pieces of equipment needed to satisfy the functional unit. For example, 4 Phononic totes are required to meet the functional size equivalent of a reach-in. This represents a full capacity comparison, which is conservative as fewer totes would be required to operate if a reach-in were operated at less than full capacity, which is likely the typical case. The tote lifetime is 5 years, therefore the number of totes required per year is *4 totes / 5 years = 0.8 totes*.

3.1.4 Use Phase

The Phononic totes and comparison reach-ins are powered by electricity to provide cooling to grocery products. The comparison reach-ins are assumed to be plugged in and powered on 24 hours per day, based on typical supermarket operating procedures and the required cool-down time when a refrigerator or freezer is turned on. The Phononic totes are able to provide on-demand cooling and are designed to be switched on/off as needed to satisfy curbside order demand. The typical average hours of operation for the Phononic totes is 12 hours or less per day. Therefore, Phononic's fridge and freezer totes typically sit unplugged and empty for 12 hours per day.

The use phase energy requirements of Phononic's fridge and freezer totes, as well as the four comparison cases, was provided by Phononic via results of a customized energy model based on actual operations at a pilot customer's store. It should be noted that the comparison data is based on performance specs, while the Phononic energy use is based on actual field usage. Thus, it inherently includes inefficiencies from opening and closing during operation, as well as energy losses realized through, for example, incomplete door shutting, whereas the comparison case does not. It is anticipated that in the field, the comparison case data would have a decreased energy efficiency compared to the specification data used in this analysis.

The traditional fridge and freezer reach-ins require R134a and the natural fridge and freezer reach-ins require R744 for operation. The use phase refrigerant charge for the four comparison cases was provided by (Rossi, Favi, Germani, & Omicioli, 2021). The refrigerant charge was used to calculate the refrigerant leakage, using a 15% leakage rate annually as reported by the US Environmental Protection Agency (US EPA, 2014). Table 10 provides detail on the use phase requirements for Phononic's totes and the comparison reach-ins.

Table 10: Phononic totes and comparison reach-ins use phase requirements

Product	Energy Use [kWh/year]	Refrigerant Charge/Unit [g]	Refrigerant Leak Rate, Annual [%]	Refrigerant Leakage [g/year]
Phononic fridge tote	4.82E+02	N/A	N/A	N/A
Phononic freezer tote	3.15E+03	N/A	N/A	N/A
Traditional refrigerant fridge	1.04E+03	4.62E+03	15%	6.90E+01
Traditional refrigerant freezer	3.32E+03	4.62E+03	15%	6.90E+01
Natural refrigerant fridge	1.04E+03	3.58E+03	15%	5.40E+01
Natural refrigerant freezer	3.32E+03	3.58E+03	15%	5.40E+01

3.1.5 End-of-Life

At EoL it is assumed that all of the products are disassembled and disposed of in various waste streams depending on material type. A simplified EoL model was developed given the relatively small contribution of EoL to the cradle-to-grave life cycle of each of the products under study (more detail on contributors to results can be found in Section 4).

For both Phononic's totes and the comparison reach-ins, it is assumed that all metal is recovered and sent to recycling. All other solid waste is sent to landfill. Nitrogen contained in the reach-ins is emitted to the air.

It was assumed that the R134a for the traditional refrigerant fridge and freezer is recovered, with a 30% loss during recovery as an emission to the air (US EPA, 2014). It is assumed that the CO_2 for the natural refrigerant fridge and freezer is not recovered, and is fully emitted to the air at EoL. It was assumed that all nitrogen (which is used a raw material in the bill of materials) supplied for the reach-ins as seen in Table 7 would be released to the air at EoL.

Table 11: Percentage of waste streams at EoL (as % of each waste stream in BOM)

Waste Stream	Phononic Fridge Tote	Phononic Freezer Tote	Traditional Refrigerant Fridge/Freezer	Natural Refrigerant Fridge/Freezer
Metal waste to recycling	100%	100%	100%	100%
General waste to landfill	100%	100%	100%	100%
Nitrogen emission to air	N/A	N/A	100%	100%
R134a emission to air	N/A	N/A	30%	N/A
R744 emission to air	N/A	N/A	N/A	100%

3.2 Background Data

Background data for modeling inventory and impact categories were sourced from ecoinvent version 3.9.1. No primary data for the four comparison cases were provided by Phononic, therefore JBE used literature sources to gain information on the materials and manufacturing for the cases. The ecoinvent database was then used to find applicable datasets to model the flows from the literature. All ecoinvent datasets are listed in Annex A: Background Data and literature sources are listed in the References section.

3.3 Data Quality

3.3.1 Requirements

The key requirement for data quality is that data be as accurate and representative as possible. Data quality evaluations are described in
Table 12 and are based on the ISO 14044:2006 standard. To fulfill these requirements and to ensure reliable results, primary data in combination with representative, secondary literature, and consistent background LCI information from ecoinvent (v3.9.1) were used.

Table 12: Data quality requirements and evaluation of data quality

Parameter	Evaluation of Data Quality for this Study
Time-related coverage	Manufacturing and supply chain data are representative of the prospective Gen 2 products, representing the 2022 calendar year for the Phononic cases. The use phase energy is representative of the Gen 1 product in 2023. Background data from ecoinvent v3.9.1 represents the year 2022 (per the ecoinvent version's release date). Therefore, temporal representativeness for the Phononic cases is considered to be high. Manufacturing and supply chain data for the comparison cases was obtained using peer-reviewed published LCAs from 2021. JBE determined the temporal representativeness to be high as it is assumed the technology has not changed in such a large way over the past three years that the data would be outdated.
Geographical coverage	Primary data was collected from Phononic for their thermoelectric cooling chips and totes manufactured in the U.S. and Thailand respectively. Datasets representative of the manufacturing plant's country are chosen where possible, and Rest of World (RoW) and Global (GLO) datasets are used if country-specific data were unavailable. Therefore, geographical representation for Phononic's products is considered to be high. U.S-specific datasets are used for the comparison case, supplemented by RoW and GLO datasets when country-specific was unavailable. Geographical representativeness is considered to be high.
Technology coverage	For the Phononic cases, the materials data are representative of the Gen 2 products, which were not in production at the time of assessment. The tote manufacturing is based on historic actual data provided by the facility in Thailand for the 2022 calendar year. The energy model data is representative of the Gen 1 products in 2023. Therefore, the technology coverage is moderate as it combines two generations of technology. The materials and manufacturing data for the comparison cases is representative of the fridge technologies studied in the referenced literature. JBE assumed the materials and manufacturing are the same for the traditional refrigerant fridge and traditional refrigerant freezer, as well as for the natural refrigerant fridge and the natural refrigerant freezer. The energy model provided by Phononic is used to model differences in energy and refrigerant requirements, therefore coverage is considered to be moderate.
Precision	Primary data for Phononic's materials, manufacturing, and use phase energy requirements were provided by Phononic. Where specific data points were unavailable, such as those for EoL, reasonable assumptions are developed.
Completeness	All relevant process steps within the study boundary are considered and included in this study for both Phononic's products and the comparison case products. Where specific data points were unavailable, representative estimates are used.
Representativeness	Data is considered to be representative of the defined time-related, geographical, and technological scope.
Consistency	The study methodology is applied to all components of this analysis. Additionally, to ensure consistency, only primary and secondary data of the same level of detail and granularity are used.

Parameter	Evaluation of Data Quality for this Study
Reproducibility	The study results are reproducible through provision of this report, along with supplemental documentation that was developed throughout this assessment.
Sources of the data	Data was derived from credible sources and databases, with reference to the primary or secondary nature of the data.
Uncertainty of the information	Uncertainty was not quantitatively assessed in this study. However, all areas of uncertainty have been addressed using conservative data and assumptions with actual data likely leading to a more favorable result for Phononic's products versus the competing product systems. Some level of uncertainty exists in the data, particularly in the use phase energy use data for the Phononic cases, as they are based on the Gen 1 product range. The manufacturing data was based on the facility share of Phononic's products in the 2022 calendar year, which was not a timeframe in which Gen 2 was or will be manufactured. Additionally, there is some level of uncertainty in the use phase information as Phononic's products are new and so the way they are used by customers may be different to the 12 hour per day use as modelled. The energy consumption was based on an energy model using the Gen 1 prototype, therefore some uncertainty exists. Additionally, a sensitivity scenario was undertaken which assessed the impact of changing the number of hours per day Phononic's totes were turned on, and gave break-even points compared to the comparison cases. The 5 year lifetime of Phononic's totes was provided by Phononic as a conservative estimate. Therefore although the lifetime may have some level of uncertainty, a longer actual lifetime would result in a more favorable result for Phononic's cases. The best available use phase data was used for the model. Additionally, a sensitivity scenario was undertaken which assessed the impact of changing the number of years Phononic's totes had in their lifetime, and gave break-even points compared to the comparison cases. There is uncertainty related to the competitor data, as this was scaled from the literature. The scaling assumes that masses of materials scale linearly, which may not be the case in reality. It was deemed a conservative approach to assume linear scaling, which would result in a more beneficial result for Phononic's case, if more material was required than modelled for the competitor cases. There is uncertainty in the BWC result from the chip manufacturing stage of Phononic's fridge and freezer totes, generated by an error in the chosen dataset. This error has been recognized by ecoinvent in v3.9, and amended in v3.10. In reality, the BWC footprint of the chip manufacturing stage would not be negative, however is not assumed to be significantly impactful on overall results, therefore some uncertainty remains about this result.

3.3.2 Gaps, Assumptions, and Limitations

This section identifies data gaps, assumptions, and limitations; discusses how they are anticipated to affect results; and notes whether the approach is justified or if additional analysis is necessary.

Table 13: Data gaps, assumptions, and limitations

Description	Potential Implication
Use of assumptions for refrigerant leakage at use phase	A 15% annual leakage rate of refrigerants for the comparison cases is assumed, based on EPA data (US EPA, 2014). This is a conservative estimate and has a potentially significant effect on the GWP results, but a minimal effect on other impact categories.
Use of literature for the comparison case gate-to-gate manufacturing	A peer-reviewed published LCA of traditional and natural refrigerant fridges is used for the cradle to gate part of the cradle to grave model for the comparison cases (Rossi, Favi, Germani, & Omicioli, 2021). The paper provides a BOM for a traditional refrigerant fridge and a natural refrigerant fridge, including type of refrigerant and refrigerant charge. JBE scaled the equipment to the size of the expected comparison reach-in capacity. The traditional refrigerant is R134a (1,1,1,2-Tetrafluoroethane). The

Description	Potential Implication
	natural refrigerant is R744 (Carbon dioxide). The fridge BOM is used as a proxy for the freezer BOM. This assumption has a potentially moderate effect. A peer-reviewed published LCA of a domestic refrigerator is used for the comparison case's manufacturing. (Lewandowska, Kurczewski, Joachimiak-Lechman, & Zablocki, 2021). The paper provides manufacturing requirements, which JBE scaled to the size of the comparison reach-in capacity. The fridge manufacturing requirements are used as a proxy for the freezer manufacturing requirements. This assumption has a potentially moderate effect. The combination of two sources for the comparison cases and a lack of primary data for the comparison case has a potentially moderate effect.
Use of assumptions for EoL pathways	It is assumed that for all Phononic and comparison cases that during EoL metals are recycled, and all other materials are landfilled (excluding refrigerants). The EoL pathways are assumed and may be different in reality. There is a potentially minimal effect to the results because end-of-life is not a significant contributor to results. 30% of the traditional refrigerant (R134a) is assumed to be leaked to the air at EoL, to be conservative. It is assumed that 100% of the natural refrigerant (CO_2) is emitted to the air at EoL. This is a conservative estimate and may have a potentially moderate effect on GWP results.
Use of assumptions for manufacturing impacts	It is assumed that the manufacturing impact to make one fridge tote and one freezer tote is the same. The impact of manufacturing the chips may not be the same, however the impact of manufacturing is not a high contributor to overall footprint, therefore there is a potentially minimal effect.
Use of assumptions for emissions	It is assumed that zero emissions from the insulation blowing agent occur. The mass of blowing agent is low therefore there is a potentially minimal effect.
Use of assumptions for wastewater	It is assumed that all municipal water input for chip manufacturing is sent as wastewater to POTW at the end of manufacturing. There is no wastewater recovery, however the impact of manufacturing is not a high contributor to overall footprint, therefore there is a potentially minimal effect.
Use of assumptions for transport	It is assumed that at EoL waste was transported 50km by truck for disposal or recycling. It is assumed that all traditional refrigerant and natural refrigerant materials are transported to their manufacturing facility a distance of 500km by truck. The impact of manufacturing is not a high contributor to overall footprint, therefore there is a potentially minimal effect.

4 LCIA Results

The life cycle impact assessment (LCIA) phase connects the life cycle inventory results and potential environmental impacts. This section presents the environmental impact results for this study and accompanying discussion to interpret the results. All results are presented per 1 year of product use, equivalent to a typical reach-in. The typical reach in volume is 0.65m^3.

The LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

4.1 Overall Results

Cradle-to-grave results for Phononic's fridge and freezer totes, the traditional refrigerant fridge and freezer, and the natural refrigerant fridge and freezer are presented in Table 14 and Table 15.

