Life Cycle Assessment of Medical Oxygen

by

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A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Master of Environmental Studies

in

Sustainability Management

Waterloo, Ontario, Canada, 2023

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Medical oxygen is a vital healthcare resource provided to a patient to achieve their minimum required oxygen blood saturation. There is a growing interest in medical oxygen due to supply shortages experienced during COVID-19. There is limited sustainability research on medical products, their production and consumption, and their environmental impact. The World Health Organization has emphasized the need for environmental sustainability efforts and the resilience of health systems. This project considered a cradle-to-gate life cycle assessment (LCA) of medical oxygen. Medical oxygen, which accounts for a small fraction of total refined oxygen production, is produced using two technologies: (1) cryogenic distillation, where liquid oxygen is produced via liquefaction of air and then is transported to the site, (2) and pressure swing adsorption (PSA), where gaseous oxygen is produced, typically on-site, by passing ambient air through a molecular sieve. Four product systems for the LCA were considered. Product system 1, the baseline system, is a typical North American scenario: production via cryogenic distillation. Bulk liquid oxygen is transported to a hospital and then gasified for delivery via a pipe to the patient's bedside. In product system 2, oxygen is produced similarly to system 1, except liquid oxygen is transported and gasified at a regional facility. Oxygen gas is filled into cylinders, which are transported to the hospital. In product system 3, oxygen is produced at a hospital site via a PSA plant, which is then piped into the building. In product system 4, oxygen is produced and delivered immediately via a personal oxygen concentrator unit (which utilizes PSA technology) to a patient's bedside. Data were collected from the ecoinvent 3.8 database, industrial gas and medical experts, and publicly available information on company websites. OpenLCA software for running the system models and the TRACI life cycle impact assessment method were used. The reference period was 2021/2022, and the default location was Toronto, Canada, which has a relatively clean, low-carbon electricity grid. LCA results for the baseline system showed a global warming potential indicator value of 1.70×10^{-4} kg CO_2eq/litre of gaseous oxygen, with electricity as the key driver. Results for system 2 were more than double, at 4.11×10^{-4} kg CO_2eq/litre, with cylinder-related activities such as transportation adding to environmental burdens in the supply chain. In comparison, for system 3, the PSA plant, yielded 8.44×10^{-5} kg CO_2eq. Results for scenario 4, the personal concentrator, was incrementally higher, given its lower energy efficiency (1.23×10^{-4} kg CO_2eq). A scenario analysis considering oxygen production in various locations of the world was also conducted. Overall, medical oxygen, when delivered efficiently to a hospital, has a

relatively small environmental burden. However, the use of this critical resource is often wasteful. The results of the LCA can be useful to healthcare organizations, policy decision-makers and medical gas suppliers to improve sustainability practices of medical products and resource supply chains. The results also highlight aspects of the medical supply chain where there is a risk of disruption and where attention to health system resilience is needed.

Acknowledgements

I would like to thank my supervisor Prof. Steven B. Young for his continued support, guidance, patience and understanding throughout the thesis process. I would like to thank my committee, Prof. Komal Habib for the guidance and feedback. Thank you to Prof. Goretty Dias for being the reader of this thesis, and for teaching me the LCA method. To Dr. Jodi Sherman, thank you for your patience and incredible input.

I would also like to thank Ankesh Siddhantakar and Alex Cimprich for their expertise and assistance along this journey. Thank you to Fiona Miller and Nicole Simms from the University of Toronto – the opportunity to work on healthcare sustainability projects provided insight on this thesis.

Finally, I would like to thank my personal support network – my best friends for their everlasting love, faith and encouragement; the wonderful friends I made during this journey, my mentors and colleagues – I would not be able to complete this without them. I would like to thank my dearest parents, my brothers, and my family for their unconditional love, patience, and support.

To Nano and Nanaboo (my grandparents) – I miss you. This is for you.

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List of Abbreviations

Greenhouse Gas	GHG
Air Separation Unit	ASU
Carbon dioxide	CO_2
Chloroethylene	C_2H_3Cl
Emissions Factor	EF
environmentally extended input-output	EEIO
Equivalent	eq (in the context of kg CO_2eq or PM 2.5 eq)
Food & Drug Administration	FDA
Global Warming Potential	GWP
Gross Vehicle Weight	GVW
IMPact Assessment of Chemical Toxics 2002+	IMPACT 2002+
International Organization for Standardization	ISO
Life cycle Assessment	LCA
Life cycle Impact Assessment	LCIA
Life cycle Inventory	LCI
National Health Service	NHS
Nitrous oxide	N_2O
particulate matter 2.5	PM 2.5
Pressure Swing Adsorption	PSA
Publicly Available Specification	PAS
Sustainable Development Goals	SDGs
Tool for the Reduction and Assessment of Chemical and other Environmental Impacts	TRACI
Triethylene glycol	TEG
U.S. Environmental Protection Agency	U.S. EPA
United Nations Children's Fund	UNICEF
World Health Organization	WHO

List of Units

atmosphere	atm
Comparative Toxic Unit	CTU
cubic metre	m^3
day	d
degrees celsius	°C
horsepower	hp
kilogram	kg
kilometre	km
kilopascal	kPa
kilowatt	kW
kilowatt-hour	kWh
litre per minute	L/min
Megajoule	MJ
Normal cubic metre	Nm^3
pounds per square inch absolute	psia
pounds per square inch gauge	psig

Chapter 1 Introduction

1.1 Healthcare and sustainable development

The healthcare sector provides critical services to people and society but, ironically, has substantial environmental impacts that can harm public health (Sherman et al., 2020). Direct and indirect greenhouse gas (GHG) emissions from the national healthcare sectors are approximately 10% of the national total in the U.S. (Eckelman & Sherman, 2016), 6% in the U.K. (Sustainable Development Unit, 2018), 4.6% in Canada (Eckelman et al., 2018), and 2.7% in China (Wu, 2019).

The Brundtland Report defines sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987). Based on this definition, and about 30 years later, the United Nations developed the 17 Sustainable Development Goals (SDGs), embracing social, environmental, and economic development for a more sustainable future (United Nations, 2015). Building a sustainable health system would not only increase access to healthcare services to all 7.8 billion people in the world, but would also help meet the SDGs, such as good health and well-being (SDG 3), responsible consumption and production (SDG 12), and climate action (SDG 13).

Healthcare organizations must manage the environmental impact of all their activities as an essential strategy for achieving sustainable development. An environmentally sustainable health system would improve and maintain the health of current and future generations while minimizing negative impacts on the environment (World Health Organization, 2017). Environmental sustainability in healthcare can help reduce costs and increase the resilience of health systems (World Health Organization, 2017). The World Health Organization (WHO) mentions a growing concern for the high consumption of energy and resources and the resulting impacts on climate from the healthcare sector (Chartier, 2014). For example, healthcare buildings operate 24 hours a day, seven days a week, requiring significant energy for heating, cooling, and ventilation systems, computing, medical and laboratory equipment use, sterilization, refrigeration, laundry, and food service (U.S. Energy Information Administration, 2016). In Canada, hospitals have the highest energy intensity of all commercial and institutional buildings (Government of Canada, 2016). In the United States, inpatient healthcare buildings were the third-most energy-intensive commercial buildings in the country in 2018 (U.S. Energy Information Administration, 2022). The healthcare system also uses energy-intensive goods and services, such as pharmaceuticals and medical equipment (Eckelman & Sherman, 2016). These activities contribute to the environmental impact of the health system. However, environmental impact work on medical products and services is limited. Oxygen is one product used in healthcare, and the focus of this study.

1.2 Industrial gases and sustainability

Industrial gases are produced in a niche industry with specialized equipment and technology for the production, distribution, storage, and use of these gases. In the economy, the leading industrial gases are nitrogen, oxygen, carbon dioxide, argon, hydrogen, helium, and acetylene (Fernández, 2022). These are manufactured through chemical reactions (e.g., acetylene), recovered with other products (e.g., helium is a byproduct of natural gas processing), or separated and purified from the air (e.g., oxygen) (Wingeter, 2019). A handful of international companies serve the industrial gas market, and there is a limited number of experts in the industry with experience and knowledge on the production, distribution, and safety aspects of industrial gases.

Industrial gas companies such as Linde plc have started to identify the need for sustainability and environmental efficiency in their operations in transporting, delivering, and manufacturing goods (Linde plc, 2019). Air Liquide S. A. wants to reduce a third of its greenhouse emissions by 2035 and reach carbon neutrality by 2050 (Air Liquide S.A., 2022). Air Products and Chemicals, Inc. has mentioned the importance of investing in clean energy and mitigating climate change (Air Products and Chemicals, Inc., 2022). However, there is little academic work in quantifying and assessing the environmental impacts of industrial gas production. Focusing on the environmental impact of industrial gas production can help companies meet sustainability targets, improve efficiencies, build resilient supply chains, and reduce impacts on the climate.

1.3 Medical gases and sustainability

Industrial gases that meet healthcare standards are referred to as medical gases. Oxygen, helium, and anesthetic gases are a few critical medical gases used in healthcare. Medical oxygen, used for treating respiratory distress, is the most needed therapeutic intervention in hospitals (Gómez-Chaparro et al., 2018). It is an essential life-saving medicine for treating illnesses like COVID-19 and pneumonia and is also needed for surgery and trauma (World Health Organization, n.d.). Helium has the lowest boiling point among the elements of the periodic table. For this reason, it is used in magnetic resonance imaging (MRI) machines for cooling magnets to extremely low temperatures (Royal Society of Chemistry, n.d.). Anesthetic gases are used to keep patients unconscious during surgery. Some main anesthetic gases include isoflurane, desflurane, sevoflurane and nitrous oxide (Sherman et al., 2012).

Using medical gases in hospitals consumes resources and generates “high environmental risk” (Gómez-Chaparro et al., 2018). This risk is especially true of gases which involve the generation of NO_x compounds (e.g., nitrous oxide). These gases can lead to environmental emissions. Gómez-Chaparro et al. also note that intakes are left open after surgeries in operating theatres which is a cause of misuse and mismanagement of resources and waste.

Medical gases and sustainable development are under-researched. Life cycle greenhouse gas emissions of anesthetic gases have been studied (Hu et al., 2021; McGain et al., 2020; Seglenieks et al., 2021; Sherman et al., 2012). Anesthetic gases have high environmental impacts associated with their use. Desflurane and nitrous oxide (N_2O) have higher environmental impacts than other anesthetics and gases such as carbon dioxide (CO_2) (McGain et al., 2020; Sulbaek Andersen et al., 2012). The Global Warming Potential over a 100-year period (GWP_{100}) – the amount of energy absorbed by 1 ton of the gas relative to 1 ton of CO_2 – of desflurane is 2540 (Sulbaek Andersen et al., 2012). N_2O is one of the most significant ozone-depleting substances and contributes 6% to anthropogenic global warming (World Meteorological Organization, 2018). Additionally, waste anesthetic gases are released into the atmosphere, unmetabolized and unregulated (McGain et al., 2020). The sustainability of helium in healthcare is also starting to be examined. More recently, work has been done on the supply risk of helium (Siddhantakar et al., 2022).

Medical oxygen makes up 1% of global liquid oxygen production (Davies & Furneaux, 2021). The remaining 99% is produced for industries such as metals and alloys, mining, petrochemicals, aeronautics, industrial chemistry, and water treatment (Air Products and Chemicals, Inc., 2015). Even though this is a very small percentage, oxygen is required for an essential life-saving purpose. This critical resource is often wasted in large quantities in hospitals (J. Sherman, personal communication, June 24, 2021). Given its necessity, the healthcare and industrial gas sectors would benefit from introducing sustainability practices into medical oxygen's supply chain.

Medical oxygen reliability and supply chain resilience are essential in building sustainable health systems. The 2019 global pandemic of the coronavirus disease (COVID-19) highlighted the importance of the reliability of supplies to patients, including medical oxygen. Although problems were most acute in less-developed countries, even North American facilities faced supply chain challenges during the pandemic. In August 2021, the Florida Hospital Association reported that 68 Florida hospitals had less than a 48-hour supply of oxygen (Aboraya, 2021; Suran, 2022). Other parts of the world, especially low-and-middle-income countries (LMICs), saw a lethal supply shortage (Davies & Furneaux, 2021; Hinnant et al., 2020). This drew attention to medical oxygen in the news and other sources.

Given the growing attention to the oxygen supply chain, recent consideration has been given to the supply chain of oxygen, supply chain risks, and environmental impact (Bałys et al., 2021; Bonnet et al., 2021; Botney et al., 2020; Seglenieks et al., 2021; Zhong et al., 2020). The cited works link medical oxygen supply and environmental impact. Even though there is growing scrutiny on sustainable development in the medical gas world, more work is needed to understand the effects of these gases on the environment. More broadly, there is mounting urgency for sustainability-related studies on individual products, technologies, and resources used in healthcare; in particular, policymakers and industry experts highlight the need for attention to this area (Sherman et al., 2020). In this context, quantifying the environmental impacts of medical oxygen will help highlight hotspots in the medical gas life cycle, informing healthcare systems' decision-making on reducing this impact.