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Table 14: Cradle to grave results for Phononic's and the comparison case fridges, per 1 year of product use

Case	GWP [kg CO_2e]	EP [kg N-eq]	AP [kg SO_2-eq]	BWC [m^3]	PED [MJ]
Phononic fridge tote: Total	3.23E+02	1.75E+00	1.66E+00	7.40E+00	4.27E+03
Chip Materials	4.99E+00	1.48E-01	3.02E-01	3.18E-01	5.73E+01
Chip Manufacturing	1.49E+00	7.01E-03	4.01E-03	-1.21E+00[2]	2.03E+01
Tote Materials	7.71E+01	4.80E-01	7.72E-01	1.23E+00	1.02E+03
Tote Manufacturing	1.13E+01	5.15E-02	3.54E-02	4.12E+00	1.52E+02
Use Phase	2.28E+02	1.07E+00	5.42E-01	1.85E+00	3.02E+03
End of Life	2.97E-01	1.27E-03	1.54E-03	3.94E-03	3.97E+00
Traditional refrigerant fridge: Total	8.46E+02	2.73E+00	1.49E+00	5.07E+00	6.90E+03
Materials	3.14E+01	4.14E-01	3.01E-01	9.57E-01	3.18E+02
Manufacture	1.97E+00	8.40E-03	1.08E-02	7.53E-02	2.31E+01
Use Phase	6.01E+02	2.31E+00	1.18E+00	4.04E+00	6.55E+03
End of Life	2.11E+02	8.82E-04	1.59E-03	3.75E-03	2.65E+00
Natural refrigerant fridge: Total	5.11E+02	2.43E+00	1.34E+00	4.20E+00	6.75E+03
Materials	1.60E+01	1.18E-01	1.61E-01	2.01E-01	1.85E+02
Manufacture	1.33E+00	5.67E-03	7.29E-03	0.00E+00	1.56E+01
Use Phase	4.94E+02	2.31E+00	1.17E+00	4.00E+00	6.55E+03
End of Life	5.01E-01	6.50E-04	1.10E-03	0.00E+00	1.85E+00

[2] Phononic's fridge and freezer totes' chip manufacturing stage results in a negative value in the BWC impact category. It is recognized by JBE that this is an inherent flaw in the ecoinvent v3.9 dataset, and is explained more in depth in section 4.2.

Table 15: Cradle to grave results for Phononic's and the comparison case freezers, per 1 year of product use

Case	GWP [kg CO_2e]	EP [kg N-eq]	AP [kg SO_2-eq]	BWC [m^3]	PED [MJ]
Phononic freezer tote: Total	1.65E+03	9.10E+00	7.39E+00	2.02E+01	2.17E+04
Chip Materials	5.76E+01	1.55E+00	2.99E+00	3.44E+00	6.63E+02
Chip Manufacturing	8.91E+00	4.21E-02	2.41E-02	-7.27E-01	1.22E+02
Tote Materials	7.83E+01	4.82E-01	8.00E-01	1.23E+00	1.03E+03
Tote Manufacturing	1.13E+01	5.15E-02	3.54E-02	4.12E+00	1.52E+02
Use Phase	1.49E+03	6.97E+00	3.55E+00	1.21E+01	1.98E+04
End of Life	2.85E-01	1.27E-03	1.50E-03	3.96E-03	3.82E+00
Traditional refrigerant freezer: Total	1.92E+03	7.77E+00	4.05E+00	1.38E+01	2.12E+04
Materials	3.14E+01	4.14E-01	3.01E-01	9.57E-01	3.18E+02
Manufacture	1.97E+00	8.40E-03	1.08E-02	7.53E-02	2.31E+01
Use Phase	1.68E+03	7.35E+00	3.74E+00	1.28E+01	2.08E+04
End of Life	2.11E+02	8.82E-04	1.59E-03	3.75E-03	2.65E+00
Natural refrigerant freezer: Total	1.59E+03	7.47E+00	3.90E+00	1.33E+01	2.10E+04
Materials	1.60E+01	1.18E-01	1.61E-01	5.40E-01	1.85E+02
Manufacture	1.33E+00	5.67E-03	7.29E-03	5.09E-02	1.56E+01
Use Phase	1.57E+03	7.35E+00	3.73E+00	1.27E+01	2.08E+04
End of Life	5.01E-01	6.50E-04	1.10E-03	2.62E-03	1.85E+00

Figure 3 displays the results for Phononic's fridge tote, the traditional refrigerant fridge, and the natural refrigerant fridge. The comparison case results are presented as a percentage of the Phononic case.

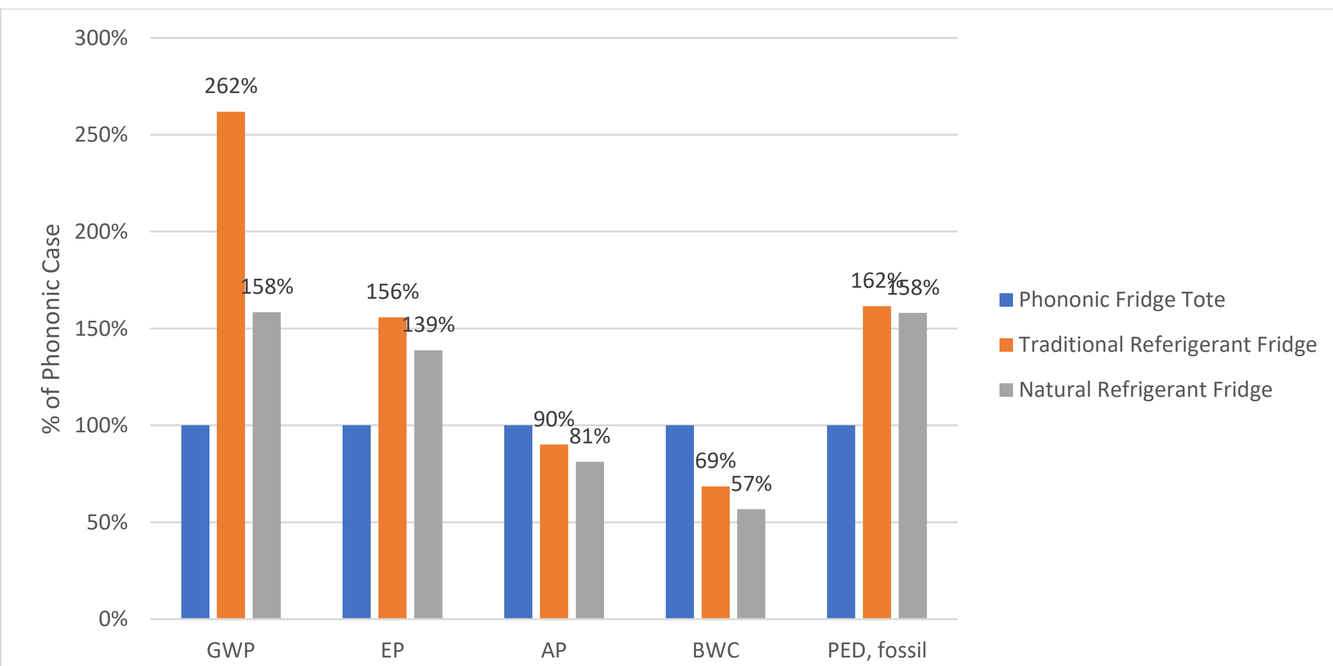

Figure 3: Results of Phononic's fridge tote, traditional refrigerant fridge, and natural refrigerant fridge

Figure 4 displays the results for Phononic's freezer tote, the traditional refrigerant freezer, and the natural refrigerant freezer. The comparison case results are calculated based on the Phononic case.

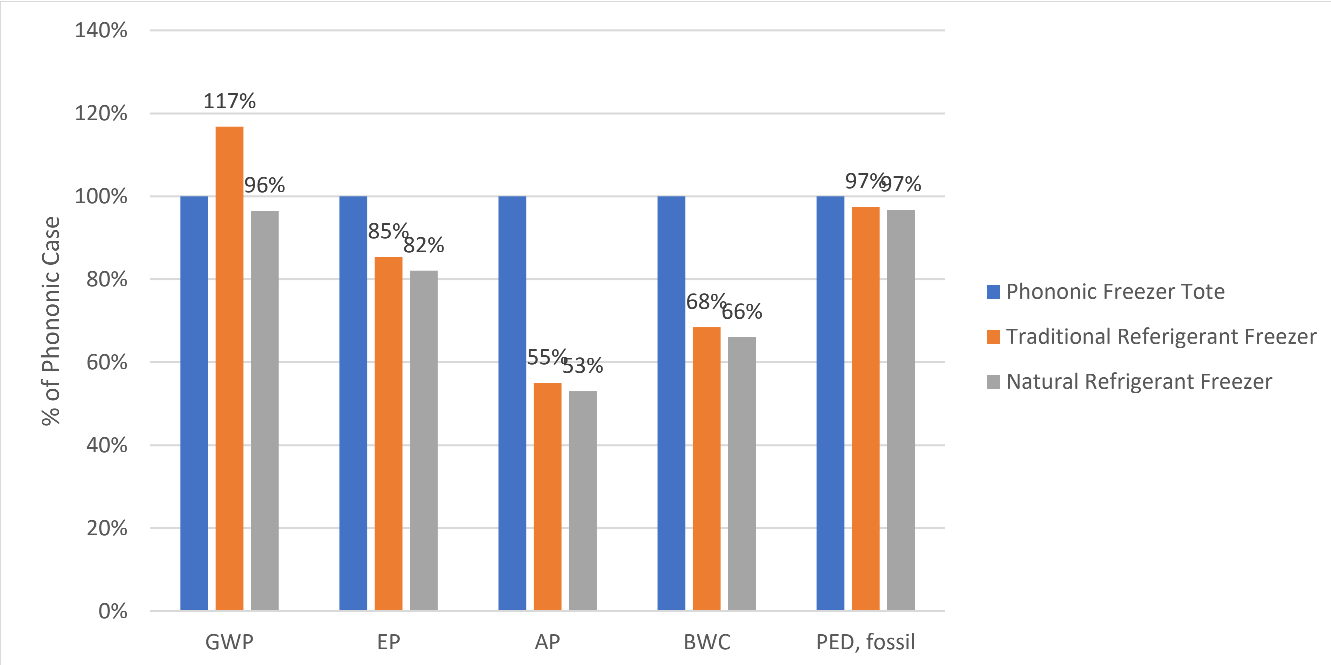

Figure 4: Results of Phononic's freezer tote, traditional refrigerant freezer, and natural refrigerant freezer

4.2 Detailed Results - Phononic

The following section provides details on the key contributors to impacts for GWP, EP, AP, BWC, and PED, fossil. Results for Phononic's totes are disaggregated into the following life cycle stages:

- Chip Materials: All materials in the BOM for chips. All inbound transport for the materials from their suppliers.
- Chip Manufacturing: Utilities, fuels, water, waste, emissions, and waste transport from the manufacturing of chips.
- Tote Materials: All materials in the BOM for totes. All inbound transport for the materials from their suppliers.
- Tote Manufacturing: Utilities, fuels, water, waste, emissions, and waste transport from the manufacturing of the totes.
- Use Phase: Energy use.
- End of Life: Various waste streams such as recycling and landfill, emissions, and waste transport to final destinations.

The intent is to provide additional insight into key drivers of the product environmental footprint.

Figure 5 provides disaggregated cradle to grave results for Phononic's fridge tote for each impact category. The key contributor to GWP and EP is the energy use during the use phase. The key contributors to AP are the copper and aluminum tote materials. The key contributor to BWC and PED, fossil is the electricity usage in the Thailand manufacturing facility. Figure 6 provides disaggregated cradle to grave results for Phononic's freezer tote for each impact category. The key contributor to all impact categories is the energy use during the use phase of the tote. A key contributor to AP is also the copper in the heat exchanger in the chip materials of the tote.

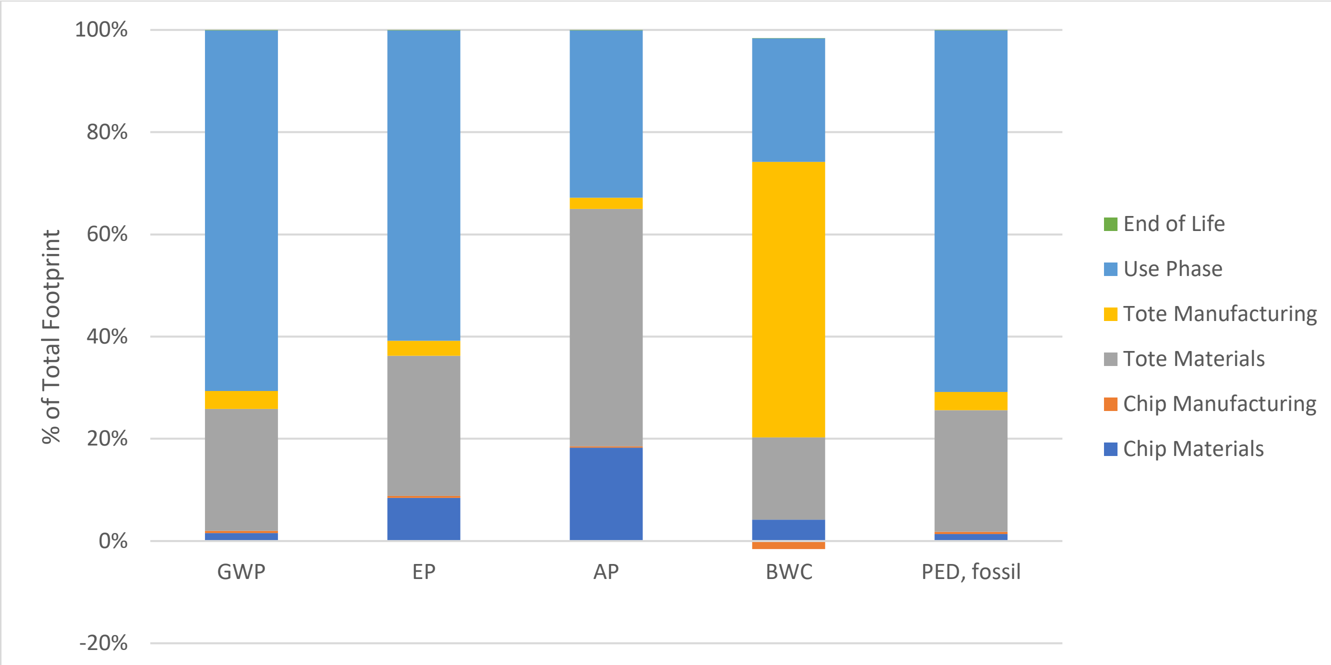

Figure 5: Phononic fridge tote, cradle to grave results by life cycle stage, stacked to 100%

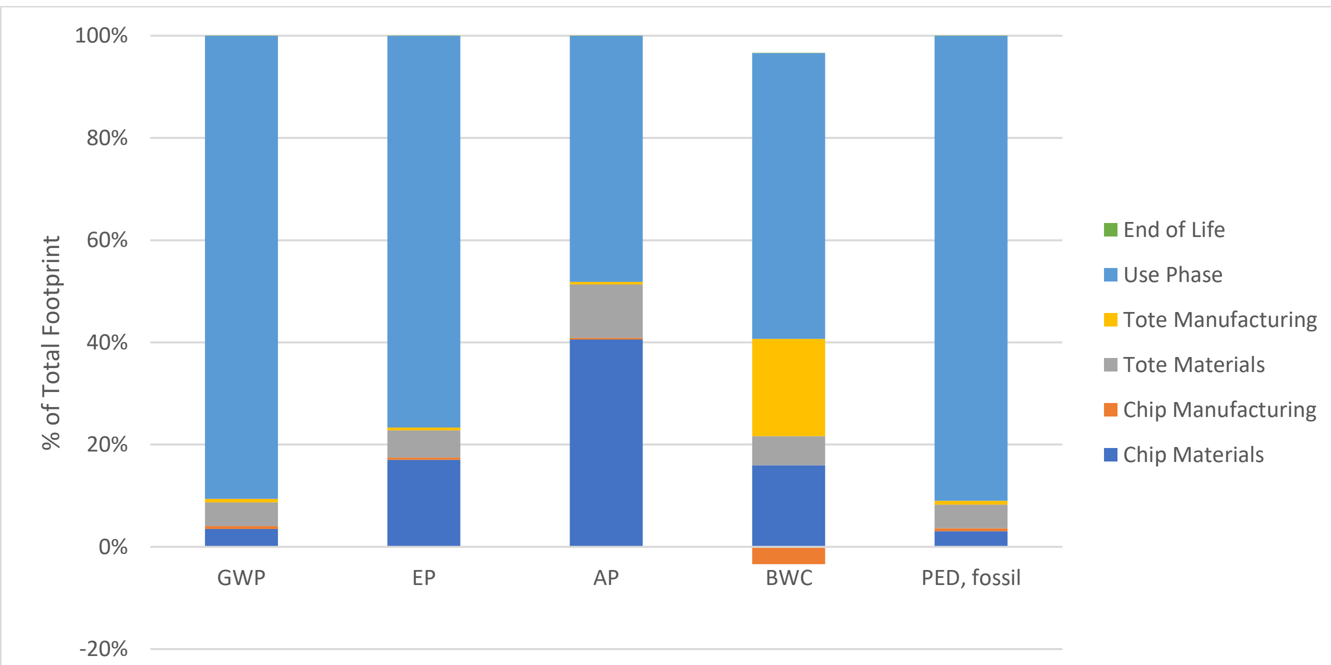

Figure 6: Phononic freezer tote, cradle to grave results by life cycle stage, stacked to 100%

As mentioned in the footnote of Table 14, the modelling of Phononic's fridge and freezer totes has provided negative (below zero) results for the BWC impact category. During chip manufacture, Phononic takes in municipal water and releases it to wastewater treatment. The dataset chosen for the wastewater treatment in ecoinvent v3.9 was *treatment of wastewater, average, wastewater treatment, RoW*. The resulting negative BWC result has been acknowledged by ecoinvent as an error in the water balance of wastewater treatment datasets. It has been resolved for v3.10, however as this assessment was conducted in v3.9, the error remains. As the chip manufacturing stage is such a small contributor to the overall cradle to grave footprint of Phononic's thermoelectric cooling totes, it was agreed upon by both JBE and the critical review panel to leave the BWC error in the assessment.

4.3 Detailed Results - Comparison Cases

The following section provides details on the key contributors to impacts for GWP, EP, AP, BWC, and PED, fossil. Results for the comparison case reach-ins are disaggregated into the following life cycle stages:

- Comparison Case Materials: All materials in the fridges/freezers from the BOM in the literature.
- Comparison Case Manufacturing: All materials and requirements from the manufacturing in the literature.
- Use Phase: Energy use, refrigerant leakage emissions, and refrigerant replenishment.
- End of Life: Various waste streams such as recycling and landfill, emissions, and waste transport to final destinations.

The intent is to provide additional insight into key drivers of the product environmental footprint.

Figure 7 and Figure 8 provide disaggregated cradle to grave results for the traditional refrigerant fridge and the natural refrigerant fridge comparison cases for each impact category.

For all four comparison cases, the key contributor to all categories is the energy use during the use phase. For the traditional refrigerant fridge and freezer cases, the emission of the R134a refrigerant at EoL is also a key contributor to GWP.

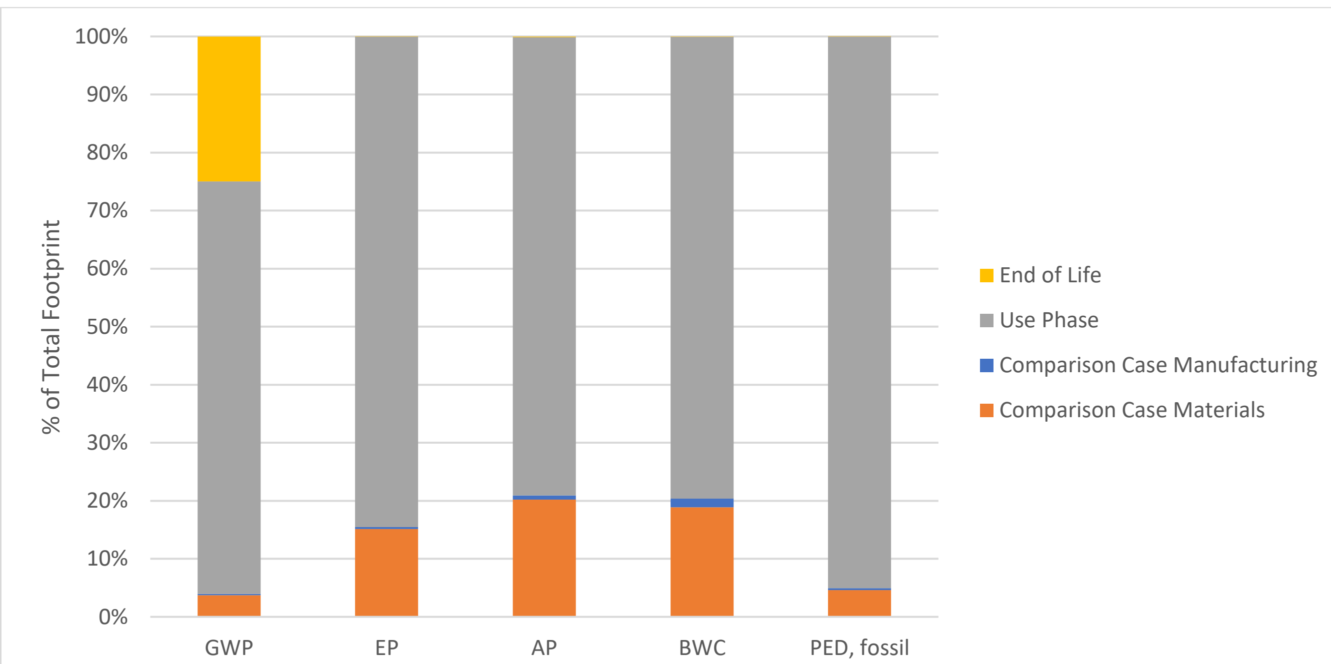

Figure 7: Traditional refrigerant fridge cradle to grave results by life cycle stage, stacked to 100%

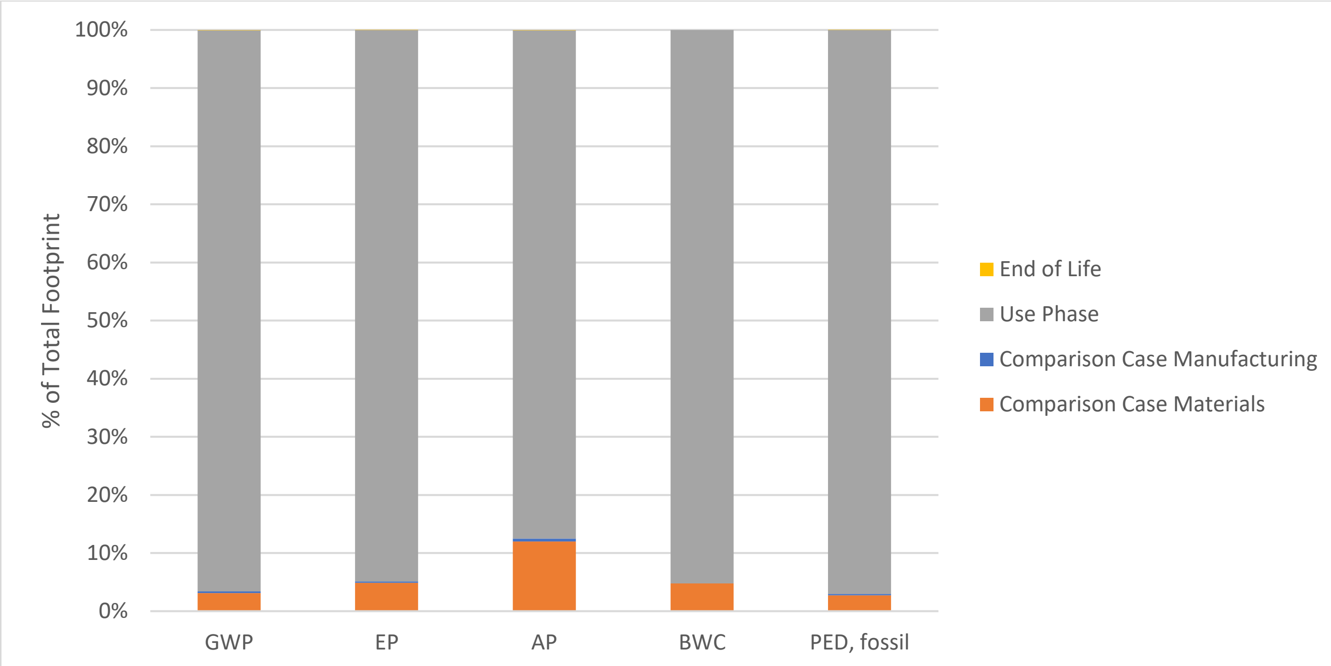

Figure 8: Natural refrigerant fridge cradle to grave results by life cycle stage, stacked to 100%

Figure 9 and Figure 10 provide disaggregated cradle to grave results for the traditional refrigerant freezer and the natural refrigerant freezer comparison cases for each impact category.

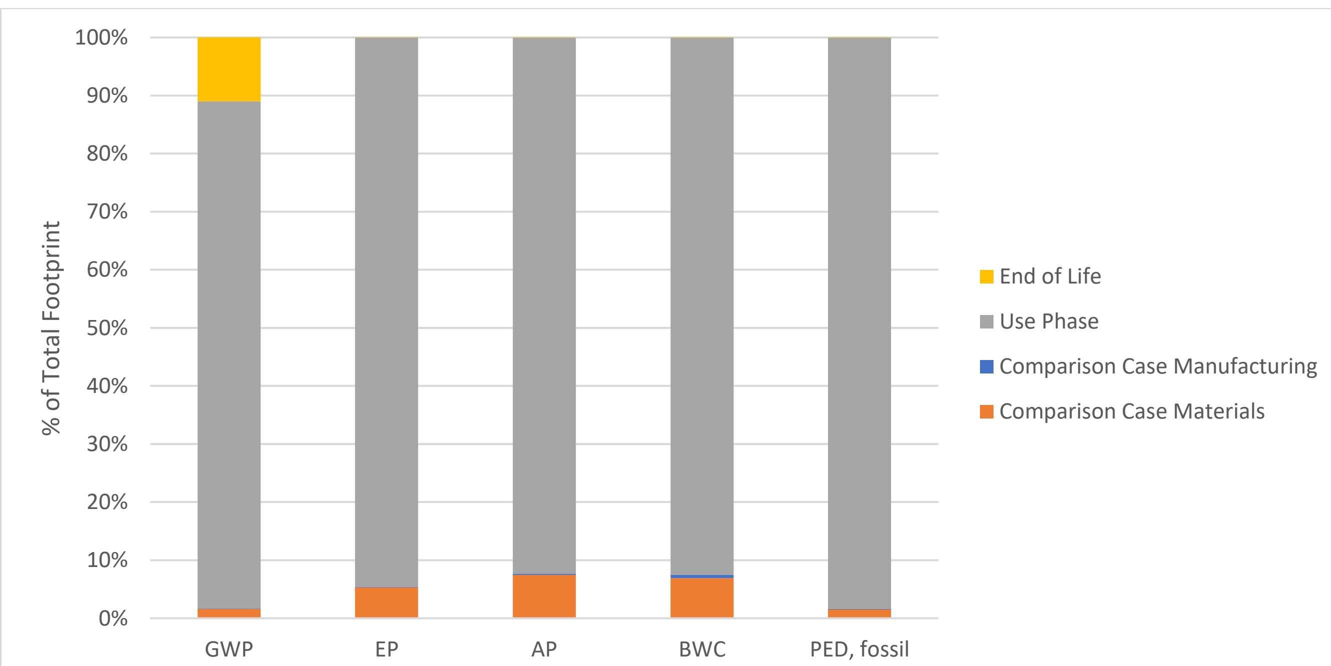

Figure 9: Traditional refrigerant freezer cradle to grave results by life cycle stage, stacked to 100%