1.4 Thesis overview

This chapter introduced concepts of sustainable development, healthcare sustainability, and how sustainability can be linked to industrial gases and medical gases. It set the tone and introduced themes which will later be explained and linked to the purpose of this study. Chapter 2 gives the reader a deeper understanding of medical gases, medical oxygen, and how sustainability in healthcare is currently being addressed. Chapter 3 then highlights the gaps in literature and industry, the importance of this study and its contribution to existing literature. Chapter 4, Chapter 5 and Chapter 6 report on the methodology, results, and discussion of this thesis. Chapter 7 presents the conclusion, which reflects upon the entire thesis, and the key takeaway message.

Chapter 2 Literature Review

2.1 What are medical gases?

Medical gases are regulated by regulatory bodies controlling the approval of "drugs and health products," such as Health Canada and the U.S. Food and Drug Administration (FDA). Health Canada defines medical gases as: "any gas or mixture of gases manufactured, sold, or represented for use as a drug" (Health Canada, 2018). The FDA's Federal Food, Drug, and Cosmetic Act's Section 575 defines "medical gas" as "a drug that (A) is manufactured or stored in a liquefied, nonliquefied, or cryogenic state; and (B) is administered as a gas" (FDA, 2022). "Designated medical gases" include oxygen, nitrogen, nitrous oxide, carbon dioxide, helium, carbon monoxide, and medical air (FDA, 2022) which are fabricated, packaged/labelled, and stored as per regulations and guidelines.

Medical gases are produced and handled in the same manner as industrial, or non-medical gases, however, they are subject to rigorous guidelines that ensure the purity and integrity of the gas for medical use. As per Health Canada, "parts in contact with medical gases are designed, constructed and located in a way that allows cleaning and avoids contamination" (Health Canada, 2018). Specialists or handlers may store or transport medical gases in bulk tanks, containers, or tankers used for non-medical gas if the quality of the non-medical gas is equal to the minimum required quality of the medical gas. Additionally, good manufacturing practices must be maintained (Health Canada, 2018). Oxygen is an industrial gas with varying uses in the metals and alloys, mining, petrochemicals, aeronautics, industrial chemistry, water treatment, and medicine industries. While the oxygen produced, stored, and handled for these various applications may be through one process or batch, the oxygen designated for medical use must fulfill all relevant drug and health regulatory guidelines.

This thesis focuses on oxygen used in medicine, referred to as "medical oxygen" herein. This is an industrial gas fulfilling the criteria and definition of medical gas as previously defined.

2.2 Medical oxygen supply chain

The steps in the supply chain of oxygen for use as a medical gas are summarized in Figure 1. The supply chain of oxygen is straightforward; oxygen retrieved from the atmosphere is purified, then transported to a healthcare setting where it is used. In clinical use, oxygen is either emitted un-used during the patient application or is dissipated from the patient through respiration or metabolism.

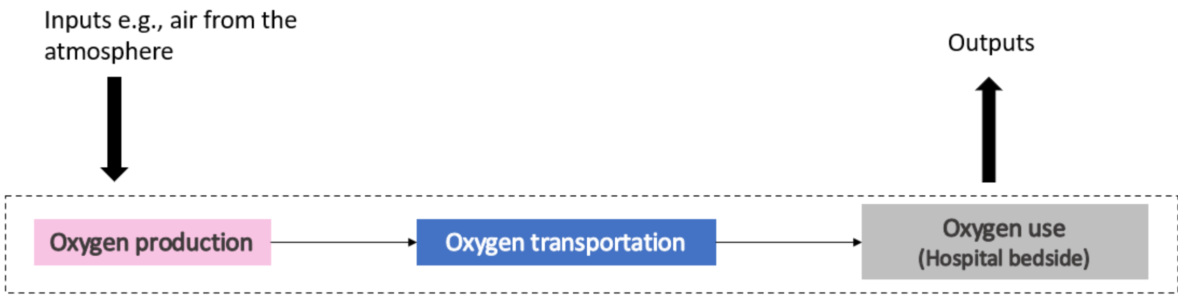

Figure 1: Medical oxygen's life cycle

2.2.1 Oxygen production

Different methods of medical oxygen production produce distinct levels of oxygen purities based on the utilized method. Medical oxygen is manufactured and sold under two main purities: Oxygen 93 and Oxygen 99. Oxygen 93 contains 90% to 96% volume/volume (V/V) oxygen, and Oxygen 99 contains 99.5% V/V oxygen. For oxygen produced by cryogenic distillation, the International Pharmacopoeia requires that oxygen not contain less than 99.5% V/V of oxygen. The WHO guidance specifies that Pressure Swing Adsorption (PSA) plants produce medical-grade Oxygen 93 (World Health Organization, 2020). For oxygen concentrators, the WHO states that oxygen should be produced at a concentration of greater than 82% (WHO & UNICEF, 2019).

2.2.1.1 Cryogenic Distillation

The most common method for medical oxygen production involves the purification of oxygen via cryogenic distillation. In this process, air is fed into an air separation unit (ASU), where it is compressed to 650 kPa (6.5 atm) and cooled to -181°C which is the critical temperature of oxygen (Gardner, 2013). Above the critical temperature, oxygen cannot exist as a liquid, regardless of the pressure applied. The boiling point of oxygen is -183ºC at 1 atm at which point oxygen separates from nitrogen in the air into a liquid. At this stage in the air separation process, argon is also present in the liquified oxygen as its boiling point is closer to that of oxygen (-185.7ºC) (Gardner, 2013). The liquid oxygen-argon mixture is passed through a second purification process (low-pressure distillation column) to allow the oxygen to separate. The final purified liquid product is 99.5% oxygen and 0.4% argon (Gardner, 2013). Cryogenic distillation produces the purest form of oxygen in large quantities. Liquid oxygen, the result of cryogenic distillation, is a common form of oxygen storage method in hospitals allowing a large reservoir of oxygen to be maintained in a relatively small space (Nini Malayaman et al., 2021).

2.2.1.2 Pressure Swing Adsorption (PSA)

A second method of purification for medical oxygen is PSA; a process suitable for producing small or medium-scale quantities of oxygen. PSA involves passing ambient air through a filtration system such as a molecular sieve under pressure which separates the nitrogen from the air and concentrates the remaining oxygen to a known purity (World Health Organization, 2020). Nitrogen is vented to the atmosphere, while oxygen is used. Industrial PSA plants produce medical oxygen of purity 93±3% (World Health Organization, 2020).

2.2.1.2.1 Oxygen Concentrators

Oxygen gas concentrators are stationary or portable devices that also use PSA technology, concentrating the oxygen from ambient air. The use of oxygen concentrators is gaining traction because the equipment can be set up immediately adjacent to a patient in the healthcare facility to produce and deliver oxygen. The purity of the oxygen produced is typically between 90% to 96% (Friesen, 1992; Nini Malayaman et al., 2021).

2.2.2 Oxygen transportation

Liquid oxygen from cryogenic distillation plants is distributed to hospitals by railroad tank cars, liquid transport trailers, or mobile pumping units, which are special liquid-carrying trucks that can deliver liquid (Shen & Wolsky, 1980). Liquid oxygen has a very low boiling point (-183ºC), so its transportation should be in the most effective way possible. Liquid oxygen transport units resemble insulated metal vacuum bottles to maintain required temperatures (Nini Malayaman et al., 2021). The liquid oxygen is conveyed to the central supply system (bulk storage vessels) in healthcare settings, to which a supply truck supplies liquid oxygen through a cryogenic hose (Nini Malayaman et al., 2021; Shen & Wolsky, 1980). Alternatively, liquid oxygen can be gasified after which gaseous oxygen can be stored in high-pressure cylinders and transported to healthcare facilities in cylinders. Gaseous oxygen produced from PSA plants can be piped (transported) directly from the production unit in the plant to hospital wards. An oxygen concentrator placed next to a patient is tubed directly to the patient (discussed in Section 2.2.3).

2.2.3 Oxygen use

The installation of medical gas (including oxygen) facilities in healthcare buildings require a variety of storing and distribution equipment, such as portable gas cylinders, cryogenic tanks, and specific devices for the self-production of medical gases (Harsoor & Bhaskar, 2007). In a hospital, liquid oxygen is stored in a bulk storage vessel, where it is connected to the operating room or intensive care unit (ICU) via pipelines and connectors (Nini Malayaman et al., 2021). Most hospitals store their bulk oxygen in liquid form, which enables a large reservoir of oxygen to be stored in a small space. The liquid oxygen system contains vaporizers that heat the liquid and convert it to a gas before it is piped into the hospital. A mechanical heat source can be used to aid in vaporization (Nini Malayaman et al., 2021). Gaseous oxygen produced from an on-site PSA plant is directly piped into the hospital through a pipeline.

Cylinders can be used for backup oxygen supply or as the main supply if pipeline supply is not available. Sufficient cylinder availability is critical at hospitals as a contingency measure should the primary oxygen supply be disrupted. It is more common for cylinders to be the only oxygen supply source in facilities such as dental clinics (Nini Malayaman et al., 2021). Oxygen stored in cylinders must be maintained in a location free of fire hazards. Often the cylinders are connected by a manifold system – comprised of a group of cylinders connected to the oxygen supply pipeline (Nini Malayaman et al., 2021). The cylinders are attached to an anesthesia gas machine or other machinery when needed. The pipeline connected to the oxygen bulk storage and the manifold system is made of copper piping (ASTM International, 2019). Oxygen delivery from the pipeline to the hospital room and, subsequently, the patient consists of valves, gauges, and alarm systems used to control the flow of oxygen, monitor pressure, and determine if oxygen flow to the patient is running low.

The output delivery pressure of oxygen gas is usually 20 pounds per square inch gauge (psig) to 50 psig[1]. The pressure of the oxygen pipeline is usually maintained at 50 psig. The pipeline is therefore designed to support the pressure drop from the bulk liquid storage vessel (storage pressure = 85 psig) or a high-pressure cylinder (storage pressure ≥ 2000 psig) (Gardner, 2013; Nini Malayaman et al., 2021). Cylinders will generally have a *reducing valve* attached (Nini Malayaman et al., 2021), reducing the oxygen gas pressure to the output delivery pressure as needed. If oxygen is to be provided to a patient or small group of patients, a pressure of 20 psig is acceptable (J. Klein, personal communication, November 24, 2021). Smaller output devices, such as the oxygen concentrator would use such a delivery pressure or lower at approximately 5 psig to 8 psig (Lewarski & Volsko, 2016).

Oxygen is administered to a patient via an oxygen delivery device. These devices require a well-regulated flow of gas, which can be achieved with devices such as flow restrictors (Lewarski & Volsko, 2016) that are attached to the delivery device. Delivery devices can be classified as low flow (e.g., a nasal cannula), high flow (e.g., a high-flow nasal cannula), reservoir (e.g., a simple mask), and enclosure (e.g., an oxygen hood). “Device selection for a particular patient will depend on how much oxygen the patient needs, how much flow the patient needs, the patient’s need for comfort and mobility, and the need for precise delivery of desired oxygen concentrations” (Lewarski & Volsko, 2016). For instance, a low-flow device provides part of the total flow of oxygen gas inhaled by a patient. The nasal cannula is a low-flow delivery device and consists of tubing connected to two prongs inserted into the nose (Lewarski & Volsko, 2016). Gaseous oxygen from an oxygen concentrator unit is directly supplied to the patient through an oxygen delivery device.

2.3 Sustainability in healthcare

There are many facets to sustainability in healthcare including but not limited to lowering the environmental impact of products or services, reducing inefficiencies, or building resilience in health systems. Due to the complexity of the healthcare system, including its many moving parts and critical nature, healthcare systems are reliant on the products and services that allow them to operate efficiently. For instance, a hospital requires many medical products (e.g., medicines, equipment,

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[1] for reference, atmospheric pressure = 14.7 pounds per square inch absolute (psia) or 0 psig; psig = psia – 1 atm (where atm is atmospheric pressure)

tools, personal protective equipment) to ensure its preparedness for varying circumstances and to run efficiently. As hospitals are divided into numerous departments, providing different areas of expertise, helping the organization operate and serve its patients effectively (e.g., emergency services department, surgery, cancer center etc.), medical product supplies must be stocked and accessible. Medical product supply chains are an essential step to "facilitate the flow of medical products from raw material or component suppliers (e.g., makers of ingredients, subassemblies) to producers (e.g., final assembly plants, fill-and-finish facilities), to distributors (e.g., wholesalers), to providers (e.g., health systems, pharmacies, retailers), and finally, to patients" (National Academies of Sciences, Engineering, and Medicine, 2022). Each step in the supply chain need to be fulfilled in a timely manner to provide an uninterrupted supply of medical products to the health systems and patients. There are many supply chain nodes. A detailed understanding of supply chains is crucial in understanding their complexity, the upstream environmental impacts each product may add to a health system, and the supply risk of products and services.

2.3.1 Environmental impact

In reported literature, environmental impacts are being brought to light (Eckelman & Sherman, 2016). The health system contributes to anthropogenic climate change, which poses sizable public health risks (i.e., air pollution, rising temperatures, flooding and drought, and change in the spread of vector-borne diseases) (Costello et al., 2009). A system dedicated to providing health and life-saving services to the public must study its contributions to the damaging climate and resulting health risks, and as a result attention to its environmental impact is needed. Environmental emissions in healthcare are predominantly indirect, and come from manufacturing and transporting products needed for healthcare facilities (McGain et al., 2020). There are many tools to measure environmental impacts.

Currently, academia and industry have identified the carbon footprint (total amount of greenhouse gases) of health services as a subject of detailed analysis. Alshqaqeeq et al. (2020) conducted a systematic literature review and reported on 48 studies that consider quantitative contributions to global warming in various healthcare sectors. Only a handful of these studies completed an LCA and considered environmental impact categories beyond climate change. Other studies published in academic literature calculate the carbon footprint of products and services using tools such as ISO 14067, PAS 2050, and the GHG Protocol Product Standard. Environmental impacts such as toxicity potential for humans and ecosystems, emissions such as particulate matter 2.5, and impact on land and water use are overlooked, while the focus remains on carbon footprint. As a result, there is a considerable need for assessments of the impact on other environmental categories to understand the possible impacts on land, air, soil, and human and ecosystem health.

Researchers and experts have conducted "top-down" environmental studies, such as the environmentally extended input-output (EEIO) modelling, mapping emissions onto economic activities and using the monetary cost of items in a category as a basis to estimate total environmental footprint (Rizan, Steinbach, et al., 2020). In this process, the higher cost items have higher environmental emissions. Some of these studies included analyses on healthcare. One study (Eckelman & Sherman, 2016) estimated the direct and indirect GHG emissions associated with the U.S. national healthcare sector to be 10% of national releases. This approach, however, has a high level of uncertainty as costs do not definitively correlate to actual environmental life cycle impacts. Top-down approaches like the EEIO are valuable for high-level overviews of national or regional sectors, while more granular studies on the product and service level, or "bottom-up" studies (such as LCA), can direct healthcare and supply chain actors to problem areas.

2.3.1.1 Life cycle assessment (LCA)

Life cycle assessment (LCA), as defined by the international standard ISO 14040, addresses potential environmental impacts (e.g., use of resources and the environmental stress of releases) throughout a product's life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e., cradle-to-grave) (ISO, 2006). The four steps of an LCA study include the following:

1. the goal and scope definition phase, which includes defining the purpose of the study, system boundary, and details required to carry out the study,
2. the life cycle inventory (LCI) analysis phase, which is the collection and analysis of the inventory of input/output data,
3. the life cycle impact assessment (LCIA) phase, which involves assessing the LCI results to better understand their environmental significance, and
4. the interpretation phase, in which the results of the LCI and LCIA phase are discussed and summarized, and conclusions, recommendations, and decisions are formed.

2.3.1.2 LCA of medical products and services

LCA of medical products and services have received recent attention in literature. Pharmaceuticals, which encompass a broad range of categories and include drugs, have been studied less than other areas. In this category, the LCA of inhalers has received scrutiny (Fulford et al., 2021; Goulet et al., 2017; Jeswani & Azapagic, 2019). LCAs of other drugs have been published, withholding the names of the pharmaceutical products (Wernet et al., 2010), as pharmaceutical companies do not want to release confidential operational data (De Soete et al., 2017; Jiménez-González & Overcash, 2014). LCA of medical equipment such as gowns (Carre, 2008; Vozzola et al., 2018; Zhao et al., 2022), medical tools (Campion et al., 2015; Ibbotson et al., 2013), masks (Boix Rodríguez et al., 2021; Eckelman et al., 2012; Li et al., 2022; Schmutz et al., 2020), personal protective equipment (Babcock et al., n.d.; Rizan, Reed, et al., 2020), containers (Grimmond & Reiner, 2012), etc.; and medical services such as surgeries (Campion et al., 2012; Tan & Lim, 2021; Thiel et al., 2015, 2017) and dental procedures (Borglin et al., 2021) have been conducted. Often, comparative LCAs are conducted to study the environmental impact differences between reusable and disposal medical items (Carre, 2008; Grimmond & Reiner, 2012; Ibbotson et al., 2013; Vozzola et al., 2018), for instance, cotton versus surgical masks (Eckelman et al., 2012; Schmutz et al., 2020). LCAs conducted on healthcare have gained traction, sparking a demand for healthcare actors and researchers to focus on sustainability and environmental impacts in this industry.

2.3.1.3 LCA of oxygen (and isotopes of oxygen) used in healthcare

Two existing studies were found in literature for the LCA of oxygen used in healthcare. The first one, by Bałys et al. (2021) studied the environmental aspects of the delivery of oxygen to patients in Poland during the COVID-19 pandemic. The study presented a "functional unit" of 64,800 m^3 of oxygen distributed to a hospital over a period of a month. The authors considered three routes for oxygen delivery: (1) oxygen gas provided to a patient in cylinders, (2) liquid oxygen transported and stored in tanks, and (3) PSA plant operation on-site. A gate-to-gate LCA scope was used, and only transportation impacts were considered for the first two while only electricity impacts were analyzed for the third route. The IMPACT 2002+ methodology for LCIA was used, and the following categories were considered: Human Health Potential, Ecosystem Quality Potential, Climate Change Potential and Resources Potential. The authors presented their results as normalized environmental impact; normalization is an optional step in LCA and involves transforming the results by a selected reference value to ease interpretation (ISO, 2006). Results showed that oxygen in cylinders distribution produced the highest values for all impact categories assessed, and liquid oxygen in tanks route produced the lowest. This study is limited as it did not consider all life cycle stages involved and did not use consistent boundaries, nor are results easily comparable across scenarios or to other systems.

Akbarian Shourkaei et al. (2018) studied the environmental impacts of an isotope of oxygen, oxygen-18, through the LCA method. Oxygen-18 is an isotope of oxygen and is used in medicine in Positron Emission Tomography, an imaging technique used in diagnosing diseases. The paper assessed the impacts from the production of 8.1 tons of oxygen-16, oxygen-18 product – the functional unit which is the reference unit needed for quantification of environmental impacts – using cryogenic distillation technology. The study was based in Iran. The system boundary for the LCA study was cradle-to-gate (raw material acquisition, transport, infrastructure, operational material, and energy needed to produce the oxygen-16 and oxygen-18 product). The required data were obtained from process simulation using SimaPro 8.3 software for the LCA calculations. The LCIA method used was ReCiPe. Environmental impacts on human health, ecosystems, and resources were assessed. Results showed that electricity is the main contributor to all 17 damage categories assessed, i.e., human health, ecosystems, and resources. The authors explained that this is reasonable considering Iran's electricity grid, which is highly dependent on fossil fuels. This study did not assess the impacts of using oxygen-18 at hospitals and its end-of-life management. The oxygen studied here differs from the commonly used oxygen-16 in healthcare and, therefore, would not be a basis for comparison for this study.

2.3.2 Resilience

Medical product shortages are a significant concern in healthcare, as timely and high-quality patient care can be affected. Shortages can happen due to demand surges, capacity reduction in supply chain processes, or coordination failure (National Academies of Sciences, Engineering, and Medicine, 2022). The U.S. National Academies of Sciences, Engineering, and Medicine (2022) devised a conceptual equation for "supply chain resilience" – to reduce total expected harm to a patient due to a disruption of a medical product. Several steps are proposed to increase a nation's medical product supply chain resilience and decrease product shortages or unavailability. These steps include awareness, mitigation, preparedness, and response. Attention to supply chains is an important step in highlighting the importance of resilience to reduce supply risks and hence harm to a patient. These interconnections are necessary for sustainable development and building a sustainable health system.

2.3.2.1 Resilience in the medical oxygen supply chain

The COVID-19 pandemic highlighted the importance of resilience in the oxygen supply chain. Here, resilience problems at various points in the supply chain are analyzed and discussed. Oxygen storage and supply infrastructure are essential in the medical oxygen supply chain and due to the increased demand for medical oxygen, equipment manufacturers had to ramp up the production of oxygen storage and supply equipment during COVID-19. For instance, Chart Industries, a U.S.-based cryogenic equipment manufacturer, produced extra liquid oxygen bulk storage tanks, cylinders, trailers and mobile equipment for oxygen storage (Parkinson, 2021). Additionally, PSA plant spare parts and oxygen concentrators have been in short supply during the pandemic (Davies & Furneaux, 2021). The World Health Organization, UNICEF, the World Bank and other non-governmental organizations have provided concentrators to countries in need during the pandemic (Davies & Furneaux, 2021).

ASUs are typically located no more than 300 miles (around 480 kilometres) from the point of gas use so that the liquid oxygen does not vaporize before it is delivered (Suran, 2022). In Florida in the summer of 2021, liquid oxygen was delivered up to 700 miles (around 1130 kilometres) away to ensure sufficient quantities of liquid oxygen products reached the customer on time (Suran, 2022). There has been a shortage of oxygen tanks and cylinders used to store pressurized oxygen gas during COVID-19. Cylinders need to be certified for medical use and must be transported, returned, and re-processed for reuse, resulting in a complex supply chain (Smith et al., 2020). Moreover, hospitals have limited on-site storage capacity, governed by the storage capacity of the bulk storage vessel at the hospital site ultimately limiting the ability to stockpile additional liquid oxygen for emergency use, regardless of manufactured quantities (Suran, 2022).

Liquid oxygen bulk delivery and oxygen gas cylinders are the primary methods of oxygen supply, however, Ghosh (2021) explains that PSA technology can also be considered as a viable option as it is clean technology and occupies minimal space. The initial set-up costs associated with

PSA plants are offset by the savings in monthly oxygen bills which arise from liquid oxygen bulk delivery and oxygen gas cylinder delivery methods (Ghosh, 2021). PSA technology can also face supply chain complexities. There is no comprehensive data on how much oxygen countries can get from PSA plants and oxygen concentrators (Davies & Furneaux, 2021), as it is challenging to calculate capacity when plants do not operate continuously (Davies & Furneaux, 2021).

Additionally, PSA technology requires a continuous, uninterrupted electrical supply (Ismail & Bansal, 2022). However, these complexities are far less compared to liquid oxygen and cylinder delivery systems. Bonnet et al. (2021) mention that PSA technology is a more environmentally beneficial form of oxygen therapy as there is no need to transport oxygen. Switching to PSA technology is thus an important step in the resilience discussion.

The maintenance of supply infrastructure is critical to oxygen supply. For liquid oxygen piping infrastructure used for PSA plant operation and delivery of gaseous oxygen, significant maintenance by highly trained technicians and engineers is needed (Smith et al., 2020). Maintenance of cylinders, although not expensive, must be conducted on a predetermined interval basis. Oxygen concentrators require some moderate maintenance by trained technicians. All technologies require maintenance, spare parts, and consumable replenishment (Smith et al., 2020). If preventative maintenance is ignored, environmental and cost burdens of oxygen supply infrastructure can increase. Liquid oxygen pipes can burst due to their extremely cold temperatures and may be unable to handle the increased oxygen demand due to COVID-19 (Rieger, 2020; Suran, 2022). These pipes have been designed for pre-pandemic times and, thus, lower volume requirements than were needed during the pandemic (Silverman, 2021). Aging infrastructure has caused a further burden on the oxygen supply. All these problems highlight the need for resilience to be strengthened in the medical oxygen supply chain. Environmental impact and resilience aspects both help build a sustainable health system.

Chapter 3 The need for this study

Oxygen production is an energy-intensive process. The low-temperature production and storage required for liquid oxygen require significant energy. Oxygen separation facilities can produce three times more nitrogen than oxygen, however, only 1.5 times more is usually produced, with the rest vented to air. Half the nitrogen produced is wasted, which results in waste of resources such as energy use. The wasted separation energy needs to be minimized (Shen & Wolsky, 1980). The study by Shen & Wolsky (1980) is more than 40 years old; however, the technology for oxygen production has not changed. Although there have been efforts to capture and sell nitrogen, efficiency and resilience issues are still very apparent in oxygen supply chains, as seen by the high volumes of waste in hospitals and disruptions in the COVID-19 pandemic. Sustainability in healthcare has only begun to receive more scrutiny over the last decade.