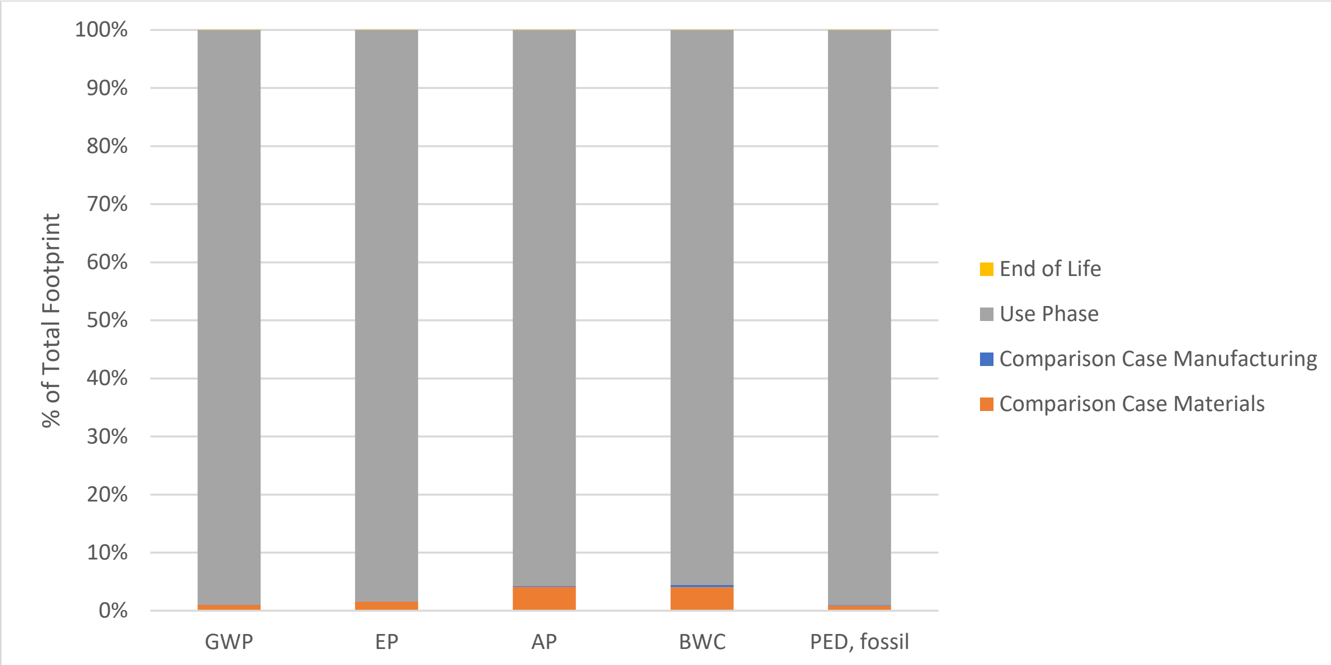

Figure 10: Natural refrigerant freezer cradle to grave results by life cycle stage, stacked to 100%

4.4 Additional Analyses

Additional scenario and sensitivity analyses are conducted during this assessment to further understand the potential benefit of raw material improvements on overall footprint, as well as to understand effect of product use characteristics on the footprint differences between Phononic's totes and the comparison case reach-ins over time:

1. An assessment of the potential impact of changing all aluminum and copper materials in the chip and tote from virgin to recycled sources is performed to understand the potential impact of the materials on the cradle-to-grave footprint of the totes.
2. An assessment of the potential impact of the lifetime of Phononic's totes, as well as a break-even point at which the fridge and the freezer tote had an equivalent impact with the comparison fridge and freezer reach-ins.
3. An assessment of the potential impact of the number of use hours per day for Phononic's totes, as well as a break-even point at which the fridge and the freezer tote had an equivalent impact with the comparison fridge and freezer reach-ins.

4.4.1 Scenario Analysis - Recycled Metals

The cradle-to-grave results of Phononic's fridge tote show that tote materials and manufacturing – particularly the materials made of metal and plastic – are high contributors to the overall footprint of the totes. Similarly, the cradle-to-grave results of Phononic's freezer tote show that chip materials are a significant contributor to overall results. This analysis changes all aluminum and copper inputs to the chips and totes from virgin to recycled metals. The impact of metal transformation (e.g. sheet rolling) is still included. The results of the recycled metals scenario are compared to the base Phononic results.

Figure 11 and Figure 12 show the difference in results from the base case to the recycled metals scenario for the fridge and freezer tote respectively. Results are presented as a percentage of the base case results.

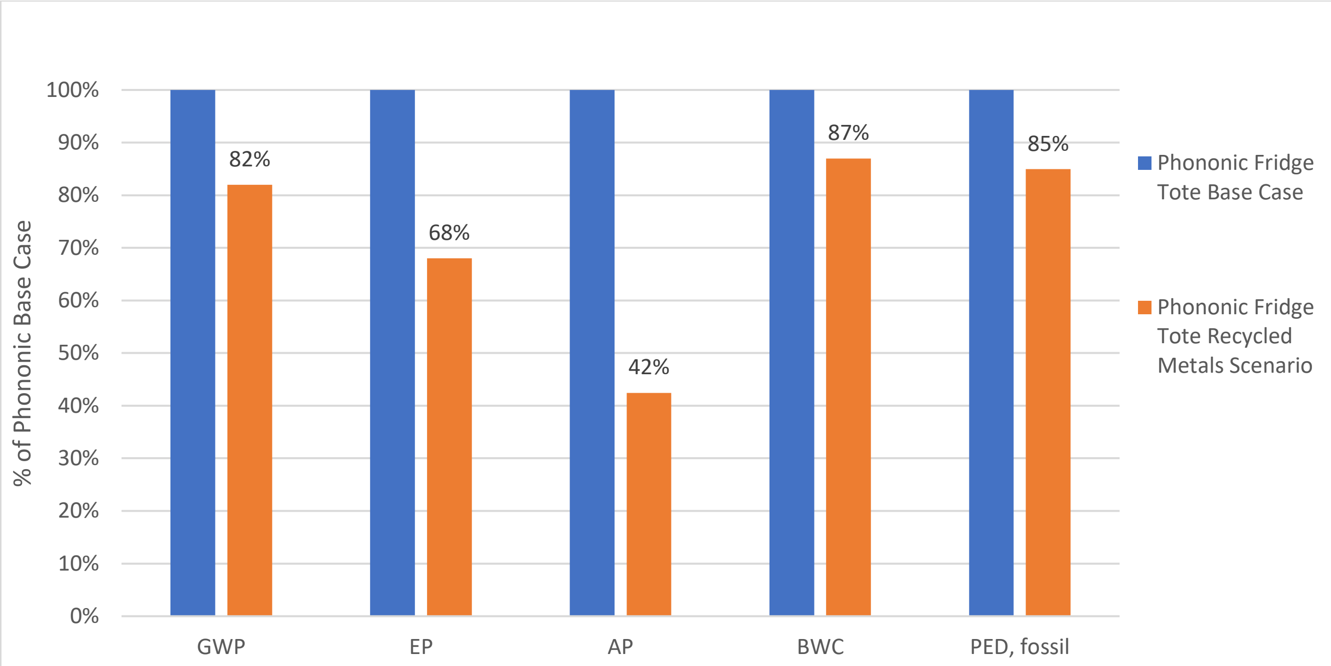

Figure 11: Cradle to grave results of the recycled metals analysis compared to the base Phononic results for the fridge tote

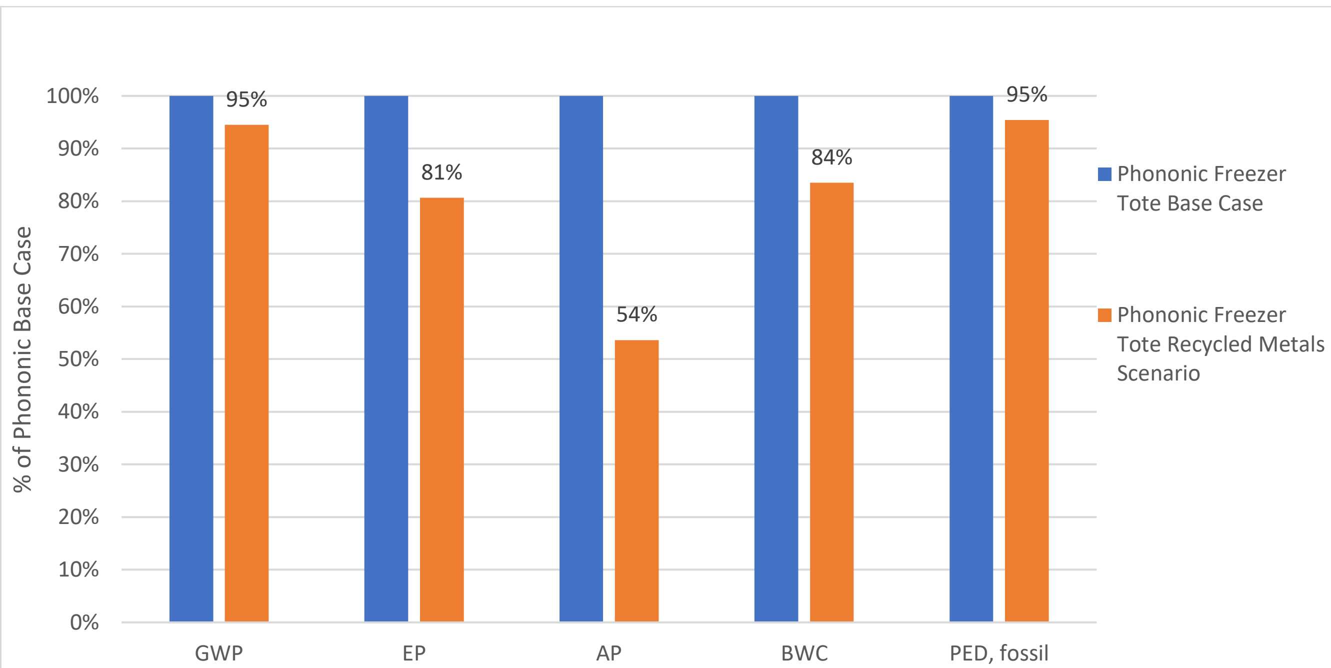

Figure 12: Cradle to grave results of the recycled metals analysis compared to the base Phononic results for the freezer tote

4.4.2 Sensitivity Analysis – Tote Lifetime

For the purpose of this analysis the estimated lifetime of the Phononic tote is assumed to be 5 years. As the totes have only recently been released into the market, the team decided on a conservative estimate. However, we expect the lifetime to exceed this and seek to understand the reduction in impact of the increased tote lifetime on GWP and other environmental metrics.

The results of the comparative assessment show a favorable result for Phononic's fridge tote compared to the comparison cases for most impact categories. However, Phononic's freezer tote does not have a lower footprint than the comparison cases in most impact categories, therefore no clear outperforming product could be seen. As such, Phononic wanted to understand if their products would have a clearer environmental benefit if the lifetime of the fridge and freezer totes were increased.

The lifetime of Phononic's fridge and freezer totes during the base assessment is 5 years. Comparatively, the traditional and natural refrigerant fridges and freezers have a lifetime of 10 years. This analysis varies the lifetime of Phononic's totes from 1-20 years.

Figure 13 and Figure 14 show the results of the tote lifetime sensitivity assessment and break-even analysis for the fridge tote compared to a traditional refrigerant fridge and a traditional refrigerant freezer reach-in respectively. The charts show the percentage difference in impact of the fridge and freezer tote compared to the traditional refrigerant fridge and freezer (y axis) if they are to last the number of years aligning with the x axis, starting with 1 year (far left of x axis) to 10 years (far right of x axis).

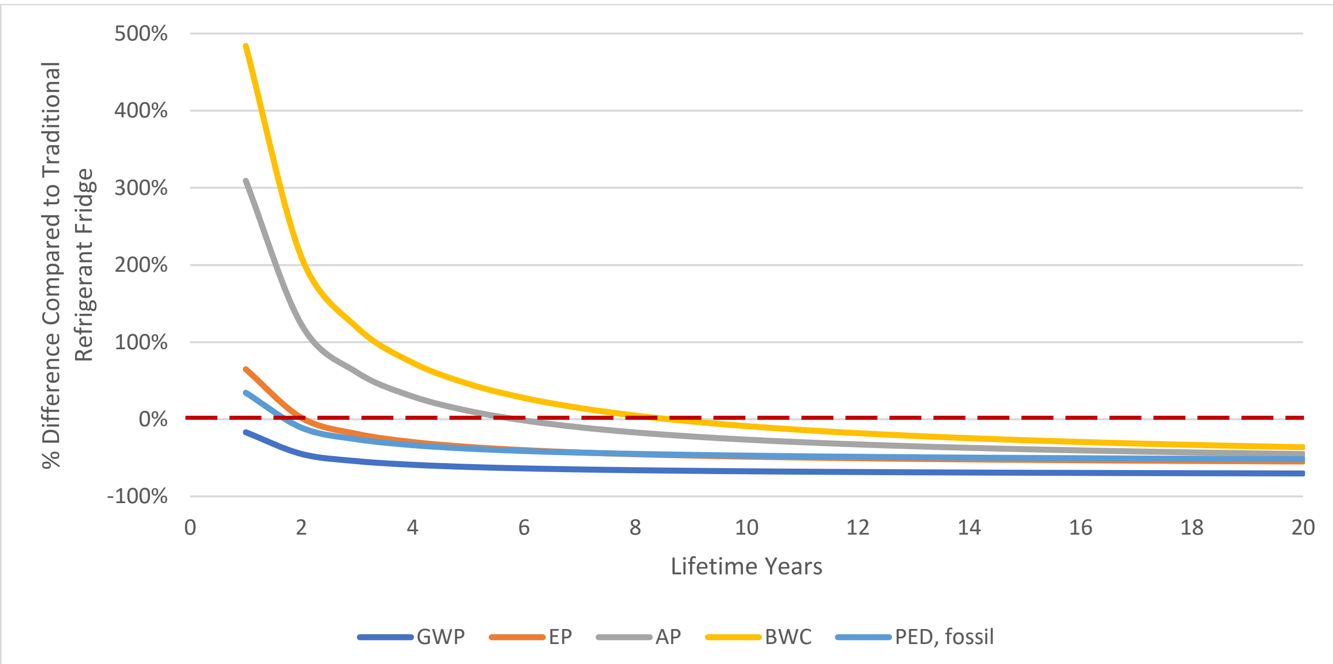

Figure 13: Results of the tote lifetime sensitivity analysis for the fridge tote, compared to a traditional refrigerant fridge (red dashed line)