High electricity usage by ASUs can lead to increased environmental impacts in the oxygen supply chain, depending on where the electricity grid sources its energy from. Manenti et al. (2013) suggest optimizing the energy consumption in ASUs can help address sustainability targets and reduce costs. Their research assessed the effectiveness of an ASU by looking at parameters such as production capacity, product quality, and energy recovery/consumption (Manenti et al., 2013).

Both cryogenic distillation and PSA plant technology are energy-intensive and have high capital costs (Chong et al., 2016). Gizicki & Banaszkiewicz (2020) present a method of optimizing the performance of oxygen generation using PSA technology. The authors inform us that there are currently no energy optimization processes. Their findings showed that the energy consumption from PSA technology could be reduced by 40% while increasing the oxygen production capacity by 80%. This study highlights the importance of reducing energy use from oxygen production technologies.

Oxygen transportation requires a large amount of energy and cost incurrence. Oxygen plants are typically planned with complex supply systems, serving several industries in adjacent locations (Shen & Wolsky, 1980). Industrial gas suppliers may have storage points where cylinders and high-pressure gas transports can also be filled. There are many areas in which energy use and cost of transportation of oxygen can be optimized (Shen & Wolsky, 1980).

To control, manage and optimize the use of medical gases (including oxygen) in healthcare settings, Gómez-Chaparro et al. (2018) determined the consumption rate of medical gases. The authors present a case that optimizing the usage of medical gases, including oxygen, at the use phase can aid in forming a sustainable healthcare model. For instance, the maintenance and hospital pharmacy departments should both be responsible for monitoring mean medical gas consumption rates and identifying any technical failures (García Sanz-Calcedo & Monzón-González, 2014) or potential gas leaks or other equipment malfunctions (González et al., 2018). In the study by Gómez-Chaparro et al. (2018), the authors identify the issues for medical gases at the user end and identify potential solutions to overcoming waste and leaks, which leads to waste of resources and incurred costs for healthcare facilities. Additional studies at the user end are needed to inform healthcare facilities of the optimal use and waste of resources.

Liquid oxygen systems must be in constant use to be cost-effective. If the system goes unused for a while, the pressure increases as some liquid oxygen boils (Nini Malayaman et al., 2021). The oxygen is then vented into the atmosphere, which leads to medical oxygen waste; the energy, materials, and resources used to produce the wasted oxygen are also wasted. If oxygen can be produced on-site, it would reduce the evaporation effect in cryogenic tanks. The evaporation losses are estimated to be around ten percent (Gómez-Chaparro et al., 2018). Additionally, not all the oxygen may be inhaled by the patient based on the oxygen delivery device used. So, when oxygen is provided at a flowrate of 2 litres per minute (L/min) using a nasal cannula, for example, not all of it may be used.

The energy, cost and waste issues discussed herein present an opportunity to understand the environmental impact of different oxygen delivery methods. This knowledge can help create optimal solutions for an efficient, regular, cost-effective, and environmentally beneficial oxygen supply in the medical gas and healthcare industry.

There is currently one prior study that assesses and compares the environmental impacts of oxygen using different production routes by Bałys et al. (2021). This study is a gate-to-gate LCA focusing on oxygen needed in the COVID-19 pandemic. A more detailed environmental impact analysis would provide insight on the hotspots in oxygen’s life cycle and provide a more comprehensive comparison of the different pathways of oxygen delivery to a patient. Such an analysis would add to the growing body of literature on the LCA of medical oxygen and would be beneficial in contributing to sustainability studies of hospitals. LCA can assist hospitals with environmentally responsible decision-making when procuring medical gases. A more holistic picture of oxygen's life cycle will provide industrial gas specialists and healthcare settings with more knowledge. An LCA would identify energy, material, and energy use in each stage of oxygen's life cycle and assess potential impacts on water, air, and soil from the life cycle stages. It would also provide an opportunity to compare different purification processes, different modes of transportation, and storage methods. It is a step towards contributing to knowledge for a sustainable healthcare model.

This research uses LCA to model the environmental impacts of medical oxygen. We asked: What is the environmental impact of medical oxygen? The LCA follows the framework established by ISO 14040 (ISO, 2006). Chapter 4 presents the details of the four steps in an LCA. Chapter 5 presents the results of the LCA. Chapter 6 presents the discussion, which includes considerations for reducing supply chain risk, building resilient supply chains, and contribution to SDGs.

Chapter 4 Methods and Data

The LCA method was used to quantify environmental impact indicators of medical oxygen. The following sections follow the LCA framework of ISO 14040 (ISO, 2006).

4.1 LCA – Goal and Scope

The goal and scope of an LCA describe the intent of the study. The goal must include the following aspects: (1) the intended application, (2) the reasons for carrying out the study, (3) the audience, and (4) whether the results will be used in comparative assertions (ISO, 2006). ISO's scope requirements include 12 elements: (1) the product system under study, (2) the functions of the product system, (3) the functional unit, (4) the system boundary, (5) allocation procedures, (6) impact categories selected, (7) data requirements, (8) assumptions, (9) limitations, (10) data quality requirements, (11) critical review (if any), and (12) type of report for the study (ISO, 2006). All these elements are touched upon in some level of detail in this thesis.

4.1.1 Goal

The overall goal of the LCA study is to quantify the environmental impact of different pathways through which medical oxygen is delivered to a patient, considering multiple environmental indicators. The study looks at two basic technologies used for oxygen production: cryogenic distillation and pressure swing adsorption. It then considers four product systems (two for each technology) that include the production, distribution, and delivery of medical oxygen to a patient. More specific goals of the LCA are:

1. Identify environmental hotspots across the life cycle for the four product systems
2. Evaluate how oxygen production in different geographies impact the environment
3. Inform oxygen use decisions and management practices from an environmental impact perspective

The study has two sets of audiences. The first set are at the oxygen supply end, including manufacturers of medical oxygen and industrial gas suppliers. Results can inform this set on the environmental impact on different oxygen production technologies. The second set includes administrators in hospitals and healthcare professionals who use medical oxygen. Results may inform this audience which oxygen delivery route is more environmentally beneficial if they wish to understand the environmental impacts of their activities and reduce this impact.

4.1.2 Scope

The life cycle system of any product or service needs to be clearly defined, and assumptions need to be stated. In this section of the thesis, the two technologies used for the production of medical oxygen and the scale of these technologies is described. Then, the scope of the LCA is discussed.

4.1.2.1 System Description

Oxygen is produced using either of two basic technologies: cryogenic distillation or pressure swing adsorption (PSA). Each technology separates the components of air (78% nitrogen, 21% oxygen, and 1% other gases) to extract pure oxygen. However, the two technologies differ in their industrial scale and the physical state of the oxygen produced (liquid vs. gas).

Cryogenic distillation technology compresses air below -183 °C to separate liquid oxygen from other gaseous components in the air. The resulting liquid may be further purified to remove argon, giving a final liquid oxygen product purity of 99% or higher. This technology primarily serves heavy industries that use large volumes of oxygen -- particularly steelmaking and petrochemical production. Cryogenic distillation plants, known as air separation units (ASUs) can produce up to 4,700 cubic meters per day of liquid oxygen (equivalent to four million cubic meters of gaseous oxygen) (calculated from Linde Engineering (n.d.)) (Table 1). The liquid needs to be transported and stored at cryogenic conditions, at or below a temperature of -183 ºC.

Pressure swing adsorption (PSA) technology passes ambient air through a gas filtration system, such as a molecular sieve, to separate the oxygen from other components. The oxygen product is typically 93% purity and is in gaseous form. A PSA plant can produce gaseous oxygen up to 1,000 cubic meters of gaseous oxygen per day (calculated from AmCareMed (n.d.)) (see Table 1). PSA technology can also be applied at much smaller scales, allowing for on-site industrial plants sized to a specific user facility or as a very small-scale personal device known as an “oxygen concentrator” that delivers oxygen gas immediately to an individual patient. Oxygen concentrators produce oxygen at 1 to 10 L/min (CAIRE, Inc., n.d.) (see Table 1).

Table 1: Comparison of oxygen production units

Technology	Production unit	Oxygen purity	Scale (m^3 gaseous oxygen/day)	Scale (L/min of gaseous oxygen)
Cryogenic distillation	ASU	> 99 %	4,000,000	2,780,000
PSA	PSA plant	93%	1,000	694
	Oxygen concentrator		1.4 – 14	1 – 10

This study considers four product systems that can provide medical oxygen to a hospital bed. All systems assume an output delivery pressure of 50 psig for oxygen gas, the standard operating pressure in medical oxygen delivery systems (Lewarski & Volsko, 2016)

1. Product system 1 (liquid oxygen delivery): In this system, liquid oxygen is produced at an ASU and transported in bulk to a hospital. It is stored in an insulated vessel at a pressure of 85 psig. As needed, it is passed through a vaporizer to convert liquid to gas, and oxygen is piped through the building to use locations like a hospital bed. As mentioned in section 2.2.3, the pipeline is designed to support the pressure drop from 85 psig to an output delivery pressure of 50 psig. Most medical oxygen is delivered to patients using this system; therefore, this is the baseline system to which all other product systems will be compared based on consultation with Director of Supply Chain at The Hospital for Sick Children in Toronto (N. Dimovski, personal communication, February 23, 2022).
2. Product system 2 (cylinder delivery): Liquid oxygen is produced via cryogenic distillation and transported as a liquid to a regional "trans-fill" facility. The trans-fill facility is an intermediate location that allows temporary storage and transfers to smaller containers. At the trans-fill facility, liquid oxygen is converted to gas, filled into aluminum cylinders, and then transferred to vehicles for transportation to the patient or hospital location. The pressure of the oxygen gas in the cylinders is about 2000 – 3000 psig, which drops to an output delivery pressure of 50 psig.

3. Product system 3 (PSA plant): Gaseous oxygen is produced locally at a hospital site in a dedicated PSA plant. The oxygen produced is piped directly into the facility to a hospital bed. PSA plants can produce oxygen around 58 – 116 psig (Oxymat, n.d.) – again this drops to an output delivery pressure of 50 psig when piped to the hospital bed.
4. Product system 4 (oxygen concentrator): Gaseous oxygen is produced immediately beside the patient using a portable oxygen concentrator device providing gas for one patient. An oxygen concentrator can produce oxygen up to 50 psig, although lower output delivery pressures are more common (see section 2.2.3).

4.1.2.2 Function, Functional Unit, Key Parameters, and Reference Flow

The function of medical oxygen is to assist a patient in breathing. Supplemental oxygen is provided that is additional to regular breathing to a patient to achieve their minimum required oxygen blood saturation and to oxygenate a patient, as may be necessary to meet specific physical demands. Clinicians administer oxygen based on a measure of litres per minute (L/min), which would be adjusted depending on patient need. The functional unit for the LCA study is defined as one "oxygen bed day," which refers to gaseous oxygen provided to one bed in a hospital over one day (24 hours). An intermediate functional unit (i.e., one litre of gas) is also considered to provide a basis for comparison to other studies. A litre is a meaningful unit for healthcare professionals administering oxygen to the patient. Both units, oxygen bed day and litre, were chosen after consultation with a healthcare professional, as they could both be useful for patient needs based on bed occupancy or amount of oxygen needed (J. Sherman, personal communication, June 24, 2021). The reference flow is the amount of manufactured oxygen gas needed to satisfy the functional unit. A key parameter is the purity of the gas, which depends on the production technology. Another key parameter is the flow rate – 2 L/min was chosen (J. Sherman, personal communication, June 24, 2021). This flowrate is commonly required or used by patients in a normal situation. The flowrate can change based on individual patient needs (discussed further in section 4.4.1.2). Based on the oxygen purity, the flow rate needs to be adjusted (Table 2). The calculations assume no losses across the four product systems.

Table 2: Summary of key parameters and reference flow for one oxygen bed day as the functional unit

Product system	Key parameters	Reference flow	Notes for reference flow
1: Liquid oxygen delivery **2: Cylinder delivery**	Oxygen purity > 99% Flowrate – 2 L/min at 100% purity (2.02 L/min at 99% purity)	2.9 m^3 manufactured oxygen gas	2.02 L/min x 60 min/hour x 24 hours/day
3: PSA plant **4: Oxygen concentrator**	Oxygen purity = 93% Flowrate – 2 L/min at 100% purity (2.15 L/min at 93% purity)	3.1 m^3 manufactured oxygen gas	2.15 L/min x 60 min/hour x 24 hours/day

4.1.2.3 System Boundary

Life cycle stages, including the production and transportation of medical oxygen, are analyzed. The use of medical oxygen (i.e., medical procedures and equipment used to deliver the oxygen to the patient) is outside the scope of the study because of time and data limitations. The production and delivery of oxygen in Ontario, Canada was considered. This geography was chosen because it is the author’s location of residence and study. Additionally, Ontario is central to many major industrial processes and has access to advanced technologies and well-laid-out infrastructure. It is also assumed that the hospital for the study is located in Toronto, Ontario, a major metropolitan area in North America. The materials and energy needed to produce and deliver medical oxygen in all four product systems were considered. Infrastructure, capital, and maintenance activities were included in some systems based on data availability.

4.2 Life cycle Inventory (LCI)

This section of the thesis presents the data used for modelling the four product systems and describes key assumptions. The ecoinvent database (version 3.8) (*Ecoinvent - Life Cycle Inventory Database. Version 3.8*, 2021) and publicly available information on company websites for data sources were used. The most appropriate available geographical location available in ecoinvent was used. The data available were quite old in some cases; for example, the unit process on the cryogenic distillation process is from 1997. However, based on consultation with industry experts, the technology is still relevant and used today (A. Siddhantakar, personal communication, December 16, 2021). Other data quality indicators are shown in section 4.2.6. The product systems were modelled using the OpenLCA software. Transportation for all materials was considered.

4.2.1 Product system 1 – Liquid oxygen delivery

The raw materials for the ASU are air, electricity, and water (Figure 2). Data for this process were available in ecoinvent, wherein the infrastructure for the air separation plant is considered. Liquid oxygen was modelled as the output, and water as an elementary output flow. The inventory data used for the modelling is shown in Table 3. Liquid argon and liquid nitrogen are also produced in the air separation process. However, these two are treated as emissions. They are withdrawn from the air and released back (as oxygen-less air). Therefore, the two are not considered co-products of the air separation process. A sensitivity analysis was also conducted, where nitrogen and argon were considered co-products (see section 4.4.2.1).

The liquid oxygen was assumed to be produced in a plant in Sarnia, Ontario, around 260 km from Toronto (Table 3). The location was chosen because Sarnia is an industrial area where Linde Canada Inc. has a plant (Google, n.d.). Liquid oxygen is then transported to the hospital in a cryogenic truck. Transport of the empty truck back to the cryogenic facility is included in the ecoinvent model.

After the liquid oxygen arrives at the hospital, it is stored in a cryogenic tank, which is a vacuum-insulated vessel (Air Products and Chemicals, Inc., 2015). When oxygen is needed, it passes through an air-heated vaporizer and gas is piped directly to the hospital ward. No external energy is required to convert liquid oxygen into gaseous oxygen (Cryonorm B.V., n.d.). The infrastructure needed to store and deliver the oxygen (i.e., storage vessel, vaporizer, pipes, valves, pressure regulators) to the hospital ward was not considered in the LCI model because of lack of primary data and due to the assumption that the impacts from these would be minimal (Table 7).

Maintenance of the ASU was not considered. The liquid oxygen produced at an ASU for medical needs is very minute compared to its production for other markets, e.g., steelmaking. In addition, it is assumed that the infrastructure itself contributes very little to the life cycle impacts. Therefore, maintenance was assumed not to affect the result significantly. Moreover, infrastructure and energy associated with loading and unloading liquid oxygen were not considered (see Table 7).

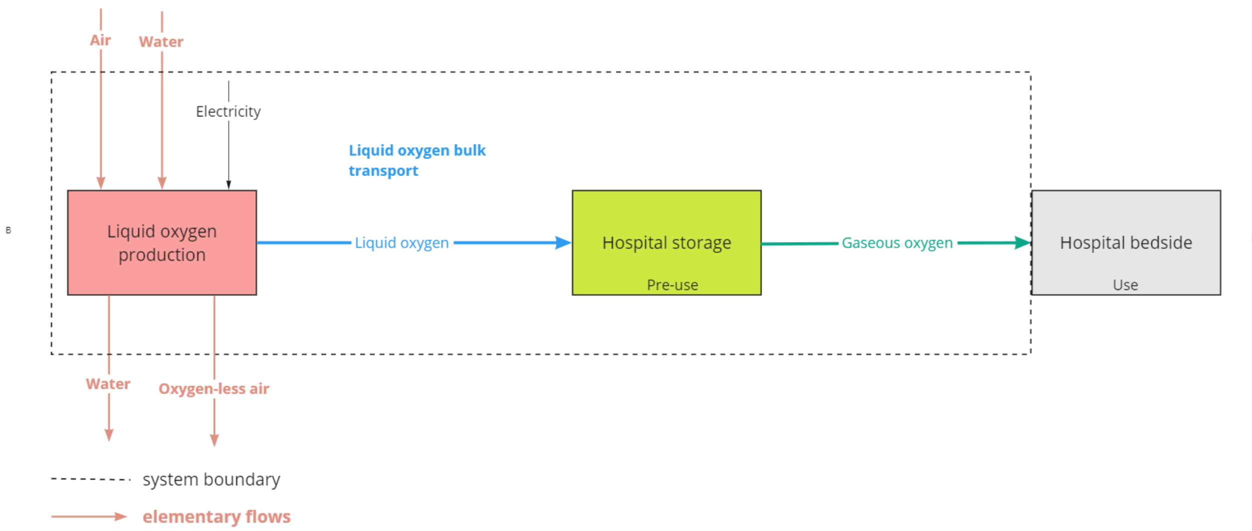

Figure 2: Flow diagram for product system 1 (liquid oxygen delivery)

Table 3: Assumptions and dataused for modelling product system 1 (liquid oxygen delivery) per oxygen bed day

Process	Assumptions and data
Liquid oxygen production (at an ASU in Sarnia, ON)	
Inputs	• Electricity: 1.42 kWh/1 kg liquid oxygen produced
Outputs	• Liquid oxygen: 3.38 L/oxygen bed day (3.86 kg/oxygen bed day)
Other inputs and outputs taken from *Ecoinvent - Life Cycle Inventory Database. Version 3.8* (2021) and listed in Appendix A	
Liquid oxygen bulk transport (from the ASU in Sarnia, ON, to a hospital in Toronto, ON)	• Transport lorry size class > 32 metric tons gross vehicle weight (GVW) • Distance: 260 km

	• Liquid oxygen transported: 3.86 kg/oxygen bed day • Mass transported over a unit of distance = 1,000 kg-km
Gaseous oxygen to hospital bedside	• No external energy required in vaporizing liquid oxygen to gaseous oxygen

4.2.2 Product system 2 – Cylinder delivery

The oxygen production process for product system 2 is the same as product system 1. However, liquid oxygen is transported to a trans-fill facility where oxygen is distributed (Figure 3). The distance from the ASU to the trans-fill facility was assumed to be 260 km (similar to product system 1). The trans-fill facility was assumed about 90 km from Toronto, near locations such as Guelph or Stoney Creek, ON where industrial oxygen is used in a wide variety of industrial plants and factories.

Liquid oxygen is converted to gaseous form at the trans-fill facility, pressurized, and filled into cylinders at around 2000 psig (Air Liquide Healthcare Canada, n.d.). The conversion of liquid to gas uses an air-heated vaporizer that does not require external energy (Cryonorm B.V., n.d.). A pump is used to raise the pressure of oxygen and the work needed for the pump was calculated using the formula provided in Table 4. An electric water pump operation for a 22-kilowatt (kW) pump from the ecoinvent database was used as a proxy. The inputs to the process are electricity from the electricity grid in Ontario. The pump's infrastructure and maintenance activities were already modelled in the database. Infrastructure for cylinder filling, such as valves, piping, and pressure regulators, was omitted (see Table 7). Cylinders are transported from the trans-fill facility to the hospital.

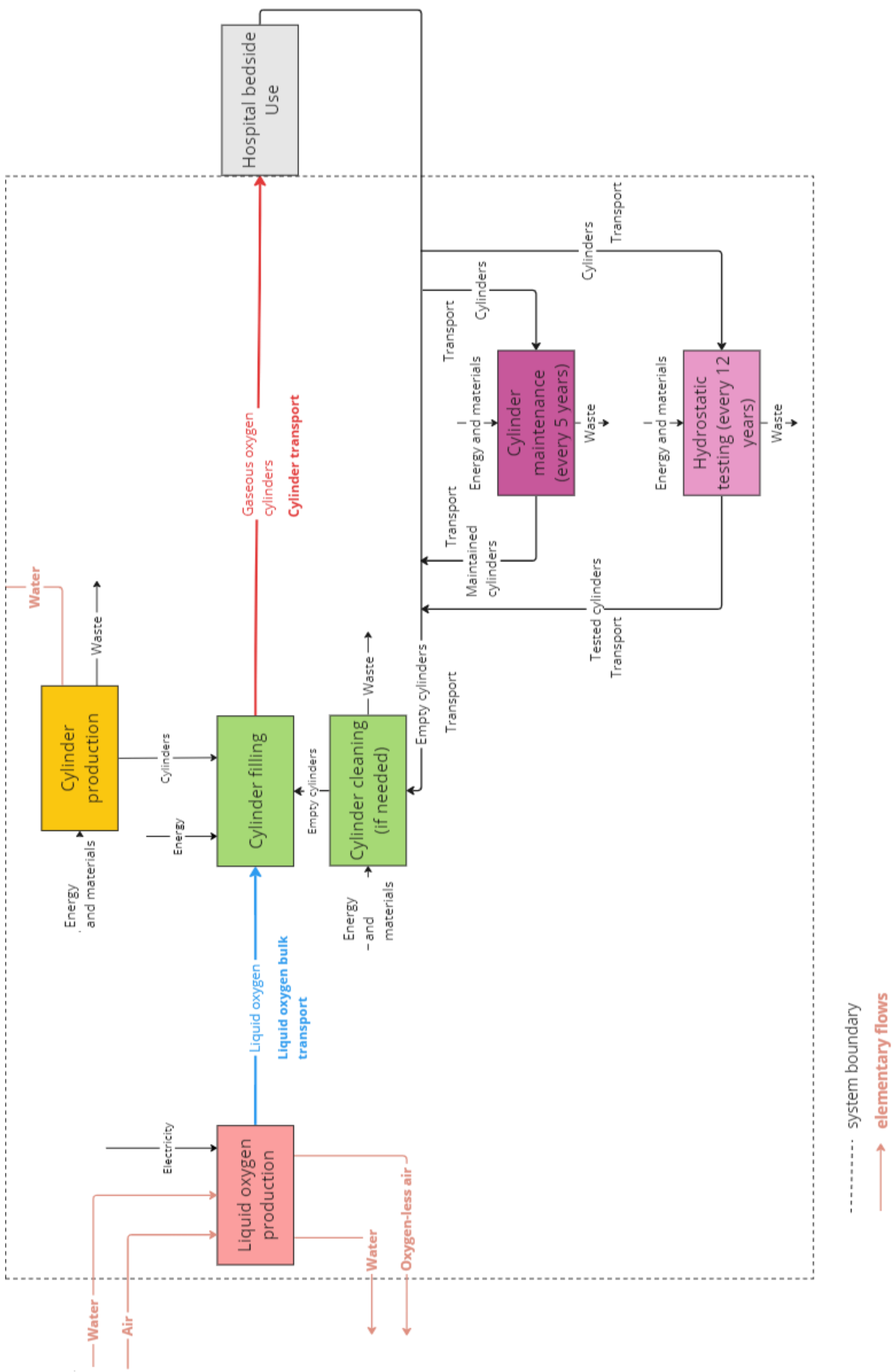

Figure 3: Flow diagram for product system 2 (cylinder delivery)

Cylinder production, cleaning and maintenance were included in the modelling, as these form an essential part of the process. Cylinders are used and reused over many years. An aluminum cylinder is considered, as it is lightweight and most used for the storage of medical gases (Air Liquide Healthcare Canada, n.d.). The cylinder's life is 15 years (ABC Fire & Safety Equipment Ltd., n.d.; Government of Canada, 2019), which gives 390 uses for one cylinder over the 15 years (Table 4). Cylinder production processes included deep drawing, pressing, tempering, cutting, carving threads, cleaning, and painting (DSCDocumentries, 2012). Instead of modelling these processes, a hot water tank production process was used from the ecoinvent database. This process was modified to suit the needs of the production process of an aluminum cylinder. Inputs included in the process were aluminum alloy with magnesium, electricity, heat, water, welding, and paint (Figure 4). Infrastructure for the cylinder production facility was considered. Outputs considered were wastewater and water (see Table 4 for LCI). The disposal of the aluminum cylinder was considered (see Table 7).