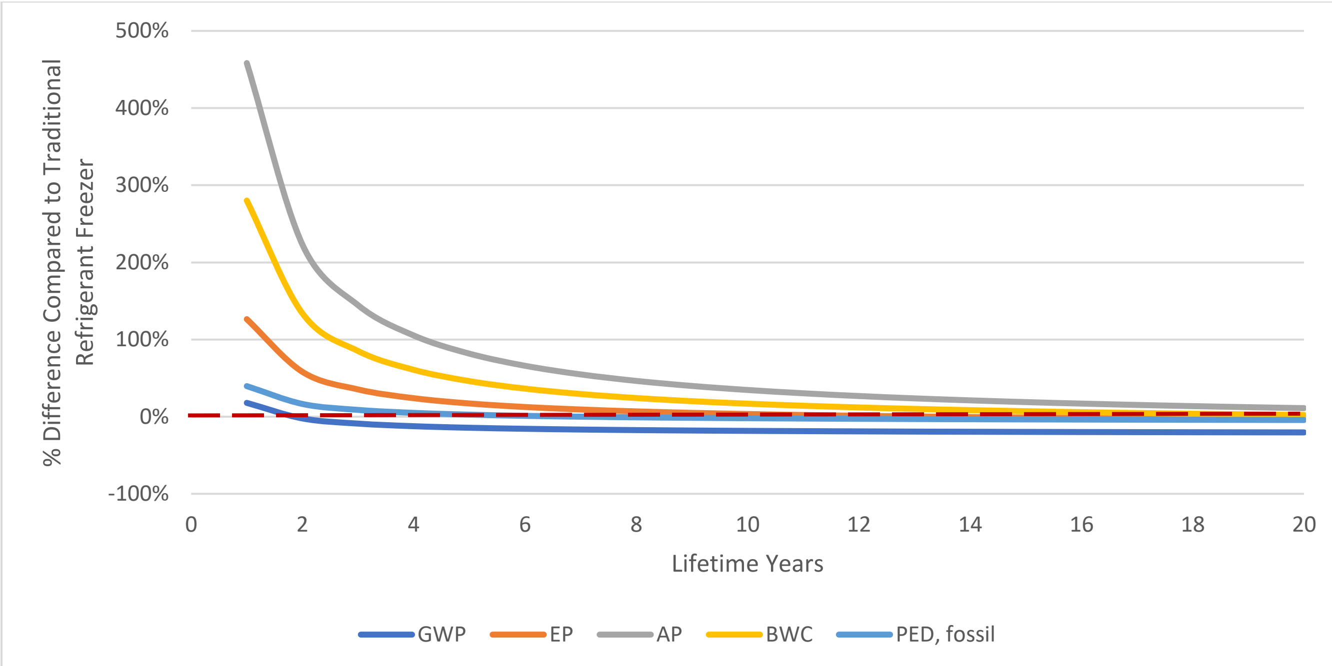

Figure 14: Results of the tote lifetime sensitivity analysis for the freezer tote, compared to a traditional refrigerant freezer (red dashed line)

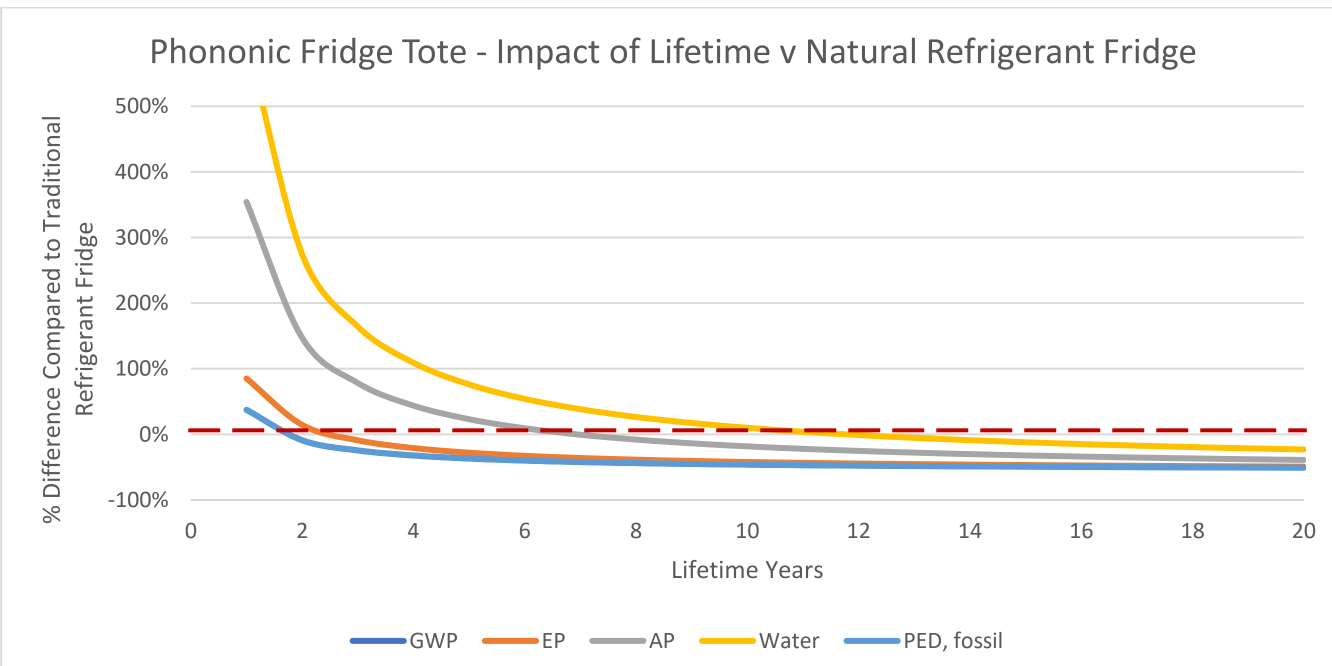

Figure 15: Results of the tote lifetime sensitivity analysis for the fridge tote, compared to a natural refrigerant fridge (red dashed line)

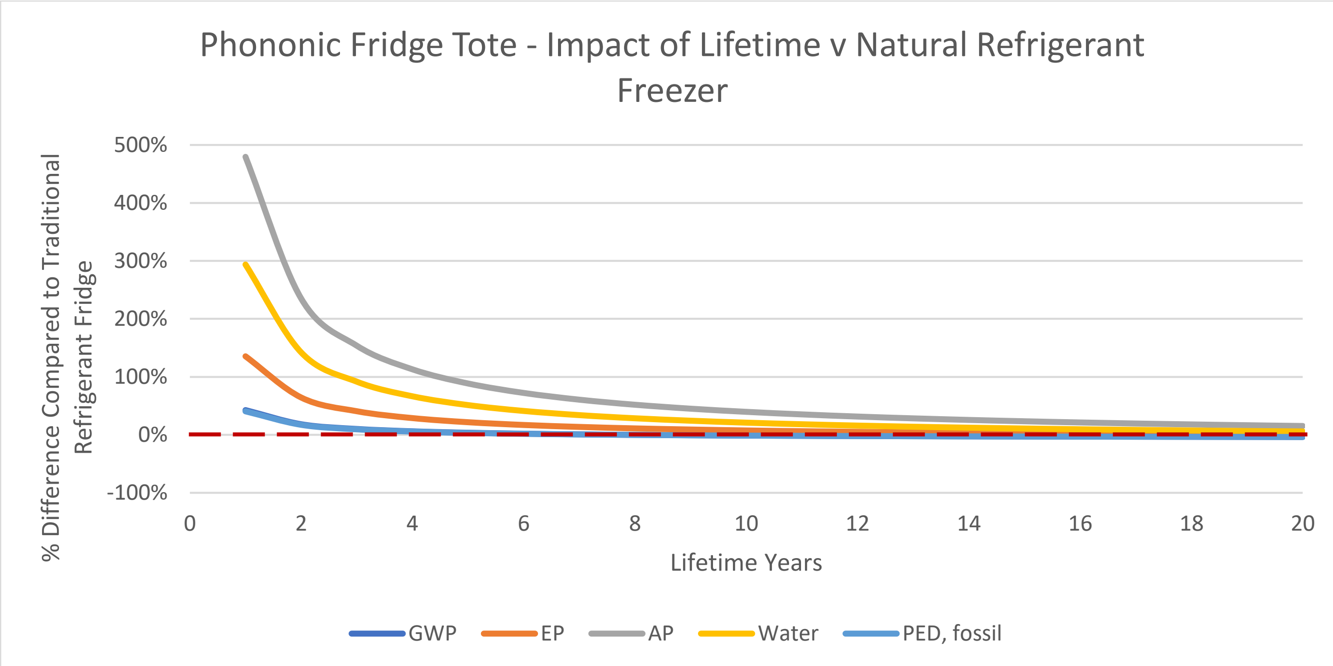

Figure 16: Results of the tote lifetime sensitivity analysis for the freezer tote, compared to a natural refrigerant freezer (red dashed line)

Table 16 and Table 17 show the break-even point (years in total lifetime) for the fridge and freezer tote respectively, when compared to a traditional refrigerant reach-in and a natural refrigerant reach-in.

Table 16: Break-even point (years in total lifetime) for the fridge tote compared to a traditional refrigerant and a natural refrigerant reach-in

	Traditional Refrigerant Reach-In	Natural Refrigerant Reach-In
GWP [kg CO_2-eq]	<1	2
EP [kg N-eq]	2	3
AP [kg SO_2-eq]	6	8
BWC [m^3]	9	13
PED, fossil [MJ]	2	2

Table 17: Break-even point (years in total lifetime) for the freezer tote compared to a traditional refrigerant and a natural refrigerant reach-in

	Traditional Refrigerant Reach-In	Natural Refrigerant Reach-In
GWP [kg CO_2-eq]	1	8
EP [kg N-eq]	15	20
AP [kg SO_2-eq]	>20	>20
BWC [m^3]	>20	>20
PED, fossil [MJ]	7	8

4.4.3 Sensitivity Analysis – Tote Hours of Operation

An advantage of Phononic totes is that, unlike reach-in units, they do not need to be powered on when not storing groceries. They are deployed flexibly to match hours of operation to online grocery demands, while the corresponding reach-ins must always be running. Phononic wanted to understand the use case limits for when parity with reach-ins occurs in terms of hours that the totes are plugged in and cooling.

Phononic's fridge and freezer totes are assumed to be turned on for 12 hours per day (see Section 3.1.4 for details). Comparatively, the traditional and natural refrigerant fridges and freezers are assumed to be turned on for 24 hours per day (i.e. they are not turned off). This is a potential benefit of Phononic's totes as they can be turned on and off depending on demand and use, and do not require electricity when they are not in use. Comparatively, the comparison case reach-ins must be turned on 24 hours per day to remain functional, and so require a constant electricity source. This analysis varies the number of use hours per day for Phononic's totes from 6-24 hours.

Figure 17 and Figure 18 show the sensitivity assessment and break-even analysis for the fridge and freezer totes compared to a traditional refrigerant fridge and a traditional refrigerant freezer respectively. Figure 19 and Figure 20 show the sensitivity assessment and break-even analysis for the fridge and freezer totes compared to a natural refrigerant fridge and natural refrigerant freezer respectively. The charts show the percentage difference in impact of the fridge and freezer tote compared to the traditional refrigerant fridge and freezer (y axis) if they were to be switched on for the number of hours aligning with the x axis, starting with 1 year (far left of x axis) to 10 years (far right of x axis).

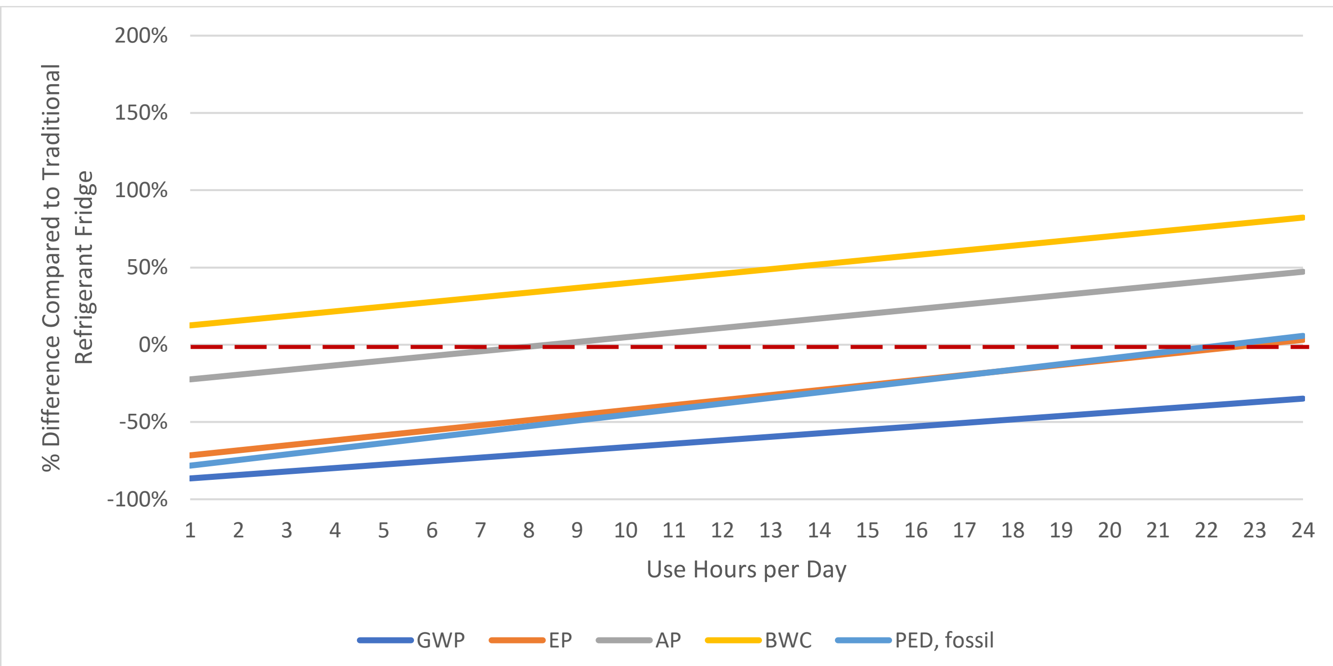

Figure 17: Results of the use hours per day sensitivity analysis for the fridge tote, compared to a traditional refrigerant fridge (red dashed line)