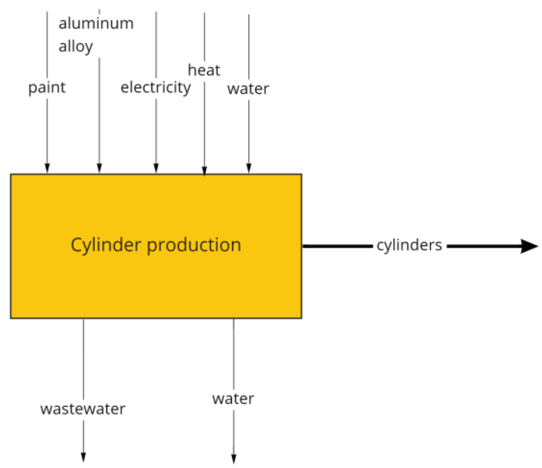

Figure 4: Inputs and outputs considered for cylinder production

It was assumed that ten percent of the cylinders need cleaning after use (based on industry expert consultation). In this study, cylinder cleaning involves washing the cylinder internally and externally with detergent and warm water (Catalina Cylinders, n.d.). Electricity was considered for: (1) a water pump used for high-pressure water, (2) a compressor used for providing compressed air for drying, and (3) a conveyor belt onto which the cylinder would be placed and cleaned. Cleaning happens at the trans-fill facility before the cylinders are filled. Figure 5 shows the inputs and outputs considered for cylinder cleaning. The equipment used for the cleaning was not included in the modelling.

Cylinder maintenance activities were considered. Each cylinder is visually inspected every five years (Compressed Gas Association, Inc., 2019). Inspection involves examining markings, corrosion limits, cuts, digs and gouges, wall loss, dents, leaks and holes, bulges, fire and thermal damage, neck defects, threads and valving etc. (Compressed Gas Association, Inc., 2019). Activities included in the modelling were the removal of corrosion and old paint and re-painting of the cylinder (Figure 6), as these were assumed to require materials or energy. A scraper is used for removing corrosion. Paint is removed from aluminum cylinders by using paint strippers instead of the traditional sandblasting technique for steel cylinders (Catalina Cylinders, n.d.). Paint strippers contain dichloromethane, found in the ecoinvent database and were used as an input. Transportation to and back from the trans-fill facility was also considered. Equipment and tools used for maintenance were not included in the modeling.

Additionally, the cylinders are hydrostatically tested every twelve years to test for strength and leaks (U.S. Government Publishing Office, 2018). The test is conducted using the water jacket method, in which the cylinder is filled with water and placed inside a water-filled test chamber (a test jacket). The cylinder is then pressurized, and the water volume displaced by the vessel's expansion is measured (under-pressure expansion) (The Precision Companies, 2019). The cylinder is then depressurized and shrinks to its original approximate size (permanent expansion). The difference between the two expansion states determines the cylinder's fitness for continued use. Figure 7 and Table 4 show the inputs and outputs considered for modelling. Transportation to and back from the test facility was also considered. The water jacket apparatus was not included.

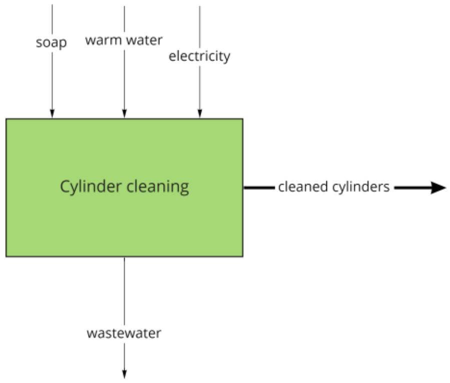

Figure 5: Inputs and outputs considered for cylinder cleaning

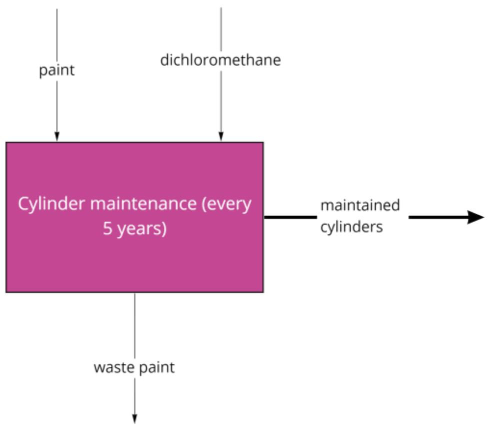

Figure 6: Inputs and outputs considered for cylinder maintenance

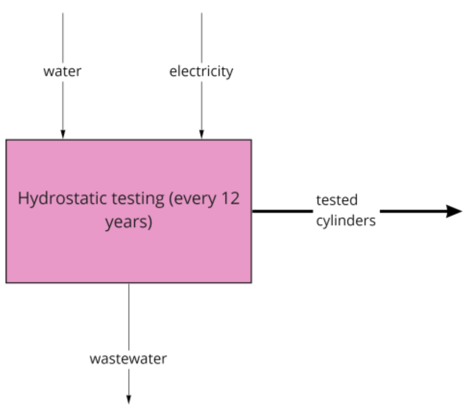

Figure 7: Inputs and outputs considered for hydrostatic testing of cylinders

Table 4: Assumptions and data used for modelling product system 2 (cylinder delivery) per oxygen bed day

Process	Assumptions and data
Liquid oxygen production (at an ASU in Sarnia, ON)	• Same as product system 1
Liquid oxygen bulk transport (from the ASU in Sarnia, ON, to a trans-fill facility)	• Distance: 260 km • Other inputs same as product system 1
Cylinder filling	
Inputs	• Vaporizing of liquid oxygen to gaseous oxygen: No external energy required • Energy required by pump to raise oxygen gas pressure to 2000 psig: 0.314 kWh/oxygen bed day • Cylinders: 0.0110 cylinders/oxygen bed day
Outputs	• Gaseous oxygen cylinders: 30 E cylinders delivered once every week (4.29 cylinders/oxygen bed day)
Cylinder transport (from a trans-fill facility to a hospital in Toronto, ON)	• Transport lorry size class 7.5 – 16 metric tons GVW • Distance: 90 km • One E aluminum cylinder carries 690 L of oxygen and weighs 3.54 kg (Air Liquide Healthcare Canada, n.d.) • Mass transported over a unit of distance = 1,540 kg-km
Cylinder production	
Inputs	• Taken from *Ecoinvent - Life Cycle Inventory Database. Version 3.8* (2021) and listed in Appendix A
Outputs	• Life of a cylinder: 15 years (based on expert consultation and web sources) • Number of re-uses over lifetime: 390 per cylinder • Cylinders: 0.0110 cylinders/oxygen bed day
Cylinder cleaning	

Inputs	• For one cleaning session per cylinder:
	  ○ Electricity: 1.19 kWh
	  ○ Warm water: 4.8 kg
	  ○ Soap: 0.0193 kg

Outputs	• For one cleaning session per cylinder: ○ Wastewater: 0.0048 m^3 • Cleaned cylinders: 0.429 cylinders/oxygen bed day

Cylinder maintenance	

Inputs	• For one maintenance session per cylinder:
	  ○ Paint: 0.0433 kg
	  ○ Dichloromethane (paint remover): 0.217 kg
	  ○ Cylinder transport distance to the cleaning facility: 20 km

Outputs	• For one maintenance session per cylinder: ○ Waste paint: 0.0433 kg • Maintained cylinders: 0.00237 cylinders/oxygen bed day
Hydrostatic testing	

Inputs	• For one testing session per cylinder:
	  ○ Electricity required by the test system: 5.44 kWh
	  ○ Water: 106 L
	  ○ Cylinder transport distance to the testing facility: 20 km

Outputs	• For one testing session per cylinder: ○ Wastewater: 0.106 m^3 • Tested cylinders: 0.00164 cylinders/oxygen bed day

4.2.3 Product system 3 – PSA plant

The PSA plant requires two inputs: air and electricity (Figure 8). The infrastructure of the PSA plant was not considered (see Table 7). Limited data was available for this, and infrastructure generally led to a small contribution of life cycle impacts in other product systems, such as for the ASU. Moreover, it is general practice in LCA not to include infrastructure. For the liquid oxygen delivery system above, infrastructure was already modelled in the ecoinvent database; therefore, it was included. The PSA plant was assumed to be at the hospital site and provided a reliable source of gaseous oxygen.

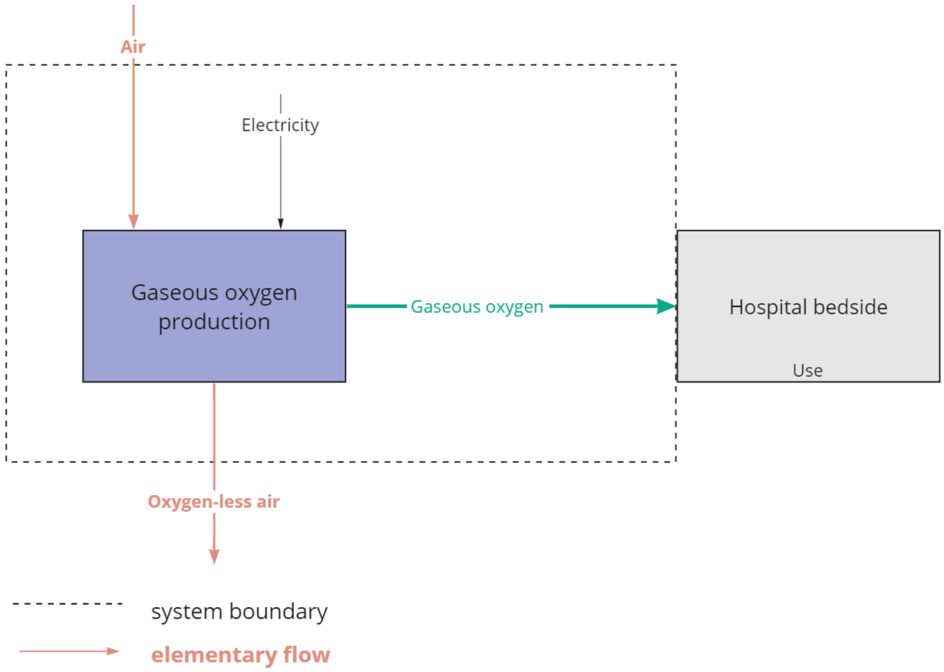

Figure 8: Flow diagram for product system 3 (PSA plant)

Maintenance activities of the plant were considered. Of note is that air separation facility maintenance is not included in product systems 1 and 2. The maintenance of PSA technology is more significant than an air separation facility and was therefore included. Maintenance of the PSA plant includes replacing filters, draining water and oil traps, and replacing the zeolite adsorbent (Figure 9). The following items were found in ecoinvent and used as maintenance inputs: air filter, ultrafiltration module, and zeolite powder. Waste from these activities includes waste filters, waste oil traps, water, waste lubricants, and waste zeolite. Disposal of these waste items was considered (see Table 5 for LCI).

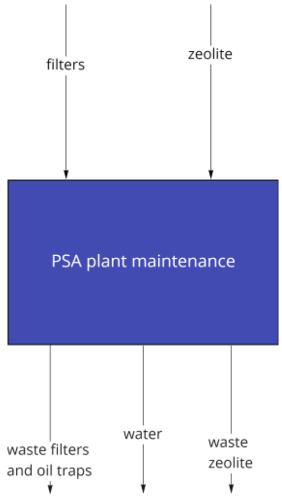

Figure 9: Inputs and outputs considered for PSA plant maintenance

Table 5: Assumptions and data used for modelling product system 3 (PSA plant) per oxygen bed day

Process	**Assumptions and data**
Gaseous oxygen production (in a PSA plant set up at a hospital in Toronto, ON)	
Inputs	• For the chosen PSA plant[2]: ○ Production capacity: flowrate of 78.9 – 97.3 Nm^3/hour and an output pressure of 65 psig ○ Electricity required: 1.22 kWh/Nm^3 ○ Oxygen gas produced: 2,510 m^3 per day
Outputs	• Gaseous oxygen: 3.10 m^3/oxygen bed day
PSA plant maintenance	• PSA plant allocation: 0.000137 items/oxygen bed day
Inputs	• Life of a PSA plant: 20 years

[2] Nm^3 refers to normal cubic metres – it means the volume of oxygen gas at normal conditions, at a temperature of 0 °C and a pressure of 14.7 psia. It is a common unit used in industry.

	• Pre-filter and coal filter change: required every 2,000 hours; 176 total filters needed over lifetime • Coalescing filter change: required every 8,000 hours; 22 filters needed over lifetime • Replacement of zeolite: required every 10 years; 2,790 kg needed over lifetime
Outputs	• Waste filters and oil traps: 198 items over lifetime • Waste zeolite: 2,790 kg over lifetime • Water: 12.0 m^3 per day

4.2.4 Product system 4 – Oxygen concentrator

The oxygen concentrator, which also uses PSA technology, was modelled similarly to product system 3 with air and electricity inputs (Figure 10). An oxygen concentrator produces oxygen on a much smaller scale than a PSA plant, and generally at lower pressures i.e., 5 – 20 psig (see section 2.2.3). However, to make a fair comparison to the other product systems in this study, an oxygen concentrator with an output pressure of 50 psig is chosen. Data were gathered through expert consultation (J. Klein, personal communication, November 24, 2021). The concentrator is placed by the patient's bedside, and gaseous oxygen is supplied to the patient directly. The infrastructure of the oxygen concentrator was not considered (see Table 7).