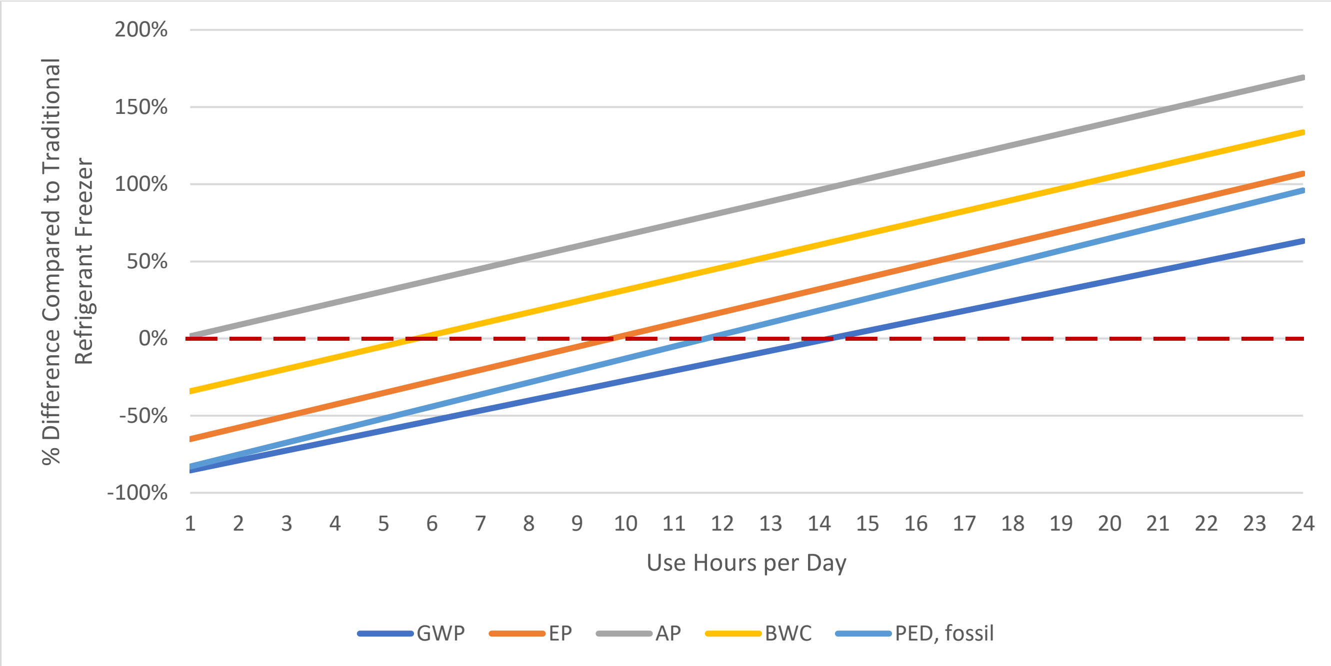

Figure 18: Results of the use hours per day sensitivity analysis for the freezer tote, compared to a traditional refrigerant freezer (red dashed line)

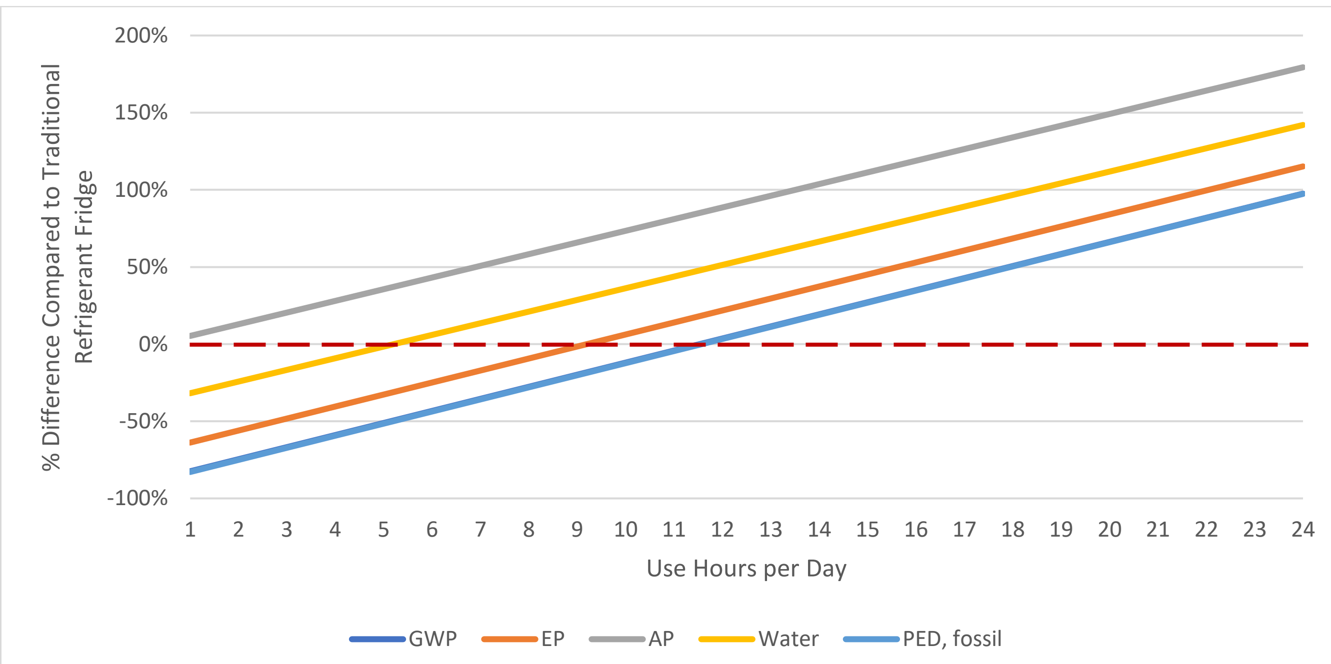

Figure 19: Results of the use hours per day sensitivity analysis for the freezer tote, compared to a natural refrigerant freezer (red dashed line)

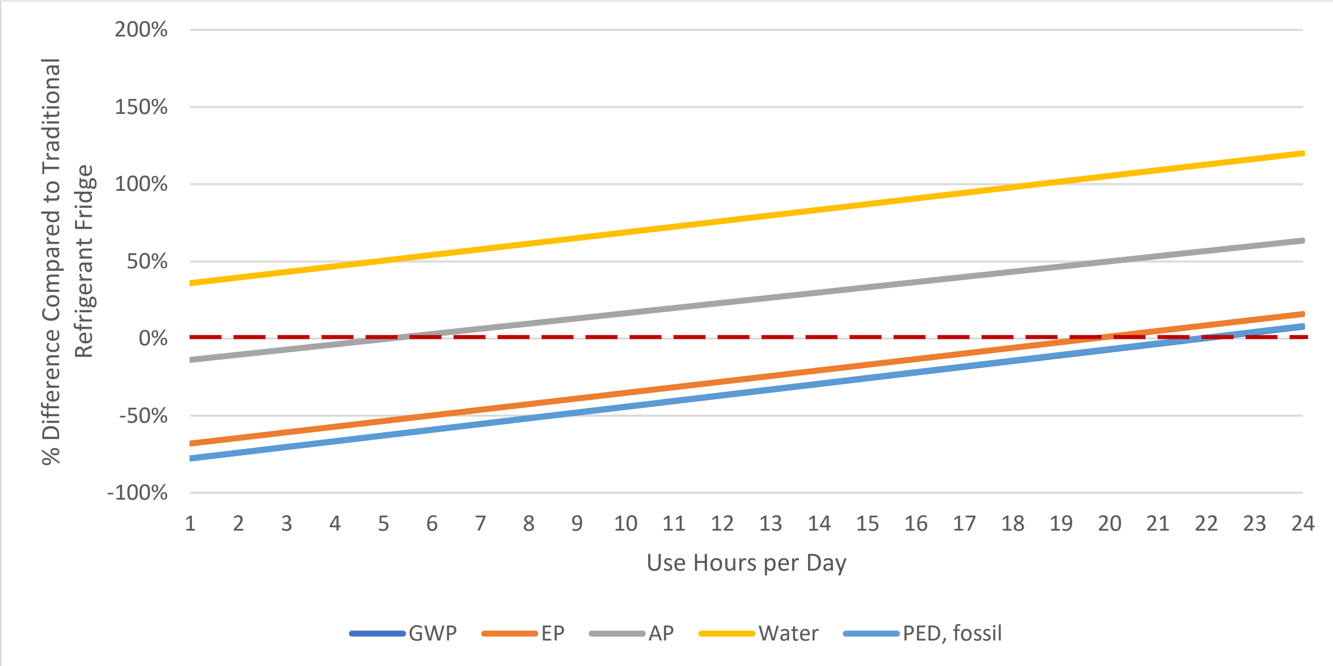

Figure 20: Results of the use hours per day sensitivity analysis for the fridge tote, compared to a natural refrigerant fridge (red dashed line)

Table 18 and Table 19 show the break-even point (daily hours of operation) for the fridge and freezer tote respectively, when compared to a traditional refrigerant reach-in and a natural refrigerant reach-in.

Table 18: Break-even point (daily hours of operation) for the fridge tote compared to a traditional refrigerant and a natural refrigerant reach-in

	Traditional Refrigerant Reach-In	Natural Refrigerant Reach-In
GWP [kg CO_2-eq]	>24	22
EP [kg N-eq]	23	20
AP [kg SO_2-eq]	8	5
BWC [m^3]	<1	<1
PED, fossil [MJ]	23	22

Table 19: Break-even point (daily hours of operation) for the freezer tote compared to a traditional refrigerant and a natural refrigerant reach-in

	Traditional Refrigerant Reach-In	Natural Refrigerant Reach-In
GWP [kg CO_2-eq]	14	11
EP [kg N-eq]	10	10
AP [kg SO_2-eq]	<1	<1
BWC [m^3]	6	5
PED, fossil [MJ]	12	12

5 Interpretation

5.1 Identification of Relevant Findings

The results of the LCA indicate that Phononic's fridge tote perform better than the traditional refrigerant fridge and the natural refrigerant fridge for GWP, EP, and PED, fossil (Figure 3, Table 14), however is outperformed by the comparison case reach-ins for AP and BWC. Tote materials contribute significantly to the cradle-to-grave footprint of the fridge tote, which is driven by aluminum and copper materials. Use phase is the highest contributor to overall footprint for the fridge tote, as electricity is required to keep the tote cool whenever it is in operation.

Phononic's freezer tote outperforms the traditional refrigerant reach-in for GWP, however is outperformed by both reach-in freezers for all other impact categories in the cradle-to-grave footprint (Figure 4, Figure 12, Table 15). The Phononic freezer tote has a high footprint compared to the reach-ins at the manufacturing end gate, attributed to the 6 chips required for a freezer tote to keep temperatures frozen, of which the copper and aluminum materials are the highest contributors to footprint. Use phase drives the cradle-to-grave footprint of Phononic's freezer tote as the tote uses electricity whenever it is in use to keep it at frozen temperatures.

The use phase is also the driver of the comparison case's footprints, as like the totes the reach-ins require frozen conditions using electricity to cool at all times when the unit is operating. The reach-ins also use refrigerants with 18% and 6% of the use phase GWP footprint being attributed to refrigerant requirements for the traditional refrigerant fridge and freezer respectively, with the remainder of the footprint attributed to energy use for both cases. Refrigerant recharge is <1% of all comparison case reach-ins' use phase impacts. Since the totes do not use refrigerants, there is no GWP impact associated with refrigerants during the use phase of the totes, in contrast to the comparison case.

EoL is an insignificant contributor to the Phononic totes' overall footprint, contributing <0.1% of total footprint for each impact category. The totes' EoL impact is low due to the high portion of material recycling, and the lack of refrigerant emission – which is emitted at EoL by the comparison case reach-ins.

EoL is an insignificant contributor to overall footprint for the natural refrigerant fridge and freezer for all impact categories as the CO_2 released has a low footprint (characterization factor of 1). Conversely, the EoL for the traditional refrigerant fridge and freezer has a significant contribution to the overall GWP footprint, with 25% and 11% of overall footprint respectively. This impact is attributed to the high impact of the R134a that is leaked to the environment at recovery at a rate of 30%. The characterization factor for the refrigerant is 1530, therefore the impact of releasing the traditional refrigerant at EoL is 1530-times higher than the impact of releasing the natural refrigerant, per kg of refrigerant released.

5.1.1 Results of Additional Analyses

Several scenario and sensitivity analyses have been performed to better understand the footprint of Phononic's totes.

Scenario – Recycled Metals

The results of the recycled metals scenario show that for the fridge tote, the footprint of each impact category reduce by 13-58% (Figure 11). A reasonable potential for reduction is shown for the fridge tote as aluminum and copper make up a significant proportion of the tote. AP shows the largest reduction, with a lowering of 58% from the baseline (from 100 at the baseline to 42% for the recycled metals scenario). EP also shows a significant reduction in cradle-to-grave footprint with a 32% reduction from the baseline. These reductions are attributed to the metal refining and heavy industrial processes associated with generating virgin metals. Recycled metals have a lower footprint than virgin metals as the impact of mining and refining the metals has already taken place, reducing the burden of the recycled metals. Transformation processes such as sheet rolling are still included where applicable.

The results of the recycled metals analysis also show that for the freezer tote, the footprint of each impact category is lower when aluminum and copper in the chips and tote is sourced from recycled metals (Figure 12). AP shows the largest reduction, with a lowering of up to 46% from the base case, depending on the impact category. AP shows this 46% decrease from 100% at the baseline scenario to 54% in the recycled metals scenario. EP also shows a significant reduction in cradle-to-grave impact, with almost a 20% reduction compared to the baseline. GWP and PED do not show a significant decrease in footprint, with a 5% reduction in each impact category.

Although there are significant reductions in raw material footprint for some impact categories for the fridge and freezer totes; in particular AP and EP, as materials footprint is a small contributor to the overall cradle-to-grave footprint of the totes, this potential reduction is not as significant. The difference in results between the base case and the recycled metals scenario is small, as the chip and tote materials have a low contribution to overall cradle to grave footprint. The use phase is the highest contributor to overall footprint for both totes. Therefore, reducing the impact of the chip and tote materials does not reduce the cradle-to-grave footprint of the freezer tote significantly.

Sensitivity Analysis – Tote Lifetime

The results of the tote lifetime sensitivity analysis show that for both the fridge and the freezer tote, as the lifetime increases, the annual impact of the totes decreases. This is because the materials and manufacturing impacts occurred once and are spread out over the lifetime of the totes. However, the use phase occurs every year, driving the footprint.

The break-even points vary by indicator for both the fridge and the freezer tote. The break even point for this analysis is the point in time when the Phononic tote outperforms the comparison case.

Compared to the traditional refrigerant cases, Phononic's fridge tote takes <1 year to break even with the traditional refrigerant comparison case for GWP, and >2 years for all other indicators (Table 16). Therefore, the tote needs to last less than a year for the GWP, and at least 2 years for all other indicators, to outperform the traditional refrigerant comparison case. This means that after 9 years, Phononic's fridge tote will outperform the traditional refrigerant fridge on a per-year basis as its impacts get smoothed out over the lifetime amortization. For Phononic's freezer tote, the tote needs to last at least one year for it to outperform the comparison case for GWP, and at least 7 years for all other indicators, to outperform the traditional refrigerant comparison case (Table 17). This means that after 7 years, Phononic's freezer tote will outperform the traditional refrigerant freezer on a per-year basis.