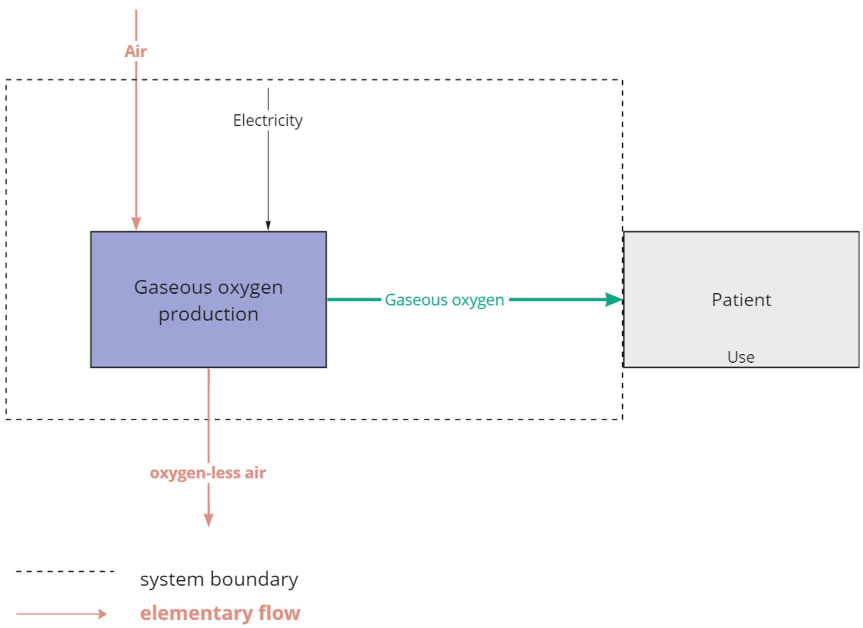

Figure 10: Flow diagram for product system 4 (oxygen concentrator)

Maintenance was considered and requires replacing air filters and cleaning the gross particle filter with water. The following items were found in ecoinvent and used as maintenance inputs: air filter and water (Figure 11). The following are outputs: waste filters and wastewater (see Table 6 for LCI).

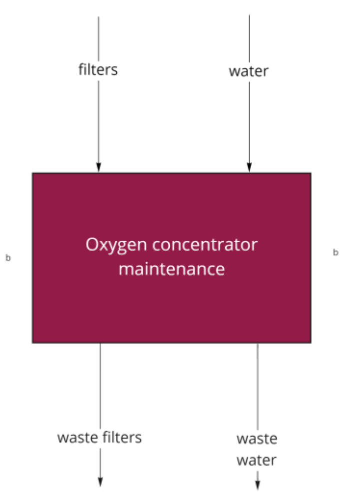

Figure 11: Inputs and outputs considered for oxygen concentrator maintenance

Table 6: Assumptions and data used for modelling product system 4 (oxygen concentrator) per oxygen bed day

Process	Assumptions and data
Gaseous oxygen production (from an oxygen concentrator by a patient's bedside)	
Inputs	• For the chosen oxygen concentrator: ○ Production capacity: flowrate of 8 L/min and an output pressure of 50 psig ○ Electricity: 1.8 kWh/Nm^3 ○ Oxygen gas produced: 11.5 m^3 per day
Outputs	• Gaseous oxygen: 3.10 m^3/oxygen bed day
Oxygen concentrator maintenance	• Oxygen concentrator allocation: 0.000548 items/oxygen bed day
Inputs	• Life of an oxygen concentrator: 5 years • Air filter change: required every 2 years; 3 filters needed over lifetime • Water required for filter cleaning: 240 L over lifetime
Outputs	• Waste filters: 3 over lifetime • Wastewater: 240 L over lifetime

Table 7: What's in scope in the life cycle modelling of the four product systems

Product system(s)	Life cycle stage	What's considered	What's omitted
Liquid oxygen delivery, cylinder delivery	Liquid oxygen production	• Inputs to the ASU • Outputs from the ASU • ASU infrastructure	• Maintenance of the ASU • Equipment and materials for medical oxygen testing

Liquid oxygen delivery, cylinder delivery	Liquid oxygen transportation	• Transport lorry with refrigeration system (including complete life cycle) • Transportation to and back from the ASU	• Loading, unloading and storage of liquid oxygen (including infrastructure required)
Cylinder delivery	Cylinder filling	• Pump electricity • Pump infrastructure and maintenance	• Infrastructures such as valves, piping, and pressure regulators
Cylinder delivery	Cylinder transport	• Transportation lorry (including full-life cycle) • Transportation to and back from the trans-fill facility	
Cylinder delivery	Cylinder production	• Inputs, i.e., materials and energy use • Outputs of production • Infrastructure for a cylinder production facility • Cylinder disposal	
Cylinder delivery	Cylinder cleaning	• Inputs, i.e., materials and energy use • Outputs i.e., wastewater	• Infrastructure/ equipment
Cylinder delivery	Cylinder maintenance	• Inputs, i.e., materials use • Outputs i.e., waste paint/removed corrosion waste	• Infrastructure/ equipment
Cylinder delivery	Hydrostatic testing	• Inputs, i.e., materials and energy use • Outputs i.e., wastewater	• Infrastructure/ equipment
PSA plant	Gaseous oxygen production	• Inputs to PSA plant • PSA plant maintenance	• PSA plant infrastructure • Equipment and materials for medical oxygen testing
Oxygen concentrator	Gaseous oxygen production	• Inputs to oxygen concentrator • Oxygen concentrator maintenance	• Oxygen concentrator infrastructure • Equipment and materials for medical oxygen testing

4.2.5 Summary of assumptions

Specific infrastructure, maintenance and ancillary activities in the product systems were not considered (Table 7). Assumptions were made that these items would not significantly alter the results. Although certain items, such as aluminum alloy from aluminum cylinder production and pump infrastructure, have notable contributions, maintenance activities were assumed not to affect the results. Given these findings, results should be interpreted carefully. Certain omitted infrastructure and ancillary activities may add burdens to the environmental impacts of medical oxygen.

Additionally, a number of assumptions were made during data modelling. These include: (1) collection and re-filling of empty cylinders occur at the hospital every week – in reality, this frequency may be more or less; (2) power rating and flowrate rating of certain equipment; and (3) use of oil-free compressor in the PSA plant because they are easier to maintain for obtaining high purity gas. Here, it is worth noting that a sensitivity analysis not conducted for certain items. For example, if a sensitivity analysis were conducted for changing the frequency of cylinder collection, re-filling and cleaning, it would not change the results significantly. Although the cylinders would be re-used on more occasions, thereby reducing the number of items allocated to one oxygen bed day, cylinder transportation would increase significantly in the modelling. The overall results would not change. Also, increasing the number of uses of cylinders would reduce their life. These assumptions would mean allocating more new cylinders to one oxygen bed day, which would not have a meaningful effect on the overall results. All assumptions and their rationale are listed in Appendix A. Assumptions may affect the results.

4.2.6 Data quality

Liquid oxygen production

The model in ecoinvent for the ASU was taken from producers in Europe, U.S., and Russia, as well as from publications from Smith & Klosek (2001) and Althaus et al. (2007). Temporally, the data were from 1997 to 2021. The technology has not changed since then, so this data applies to this LCA study. Moreover, this dataset was modified to include electricity from Ontario.

Transportation

Data from the ecoinvent database for a transport lorry for liquid oxygen and cylinder transport were used. The technology the lorries are classified using the European emission standards, as Euro VI. The datasets included the entire transport life cycle, i.e., construction, operation, maintenance, and end of life of vehicle and road infrastructures. Transport included the input of fuel, road, and vehicle infrastructure for average European journeys. The datasets included exhaust and non-exhaust emissions. Temporally, the datasets were from 2009 to 2021.

Pump for raising the pressure of oxygen gas

The technology for pumps in the ecoinvent database was considered the average and recent technology for electric water pumps.

Aluminum cylinder production

As mentioned previously, a hot water tank in ecoinvent was modified and used for modelling. Data for the hot water tank production was from 1993 to 2021. The materials being used were compiled in 1993 and the energy in 2001.

4.3 Life cycle impact assessment

The life cycle impact assessment (LCIA) method used was TRACI 2.1 (the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts). This method was developed by the U.S. Environmental Protection Agency (EPA) and provided a sophisticated and comprehensive method for quantifying stressors. The method translates the LCI into midpoint indicators categories – which focus on the environmental problem, such as ozone depletion, global warming, acidification, eutrophication, photochemical smog formation, human health particulate effects, human health cancer, human health noncancer, ecotoxicity, and fossil fuel depletion effects, applicable to the United States (U.S. EPA, n.d.). These impact categories can then be translated into endpoint or damage categories – which show how much damage a particular process has caused – such as harm to human health. This process is called characterization and is a mandatory step in LCA. Characterization uses weighting factors to translate the mass of chemicals emitted to a media (e.g., air, water, soil) into the potential impacts of the chemicals (U.S. EPA, n.d.). The generalized equation used to calculate the potential impacts of the modelled processes and flows is as follows (U.S. EPA, n.d.):

$$I^i = \sum_{xm} CF_{xm}^i \times M_{xm}$$

Where: I^i = the potential impact of all chemicals (x) for a specific impact category of concern (i)

CF_{xm}^i = the characterization factor of chemical (x) emitted to media (m) for impact category (i)

M_{xm} = the mass of chemical (x) emitted to media (m)

TRACI 2.1 is also limited in that it does not have an assessment for land use and water use metrics. Normalization – transforming the results by a selected reference value, and weighting – converting indicator results using numerical weighted factors (ISO, 2006), are an optional step in LCA, and are not comprehended in TRACI 2.1. This method was chosen because it is most relevant to North America, the geographical area assessed in this study.

Six impact categories were chosen for the LCIA: global warming potential (GWP), fossil fuel depletion, carcinogens, non-carcinogens, respiratory effects, and ecotoxicity. Each category represents an emission to air, water, or soil and assesses the damage to the atmosphere, human health, or the ecosystem. GWP was chosen because global warming is a relevant indicator in our society and measures how much a particular activity or process contributes to global climate change. It calculates emissions to the air. Fossil fuel depletion provides an assessment for resource use. Three human health indicators were chosen, i.e., carcinogens, non-carcinogens, and respiratory effects. These estimate how much life cycle activities contribute to human toxicity (based on emissions to air, water, and land). Ecotoxicity assesses environmental burdens on the ecosystem. The respiratory effects category calculates emissions to the air, whereas the carcinogens, non-carcinogens, and ecotoxicity categories calculate emissions to urban air, nonurban air, freshwater, seawater, natural soil, and agricultural soil.

4.4 Life cycle interpretation

Scenario analysis and sensitivity analysis were also conducted to better understand the life cycle impact assessment results.

4.4.1 Scenario analysis

Scenario analysis postulates how different circumstances or sequence of activity can affect the potential environmental burden of the product system. Scenario analyses were conducted here to assess how parameters of geography and gas flowrates can affect results. The geography parameter was chosen to meet the LCA goal of evaluating how oxygen production in different geographies impact the environment. The gas flowrate parameter was chosen to help inform oxygen use decisions and management practices from an environmental impact perspective.

4.4.1.1 Considering different locations around the world

The location chosen for the analysis above is Ontario, which has a relatively clean[3] electricity grid. Ontario's electricity comes from relatively clean sources of energy: 72% comes from nuclear, hydro, wind, biofuels, and solar sources (IESO, 2022). Other locations in the world where oxygen is produced may not have such a clean electricity grid. Three other locations are considered: Delaware, U.S.; Great Britain; and China. The electricity grid in the Delaware state of the U.S. sources 90% of its electricity from natural gas (U.S. Energy Information Administration, n.d.). In Great Britain, 45% of national grid electricity comes from non-renewable forms of energy and 49% from clean sources (e.g., wind, nuclear etc.) (National Grid ESO, n.d.). In China, 80% of the grid electricity comes from fossil fuels, i.e., oil, liquid natural gas, and coal in 2019 (IEA, n.d.). Additionally, Canada and U.S. are also considered for analysis to get an idea of the average national result. For instance, Ontario's electricity grid is much cleaner than Canada's average electricity grid. While Ontario relies largely on nuclear energy, provinces such as Alberta rely on natural gas and coal, which increases Canada's overall electricity grid emissions factor. Oxygen production in Ontario versus other parts of Canada would vary significantly in terms of the carbon intensity of the electricity grid.