Compared to the natural refrigerant cases, Phononic's freezer tote takes 8 years to break even for GWP and PED, and at least 20 years for EP, AP, and BWC (Figure 15). This means that after 8 years, Phononic's freezer tote will be outperforming the natural refrigerant fridge on a per-year basis. Phononic's fridge tote takes 2 years to break even with the natural refrigerant fridge for GWP and PED, and 3 years for EP. After 8 and 13 years it will have broken even for AP and BWC, respectively (Figure 16). This means that after 13 years Phononic's fridge tote will outperform the natural refrigerant fridge on a per-year basis.

Sensitivity Analysis – Tote Hours of Operation

The results of the tote daily hours of operation analysis show that for both the fridge and the freezer totes, as the number of hours of operation per day increases, the impact of the tote increases. This is due to the energy use impact increasing proportionally with the number of hours of operation per day.

The break-even points vary by indicator for both the fridge and the freezer tote. For Phononic's fridge tote, it takes <1 hour to break even with the traditional refrigerant comparison case for BWC, and >9 hours for all other indicators excluding GWP, which takes >24 hours of operation per day to break even (Table 18). This means that the fridge tote can be turned on for approximately 1 hour per day for BWC, up to 9 hours per day for AP, and 23 or more hours per day for the other indicators before it no longer outperforms the traditional refrigerant comparison case. For Phononic's freezer tote, after <1 hour of operation the tote breaks even with the traditional refrigerant reach-in for AP, and breaks even after 7 or more hours of the other indicators (Table 19). Therefore, the freezer tote can be switched on for approximately 1 hour for AP and 6 or more hours per day for the other indicators before it no longer outperforms the traditional refrigerant reach-in.

Compared to the natural refrigerant cases, Phononic's fridge tote takes <1 hour to break even for BWC, and >5 hours for all other indicators (Table 18). This means that the fridge tote can be turned on for approximately 1 hour per day for BWC, up to 5 hours per day for AP, and 20 or more hours per day for the other indicators before it no longer outperforms the natural refrigerant comparison case. For Phononic's freezer tote, after <1 hour of operation the tote breaks even with the natural refrigerant reach-in for AP, and breaks even after 5 or more hours of the other indicators (Table 19). Therefore, the freezer tote can be switched on for approximately 1 hour for AP and 5 or more hours per day for the other indicators before it no longer outperforms the traditional refrigerant reach-in. The natural refrigerant comparison case has a lower overall footprint than the traditional refrigerant comparison case, therefore the break-even points are lower for the Phononic totes. Compared to the natural refrigerant reach-in, the Phononic totes need to be switched on for even fewer hours per day than when comparing to the traditional refrigerant reach-in.

5.2 Conclusions, Limitations, and Recommendations

The goal of this study is to calculate the potential environmental impacts of Phononic's thermoelectric cooling fridge and freezer totes, compared to traditional refrigerant and natural refrigerant reach-in equivalents.

Phononic's fridge tote has a lower cradle-to-grave GWP than both the traditional and natural refrigerant reach-ins. The traditional refrigerant fridge and natural refrigerant fridge have a GWP of 262% and 158% of Phononic's fridge tote, respectively. Phononic's freezer tote has a lower cradle-to-grave GWP than the traditional refrigerant freezer and is on par with the natural refrigerant freezer. The traditional refrigerant freezer and natural refrigerant freezer have a GWP of 117% and 96% of Phononic's freezer tote, respectively. There are tradeoffs across impact categories due to material and manufacturing impacts, such as higher EP, EP, BWC, and PED. The traditional refrigerant fridge and the natural refrigerant fridge have AP and BWC values of 57%-90% of Phononic's fridge totes, as well as an EP of 156% and 139% of Phononic's totes, and PED values of 162% and 158% of Phononic's fridge tote respectively. The traditional refrigerant freezer and natural refrigerant freezer have an EP, AP, and BWC value of 53%-85% of Phononic's freezer tote, and both comparison cases have PED values of 97% of Phononic's freezer tote.

The use phase contributes the most to cradle-to-grave impacts for the freezer tote for all impact categories, and for the fridge tote in GWP, EP, and PED. Tote materials is the highest contributor to AP, and tote manufacturing is the highest contributor to BWC. Chip materials and metal tote materials are also significant contributors to Phononic's fridge tote, on a percentage basis with less – however still significant – contribution to Phononic's freezer tote. EoL for the traditional refrigerant fridge and traditional refrigerant freezer is a significant proportion of the overall GWP footprint, due to the refrigerant emissions to air during recovery.

Given that the typical order mix is 2:1 fridge to freezer ratio, and the most significant comparative benefit is shown from Phononic's fridge totes, it can be expected that the Phononic totes could result in significant GWP savings compared to equivalent reach-ins on a per-order basis. The footprint of a variety of custom orders, whereby different ratios of fridge and freezer totes can be chosen, can be calculated using the results of this assessment, however no additional scenario assessment has been generated for this case. An accompanying workbook of results has been created for Phononic to use for this purpose, which will enable representation and exploration of different customers' orders compared to equivalent reach-ins.

The recycled metals scenario analysis shows the potential of impact reduction in all impact categories; however, some impact categories could be more significantly impacted. The analysis showed that the use of recycled copper and aluminum in the chips and totes could reduce the product footprint by 58% for the fridge tote and 46% for the freezer tote in the AP category. This was the most significant reduction potential. EP also showed significant reduction potential for the fridge and freezer totes, with a 32% and 19% reduction respectively. PED showed the lowest potential impact reduction for the fridge and freezer totes at 15% and 5% respectively. BWC showed a potential reduction for the fridge and freezer totes of 13% and 16% respectively. GWP also showed a potential for reduction for the fridge and freezer totes at 18% and 5% respectively.

The tote lifetime sensitivity analysis shows that as the lifetime of the Phononic totes increases, the overall footprint decreases. The use phase drives the footprint of the totes as it occurs constantly as the tote is operational throughout its life, whereas the materials, manufacturing, and EoL occur once and are split over the lifetime. Break-even points vary by indicator and by comparison case, however Phononic's tote requires an even longer lifetime if it is to outperform the natural refrigerant reach-in rather than the traditional refrigerant reach in, as the natural refrigerant reach-in has a lower footprint than the traditional refrigerant reach-in.

The tote hours of operation sensitivity analysis show that as the hours of operation for the Phononic totes increases, the overall footprint increases. The use phase drives the footprint as the energy use needed to keep the tote switched on is proportional to the number of hours the tote is operational. Break-even points vary by indicator and by comparison case, however Phononic's tote requires a shorter daily operational time if it is to outperform the natural refrigerant reach in rather than the traditional refrigerant reach-in, as the natural refrigerant reach-in has a lower overall footprint.

5.2.1 Limitations

As stated in the goal and scope, the goal of this study is to calculate the potential environmental impacts of Phononic's thermoelectric cooling fridge and freezer totes compared to a traditional refrigerant reach-in and a natural refrigerant reach-in. The study aimed to establish a full picture of potential environmental impacts, however it does not consider human or ecological toxicity or other impacts outside of those explicitly discussed in this report.

There was limited data availability for the comparison cases. The traditional refrigerant and natural refrigerant reach-in comparison cases were developed using secondary data from two peer-reviewed published LCAs comprising a BOM and manufacturing requirements for fridges. JBE assumes that it is reasonable to combine this data with the energy use for a comparison case fridge and freezer – provided by Phononic – in order to generate four comparison cases (a traditional refrigerant fridge, a traditional refrigerant freezer, a natural refrigerant fridge, and a natural refrigerant freezer). Additionally, JBE assumes it is reasonable to scale the BOM and the manufacturing requirements to the size of the expected comparison reach-in capacity.

The results of this study are limited to the specific tote and reach-in designs under study, and should not be used as a generalization for Phononic's products compared to any reach-in fridge or freezer.

Data quality and limitations pertaining to data and analysis assumptions are discussed in Section 3.3.

5.2.2 Recommendations

JBE recognizes that the Phononic totes are a new product entering the market, just entering full production. As the product matures, we offer the following recommendations for consideration to further reduce the GWP and other impacts identified in this LCA.

JBE recommends refinement of the operational energy model to better understand the energy use of the Gen 2 tote, and to identify the potential energy efficiency differences between the traditional refrigerant and the natural refrigerant reach-ins.

JBE also recommends that Phononic educate its customers on the importance of incorporating low-carbon electricity (e.g. on-site solar), which could reduce Phononic's tote's impacts during the use phase. This would also reduce competitor electricity impacts, but would not eliminate the refrigerant requirements of the competing product systems.

JBE finally recommends Phononic engage with their material suppliers to encourage lower impact production methods, which would reduce the raw material impact of Phononic's totes.

References

Hussmann. (2022). *VRL Self-Contained, Reach-In Bottom Mount, Low Temperature Merchandiser*. Retrieved from https://www.hussmann.com/ns/Product-Sheets/VRL_SCC_032819.pdf

IPCC. (2021). *Climate Change 2021: The Physical Science Basis.* IPCC.

ISO. (2006a). *14040:2006/Amd.1:2020 – Environmental management — Life cycle assessment — Principles and framework*. Geneva: International Organization of Standardization.

ISO. (2006b). *14044:2006/Amd.1:2017/Amd2:2020 – Environmental management — Life cycle assessment — Requirements and guidelines.* Geneva: International Organization for Standardization.

Lewandowska, A., Kurczewski, P., Joachimiak-Lechman, K., & Zablocki, M. (2021). Environmental Life Cycle Assessment of Refrigerator Modelled with Application of Various Electricity Mixes and Technologies. *Energies*.

openLCA. (2023). openLCA version 2.0.

Rossi, M., Favi, C., Germani, M., & Omicioli, M. (2021). Comparative life cycle assessment of refrigeration systems for food cooling eco-design actions towards machines with natural refrigerants. *International Journal of Sustainable Science*.

US EPA. (2011). The Tool for the Reduction and Assessment of Chemical and other Environmental Impacts v2.1. *Clean Technologies and Environmental Policy*.

US EPA. (2014). *Greenhouse Gas Inventory Guidance: Direct Fugitive Emissions From Refrigeration, Air Conditioning, Fire Suppression, and Industrial Gases.*

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, 1218-1230.

Annex A: Background Data

Table 20: Material background data – Phononic chips (ecoinvent v3.9.1 – cut-off system models)

Material	Geographic region	Reference year	Dataset	Provider	Proxy?*
Bismuth telluride	RoW	2022	cadmium telluride production, semiconductor-grade | cadmium telluride, semiconductor-grade | Cutoff, S	ecoinvent	Tech
Gold	RoW	2022	gold refinery operation | gold | Cutoff, S	ecoinvent	No
Polyphenylene sulfide	GLO	2022	polyphenylene sulfide production | polyphenylene sulfide | Cutoff, S	ecoinvent	No
Copper	RoW	2022	smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, S sheet rolling, copper | sheet rolling, copper | Cutoff, S	ecoinvent	No
Printed circuit board	GLO	2022	printed wiring board production, surface mounted, unspecified, Pb free | printed wiring board, surface mounted, unspecified, Pb free | Cutoff, S	ecoinvent	No
Solder	GLO	2022	solder production, paste, Sn95.5Ag3.9Cu0.6, for electronics industry | solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry | Cutoff, S	ecoinvent	No
Solder Paste	GLO	2022	solder production, paste, Sn95.5Ag3.9Cu0.6, for electronics industry | solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry | Cutoff, S	ecoinvent	No
Sealant Polydimethylsiloxane	GLO	2022	polydimethylsiloxane production | polydimethylsiloxane | Cutoff, S	ecoinvent	No
Thermal Grease	RoW	2022	silicon production, electronics grade | silicon, electronics grade | Cutoff, S	ecoinvent	No
Nickel Plating	GLO	2022	smelting and refining of nickel concentrate, 16% Ni | nickel, class 1 | Cutoff, S	ecoinvent	No
Reject Heat Exchanger Copper	RoW	2022	smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, S sheet rolling, copper | sheet rolling, copper | Cutoff, S	ecoinvent	No
Reject Heat Exchanger Aluminum	IAI Area, North America RoW	2022	market for aluminium, primary, ingot | aluminium, primary, ingot | Cutoff, S sheet rolling, aluminium | sheet rolling, aluminium | Cutoff, S	ecoinvent	No
Recycled Heat Exchanger Copper	GLO RoW	2022	copper scrap, sorted, pressed, Recycled Content cut-off | copper scrap, sorted, pressed | Cutoff, S sheet rolling, copper | sheet rolling, copper | Cutoff, S	ecoinvent	No
Recycled Heat Exchanger Aluminum	GLO RoW	2022	aluminium scrap, new, Recycled Content cut-off | aluminium scrap, new | Cutoff, S sheet rolling, aluminium | sheet rolling, aluminium | Cutoff, S	ecoinvent	No

* Geo. = Geographical proxy, Tech. = Technological proxy

Table 21: Material background data – Phononic totes (ecoinvent v3.9.1 – cut-off system models)

Material	Geographic region	Reference year	Dataset	Provider	Proxy?*
Steel	RoW	2022 2023	sheet rolling, chromium steel | sheet rolling, chromium steel | Cutoff, S steel production, electric, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S	ecoinvent	No
Aluminum	IAI Area, Asia, without China and GCC RoW	2022	aluminium production, primary, ingot | aluminium, primary, ingot | Cutoff, S sheet rolling, aluminium | sheet rolling, aluminium | Cutoff, S	ecoinvent	No
Acrylonitrile Butadiene Styrene	RoW	2022	acrylonitrile-butadiene-styrene copolymer production | acrylonitrile-butadiene-styrene copolymer | Cutoff, S	ecoinvent	No
Insulation	RoW	2022	polyurethane production, flexible foam, MDI-based | polyurethane, flexible foam | Cutoff, S	ecoinvent	No
Batteries	RoW	2018-2025	battery cell production, Li-ion, LFP | battery cell, Li-ion, LFP | Cutoff, S	ecoinvent	No
Motors	RoW	2022	electric motor production, vehicle | electric motor, vehicle | Cutoff, S	ecoinvent	No
Copper	RoW	2022	smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, S sheet rolling, copper | sheet rolling, copper | Cutoff, S	ecoinvent	No
Recycled Aluminum	GLO RoW	2022	aluminium scrap, new, Recycled Content cut-off | aluminium scrap, new | Cutoff, S sheet rolling, aluminium | sheet rolling, aluminium | Cutoff, S	ecoinvent	No
Recycled Copper	GLO RoW	2022	copper scrap, sorted, pressed, Recycled Content cut-off | copper scrap, sorted, pressed | Cutoff, S sheet rolling, copper | sheet rolling, copper | Cutoff, S	ecoinvent	No

* Geo. = Geographical proxy, Tech. = Technological proxy

Table 22: Material background data – Comparison cases (ecoinvent v3.9.1 – cut-off system models)

Material	Geographic region	Reference year	Dataset	Provider	Proxy?*
Compressor	RoW	2022	air compressor production, screw-type compressor, 4kW | air compressor, screw-type compressor, 4kW | Cutoff, S	ecoinvent	No
Lubricating Oil	RoW	2022	lubricating oil production | lubricating oil | Cutoff, S	ecoinvent	No
Cable	GLO	2022	cable production, unspecified | cable, unspecified | Cutoff, S	ecoinvent	No
Vibration Damper	RoW	2022	brass production | brass | Cutoff, S sheet rolling, copper | sheet rolling, copper | Cutoff, S	ecoinvent	Tech
Muffler	RoW	2022 2023	sheet rolling, chromium steel | sheet rolling, chromium steel | Cutoff, S steel production, electric, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S	ecoinvent	Tech
Condenser	GLO	2022	copper production, cathode, solvent extraction and electrowinning process | copper, cathode | Cutoff, S	ecoinvent	Tech
Fan	Row	2022 2023	sheet rolling, chromium steel | sheet rolling, chromium steel | Cutoff, S steel production, electric, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S	ecoinvent	Tech
Liquid Receiver	RoW	2022 2023	sheet rolling, chromium steel | sheet rolling, chromium steel | Cutoff, S steel production, electric, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S	ecoinvent	Tech
Drier Filter	RoW	2022 2023	sheet rolling, chromium steel | sheet rolling, chromium steel | Cutoff, S steel production, electric, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S	ecoinvent	Tech
Liquid Indicator	RoW	2022	brass production | brass | Cutoff, S sheet rolling, copper | sheet rolling, copper | Cutoff, S	ecoinvent	Tech
Electrical Panel	RoW	2022 2023	sheet rolling, steel | sheet rolling, steel | Cutoff, S steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, S	ecoinvent	Tech
Valves	RoW	2022	brass production | brass | Cutoff, S wire drawing, copper | wire drawing, copper | Cutoff, S	ecoinvent	Tech
Switches	RoW	2022 2023	sheet rolling, chromium steel | sheet rolling, chromium steel | Cutoff, S steel production, electric, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S	ecoinvent	Tech
Anti Condensation	RoW	2022	synthetic rubber production | synthetic rubber | Cutoff, S	ecoinvent	No
Structure	RoW	2022 2023	sheet rolling, steel | sheet rolling, steel | Cutoff, S steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, S	ecoinvent	Tech
Insulation	RoW	2022	polyurethane production, flexible foam, MDI-based | polyurethane, flexible foam | Cutoff, S	ecoinvent	No
Pipes	RoW	2022	smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, S drawing of pipe, steel | drawing of pipe, steel | Cutoff, S	ecoinvent	No
Hardware/Fittings	RoW	2022	smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, S sheet rolling, copper | sheet rolling, copper | Cutoff, S	ecoinvent	Tech
Inverter	RoW	2022	inverter production, 0.5kW | inverter, 0.5kW | Cutoff, S	ecoinvent	No
Gas Cooler	RoW	2022 2023	sheet rolling, chromium steel | sheet rolling, chromium steel | Cutoff, S steel production, electric, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S	ecoinvent	Tech

Material	Geographic region	Reference year	Dataset	Provider	Proxy?*
Heat Exchanger	RoW	2022 2023	sheet rolling, chromium steel | sheet rolling, chromium steel | Cutoff, S steel production, electric, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, S	ecoinvent	Tech
Nitrogen	RoW	2022	air separation, cryogenic | nitrogen, liquid | Cutoff, S	ecoinvent	No
Oil	RoW	2022	lubricating oil production | lubricating oil | Cutoff, S	ecoinvent	No
R134a Refrigerant	RoW	2022	refrigerant R134a production | refrigerant R134a | Cutoff, S	ecoinvent	No
R744 Refrigerant	RoW	2022	carbon dioxide production, liquid | carbon dioxide, liquid | Cutoff, S	ecoinvent	No
Cables	GLO	2022	cable production, unspecified | cable, unspecified | Cutoff, S	ecoinvent	No
Alloy	RoW	2022	brazing solder production, cadmium free | brazing solder, cadmium free | Cutoff, S	ecoinvent	Tech

* Geo. = Geographical proxy, Tech. = Technological proxy

Table 23: Manufacturing background data – Phononic chips (ecoinvent v3.9.1 – cut-off system models)

Material	Geographic region	Reference year	Dataset	Provider	Proxy?*
Purchased Electricity	US-SERC	2022	market for electricity, medium voltage | electricity, medium voltage | Cutoff, S	ecoinvent	No
Natural Gas	RoW	2022	heat production, natural gas, at industrial furnace >100kW | heat, district or industrial, natural gas | Cutoff, S	ecoinvent	No
Municipal Water	RoW	2022	market for tap water | tap water | Cutoff, S	ecoinvent	No
Particulate Matter	Elementary flow – N/A	N/A	Particulate Matter, > 2.5 um and < 10um	ecoinvent	No
Volatile Organic Carbons	Elementary flow – N/A	N/A	VOC, volatile organic compounds	ecoinvent	No
Sulfuric Acid	Elementary flow – N/A	N/A	Sulfuric acid	ecoinvent	No
Hydrochloric Acid	Elementary flow – N/A	N/A	Hydrochloric Acid	ecoinvent	No
Nitric Acid	Elementary flow – N/A	N/A	Nitric acid	ecoinvent	No
Non-Hazardous Waste to Landfill	RoW	2022	treatment of waste electric wiring, collection for final disposal | waste electric wiring | Cutoff, S	ecoinvent	No
Hazardous Waste to Recycling	RoW	2022	treatment of waste cooking oil, purified, esterification | fatty acid methyl ester | Cutoff, S	ecoinvent	Tech
Wastewater to POTW	RoW	2022	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, S	ecoinvent	No

* Geo. = Geographical proxy, Tech. = Technological proxy

Table 24: Manufacturing background data – Phononic totes (ecoinvent v3.9.1 – cut-off system models)

Material	Geographic region	Reference year	Dataset	Provider	Proxy?*
Generated Electricity	RoW	2022	electricity production, photovoltaic, 3kWp flat-roof installation, single-Si | electricity, low voltage | Cutoff, S	ecoinvent	Geo
Diesel	GLO	2022	diesel, burned in building machine | diesel, burned in building machine | Cutoff, S	ecoinvent	No
Municipal Water	RoW	2022	market for tap water | tap water | Cutoff, S	ecoinvent	No
Purchased Electricity	TH	2022	market for electricity, medium voltage | electricity, medium voltage | Cutoff, S	ecoinvent	No
Non-Hazardous Waste to Recycling	RoW	2022	treatment of waste polyethylene, for recycling, unsorted, sorting | waste polyethylene, for recycling, sorted | Cutoff, S	ecoinvent	Tech
Water Discharge to River/Lake	Elementary flow – N/A	N/A	Water	ecoinvent	No

* Geo. = Geographical proxy, Tech. = Technological proxy

Table 25: Manufacturing background data – Comparison cases (ecoinvent v3.9.1 – cut-off system models)

Material	Geographic region	Reference year	Dataset	Provider	Proxy?*
Compressed Air	RoW	2022	compressed air production, 800 kPa gauge, <30kW, average generation | compressed air, 800 kPa gauge | Cutoff, S	ecoinvent	No
Metal Working	RoW	2022	metal working, average for metal product manufacturing | metal working, average for metal product manufacturing | Cutoff, S	ecoinvent	No
Metal Working Energy	RoW	2022	energy and auxilliary inputs, metal working factory, with heating from hard coal | energy and auxilliary inputs, metal working factory | Cutoff, S	ecoinvent	No
Electricity	GLO	2022	market group for electricity, high voltage | electricity, high voltage | Cutoff, S	ecoinvent	No
Natural Gas	GLO	2022	market group for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, S	ecoinvent	No
Steam	RoW	2022	steam production, in chemical industry | steam, in chemical industry | Cutoff, S	ecoinvent	No
Difluoroethane	RoW	2022	1,1-difluoroethane production, HFC-152a | 1,1-difluoroethane, HFC-152a | Cutoff, S	ecoinvent	No
Wastewater	RoW	2022	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, S	ecoinvent	No

* Geo. = Geographical proxy, Tech. = Technological proxy

Table 26: Use phase emissions, utilities, & materials – All cases (ecoinvent v3.9.1 – cut-off system models)

Material	Geographic region	Reference year	Dataset	Provider	Proxy?*
Natural Refrigerant Emission	Elementary flow – N/A	N/A	Carbon dioxide, fossil	ecoinvent	No
Traditional Refrigerant Emission	Elementary flow – N/A	N/A	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	ecoinvent	No
Energy	US	2022	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, S	ecoinvent	No
Natural Refrigerant Replenishment	RoW	2022	carbon dioxide production, liquid | carbon dioxide, liquid | Cutoff, S	ecoinvent	No
Traditional Refrigerant Replenishment	RoW	2022	refrigerant R134a production | refrigerant R134a | Cutoff, S	ecoinvent	No

* Geo. = Geographical proxy, Tech. = Technological proxy

Table 27: End of Life emissions, waste, & transport – All cases (ecoinvent v3.9.1 – cut-off system models)

Material	Geographic region	Reference year	Dataset	Provider	Proxy?*
Nitrogen Emissions	Elementary flow – N/A	N/A	Nitrogen	ecoinvent	No
Natural Refrigerant Emissions	Elementary flow – N/A	N/A	Carbon dioxide, fossil	ecoinvent	No
Traditional Refrigerant Emissions	Elementary flow – N/A	N/A	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	ecoinvent	No
Non-Ferrous Metal Waste to Recycling	RoW	2022	treatment of metal scrap, mixed, for recycling, unsorted, sorting | aluminium scrap, post-consumer, prepared for melting | Cutoff, S	ecoinvent	Tech
Ferrous Metal Waste to Recycling	RoW	2022	sorting and pressing of iron scrap | iron scrap, sorted, pressed | Cutoff, S	ecoinvent	Tech
General Waste to Landfill	RoW	2022	treatment of inert waste, sanitary landfill | inert waste | Cutoff, S	ecoinvent	No

* Geo. = Geographical proxy, Tech. = Technological proxy

Table 28: Transport datasets - All cases (ecoinvent v3.9.1 - cut-off system models)

Material	Geographic region	Reference year	Dataset	Provider	Proxy?*
Transport Truck	RoW	2022	market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, S	ecoinvent	No
Transport Ship	GLO	2022	transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, S	ecoinvent	No

Annex B: Critical Review Statement

Industrial Ecology Consultants

August 21, 2024

Brandie Sebastian, LCACP
Technical Director & Senior LCA Strategist
John Beath Environmental, LLC (JBE)

Verification Report: Cooling Totes LCA

The Life Cycle Assessment (LCA) Practitioner, John Beath Environmental (JBE), commissioned a panel of experts to perform an external independent verification of the **Life Cycle Assessment of Thermoelectric Cooling Totes: Fridge and Freezer Totes, Report #216-001, August 1, 2024,** on behalf of the commissioning organization, **Phononic.**

The review of the study was performed to demonstrate conformance with the following standards:

> International Organization for Standardization. (2020). *Environmental management -- Life cycle assessment – Principles and framework* (ISO 14040:2006/Amd 1:2020).
>
> International Organization for Standardization. (2020). *Environmental management -- Life cycle assessment -- Requirements and guidelines* (ISO 14044:2006/Amd 1:2017/Amd 2 2020).
>
> International Organization for Standardization. (2014). *Environmental management -- Life cycle assessment -- Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006*. (ISO/TS 14071:2014).

The independent third-party verification was conducted by the following panel of experts per ISO 14044:2006 Section 6.2: Critical review:

> Thomas Gloria, Ph.D.
> Founder, Chief Sustainability Engineer
> Industrial Ecology Consultants
>
> Terrie K. Boguski, PE/Emeritus CPM
> President
> Harmony Environmental
>
> Angela Fisher, M.S.
> Co-founder and Chief Sustainability Strategist
> Aspire Sustainability

Industrial Ecology Consultants

REVIEW SCOPE

The intent of this review was to provide an independent third-party external verification of an **LCA study report and Results Workbook** in conformance with the aforementioned ISO standards. This review did not include an assessment of the Life Cycle Inventory (LCI) model; however, it did include a detailed analysis of the individual datasets used to complete the study.

REVIEW PROCESS

The review process involved the verification of all requirements set forth by the applicable ISO standards cataloged in comprehensive review table along with editorial comments. There were several rounds of comments by the reviewers submitted to the LCA practitioner. Responses by the LCA practitioner to each issue raised were resolved and acknowledged by the review panel to have been satisfactorily addressed.

VERIFICATION STATEMENT

Based on the independent verification objectives, the **Life Cycle Assessment of Thermoelectric Cooling Totes: Fridge and Freezer Totes, Report #216-001, August 1, 2024,** was determined to be *in conformance* with the applicable ISO standards. The plausibility, quality, and accuracy of the LCA-based data and supporting information are confirmed.

As the Chair of the External Independent Third-Party Review Panel, I confirm that the members of the panel have sufficient scientific knowledge and experience of appliance production systems, and the applicable ISO standards to carry out this verification.

Sincerely,

Thomas P. Gloria, Ph.D.
Founder, Chief Sustainability Engineer
Industrial Ecology Consultants

Digitally signed by
Thomas Gloria
Date: 2024.08.21
10:22:59 -04'00'