Electricity from non-renewable sources of energy i.e., coal, oil, and natural gas, are known to lead to more environmental burdens compared to renewable sources of energy. This scenario considered how the results would change if oxygen were produced in Delaware in the U.S., Great Britain, and China. The analysis was done for liquid oxygen delivery (which includes liquid oxygen

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[3] Clean means a low GWP indicator result. Other environmental impact categories are not considered when mentioning clean energy.

production using cryogenic distillation technology and liquid oxygen transportation), and gaseous oxygen production (using PSA technology). It is assumed that the average distance from an industrial area (where an ASU is located) to the city (where a hospital is located) in North America is 260 km, as used in this study. It is also assumed that the distance in Great Britain and China is 175 km (CEIC, n.d.). These distances are used to model the liquid oxygen transportation in these geographies.

4.4.1.2 Flowrates

Patients requiring oxygen therapy may need oxygen at a different flow rate than the one used in this study, i.e., 2 L/min. Medical practitioners may need to adjust the oxygen depending on their medical condition. Standard use of medical oxygen is below 5 litres/minute (L/min) – more commonly around 2 L/min (*Oxygen Therapy*, n.d.; Suran, 2022). However, a patient with COVID-19 can require up to 60 L/min (Nishimura, 2015; Suran, 2022), which is delivered using high-flow oxygen delivery devices (see section 2.2.3). In this scenario, patients requiring oxygen at a lower flow rate, i.e., at 0.5 L/min or a higher flow rate, i.e., at 5 L/min, 10 L/min, and 60 L/min were considered.

4.4.2 Sensitivity analysis

A sensitivity analysis was conducted to see how methodological factors affect results. The variables considered here are co-product allocation of the ASU,a second impact assessment method, and a considering a different pump for cylinder filling.

4.4.2.1 Co-production allocation for the ASU

In the baseline system, nitrogen and argon are assumed to be released as emissions from the ASU. However, in some operations, these gases are captured and used commercially. If nitrogen and argon were considered co-products of the air separation process, and allocation would be needed (ISO, 2006). Two allocation methods could be used: (1) molar-based allocation and (2) economic-based allocation. In the molar-based allocation, the results of the environmental indicator impacts will be split three-ways based on the molar composition of air: 78% nitrogen, 21% oxygen and 0.9% argon. All three components are separated and purified at different temperatures and times and use different amounts of electricity. In the economic-allocation method, the cost value of each of selling each of the three products of the ASU can be used to translate into an estimated environmental impact (by multiplying the value with an emissions factor). However, this method may not be accurate as oxygen is sold and used much more than nitrogen or argon. Even through the quantity of nitrogen is more on a molar basis (78% nitrogen vs 21% oxygen), less revenue may be associated with it, which may not give an accurate number for calculated environmental impact. This sensitivity analysis considers how the results could theoretically change if a molar-based allocation method were used. The results are presented in section 5.4.1.

4.4.2.2 Impact assessment method

Two additional impact assessment methods were used to compare the results of this LCA study. IMPACT 2002+ is a commonly used LCIA method amongst LCA experts, particularly in Europe. This method was chosen to see how results from TRACI 2.1 (a North American method) would compare to IMPACT 2002+. The IMPACT 2002+ methodology utilizes the mid-point/damage-oriented approach (Jolliet et al., 2003). The midpoint occurs between the LCI results and the endpoint (which is the damage caused). Several midpoint impact categories are considered: Human toxicity, Respiratory effects, Land occupation, Ozone layer depletion. This method states midpoint characterization results in kg-equivalents of a substance (Jolliet et al., 2003). Midpoint categories point to an endpoint or damage category. For example, the midpoint category, Global Warming, points to the damage category of Climate change (Jolliet et al., 2003). The midpoints are converted to an endpoint using a formula. Several other midpoint categories point to damage categories of human health, ecosystem quality, and resources. For this study, the following midpoint categories were considered to provide a comparison for the LCA: Global warming, Non-renewable energy, Human toxicity, Respiratory effects, and Aquatic ecotoxicity.

Certain other LCIA methods are recommended for specific midpoint damage categories. USEtox is the industry-recommended method for human toxicity assessments. The model is endorsed by United Nations Environment Programme (UNEP) and is in full compliance with science-based criteria (European Commission et al., 2011). USEtox combines the environmental distribution, fate, human and ecosystem population exposure, and toxicity-related effects associated with the exposure, into a characterization factor (Fantke et al., 2017). These factors are then used to model the midpoint LCA results (Fantke et al., 2017). Human toxicity – cancer, human toxicity – non-cancer, and freshwater ecotoxicity indicators, the full list of midpoint indicators presented by this method, were considered to compare the results.

4.4.2.3 Using a different pump for cylinder filling

In the original calculations for the cylinder delivery system (system 2), a 100-horsepower (hp) or 75-kW pump was used to raise the pressure of oxygen gas to 2000 psig for storage in high-pressure cylinders (Gardner Denver, n.d.). The flowrate of filling was 530 m^3/hour. It was assumed that a high-power pump would be used at a regional trans-fill facility, where a large number of cylinders would be filled. Since the author's knowledge of equipment used at a trans-fill facility is limited, a sensitivity analysis was conducted to see if a smaller-sized pump with a lower-rated flowrate would yield different results. Moreover, as pointed out in section 5.1 of this thesis, the contributions from cylinder filling (using a 75 kW and 530 m^3/hour pump) were significant. In this case, a 40 hp or 30 kW pump was assumed, with a flowrate of 132 m^3/hour for cylinder filling, to raise the pressure of oxygen gas to 2000 psig (Made-in-China.com, n.d.).

Supplementary Content

See Appendix A for full LCI.

Chapter 5 Results

This section of the thesis presents the results pertaining to goals set for the LCA. Here and in section 5.1, the environmental impacts of the four different pathways through which medical oxygen is delivered to a patient are presented. The environmental hotspots for the four different product systems are also highlighted. Section 5.2 presents the results for environmental indicators per litre of oxygen, which is an interim functional unit considered (see section 4.1.2.2). Section 5.3 presents the results for scenario analysis which meets goals two and three discussed in section 4.1.1. Finally, section 5.4 presents the results for sensitivity analysis, where variables that may have contributed to hotspots are changed to see the difference in the results.

First, the results for the four product systems for the six impact categories assessed i.e., global warming potential (GWP), fossil fuel depletion, carcinogens, non-carcinogens, respiratory effects, and ecotoxicity are presented. Liquid oxygen delivery, the baseline system, produces 0.494 kg CO_2eq in the GWP category, 0.895 MJ surplus in the fossil fuel depletion category, 6.22×10^{-8} CTUh in the carcinogens category, and 2.09×10^{-7} CTUh in the non-carcinogens category, 2.80×10^{-4} PM 2.5-eq in the respiratory effects category, and 15.3 CTUe in the ecotoxicity category, per oxygen bed day.

In all indicator categories assessed, the cylinder delivery system (product system 2) shows the highest potential environmental burdens across all indicators, followed by the liquid oxygen delivery, oxygen concentrator, and PSA plant systems. When comparing across all product systems, liquid oxygen production is the largest contributor of calculated impacts to almost all indicator categories. For example, liquid oxygen production contributes 0.405 kg CO_2eq per oxygen bed day to GWP, making up >80% of the liquid oxygen delivery system (product system 1) value. The electricity used in liquid oxygen production (from the operation of the ASU – liquefaction of air) drives the results and is a hotspot. In the cylinder delivery system (product system 2), several activities are additional to liquid oxygen production, necessary to provide gaseous oxygen delivery. Thus, in system 2 the second highest GWP impacts come from cylinder transportation, at 0.343 kg CO_2eq, a second hotspot. Gaseous oxygen production from the oxygen concentrator (system 4) also had notable environmental indicator values, especially when compared across all four product systems – at 0.381 kg CO_2eq for GWP, per oxygen bed day, with >99% of this value attributed to electricity usage (see Figure 12), another hotspot This GWP number is quite close to the liquid oxygen production GWP number. Oxygen concentrators are useful as personal devices, compared to bulk production of oxygen, which can be more suitable for a large group of patients. Oxygen concentrators are not as efficient as the ASU or PSA plant.

Cylinder transport in the cylinder delivery system contributes significantly to the results in that system, particularly for GWP, fossil fuel depletion and respiratory effects categories, at 29%, 36% and 20% of the total, respectively. The reason cylinder transport contributes more to the calculated environmental impacts compared to liquid oxygen transportation is because the cylinders require more trips, as they carry gas, not liquid, to deliver the same quantity of oxygen – gaseous volume of oxygen is greater than liquid volume for the same mass of oxygen. Moreover, the mass of each cylinder exceeds the mass of the gaseous oxygen contained. The diesel fuel used in the cylinder transport truck drives the results. A smaller truck (truck of GVW 7.5 – 16 ton) was assumed for modelling of cylinder transport (see Table 4). A larger truck is more efficient (and carries more material) compared to a smaller truck, as was used for liquid oxygen delivery (system 1). A difference in results between liquid oxygen transport and cylinder transport is thus apparent – a larger truck has a much lower contribution to environmental impact categories compared to a smaller truck.

Some infrastructure-related considerations (e.g., raw materials needed for pumps and cylinders) add notably to the human health and ecotoxicity categories. Cylinder filling in cylinder delivery contributes noticeably to the human health impact categories: carcinogens, non-carcinogens, i.e., 11 – 13% of the results, and the ecotoxicity category i.e., 35% of the results. The pump used for cylinder filling is a contributor here – particularly the pump production itself. The materials used for the pump infrastructure (i.e., steel, cast-iron and copper) as well as handling copper waste from the pump production drive the values in these categories. Cylinder production contributes around 35% of the results in the carcinogens and respiratory effects categories. The aluminum alloy used for cylinder production contributes to the high percentage of results in the human health categories. Periodic maintenance activities in cylinder delivery, PSA plant and oxygen concentrator systems lead to a very small percentage (i.e., ≤ 3% of the total), in all impact category values assessed of the applicable product system.

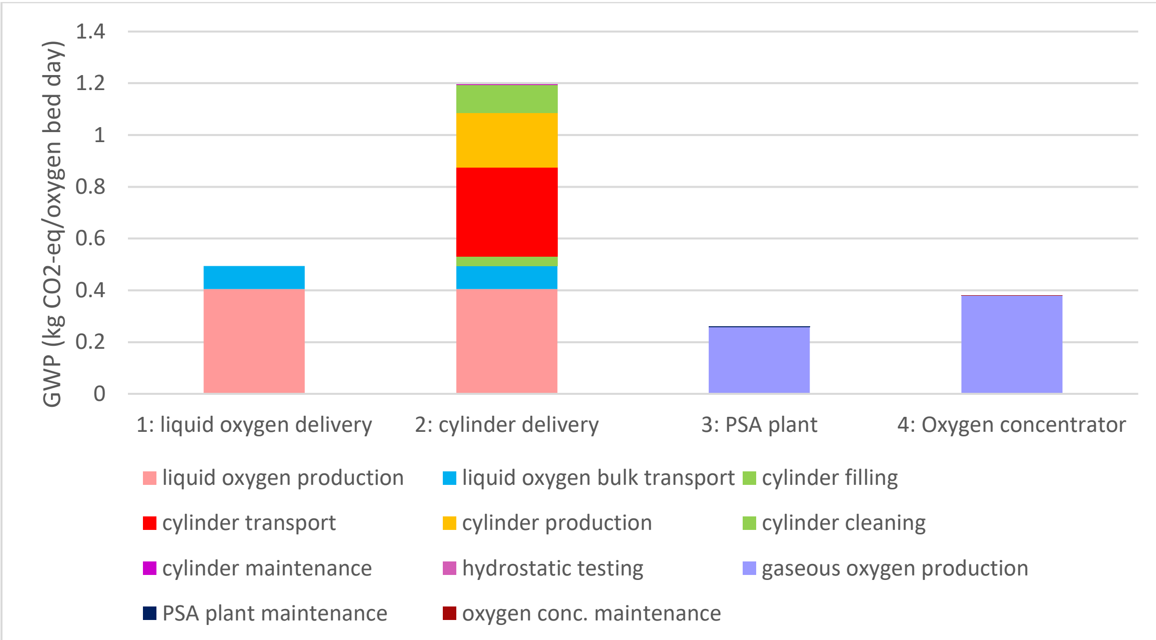

Figure 12: Results of the LCA for all four systems, for the GWP indicator – Oxygen production and cylinder transportation contribute most to GWP [4] [5]

5.1 Contribution Analysis

The results for the six indicators assessed are presented for each product system. A breakdown of the contributions of different activities provides a sense of hotspots in each product system.

5.1.1 Product system 1 – liquid oxygen delivery

Product system 1 (liquid oxygen delivery) is the baseline system. The results below are assessed per the following life cycle stages: liquid oxygen production and liquid oxygen transportation. The highest indicator values (hotspots) are associated with oxygen production from the ASU.

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[4] The colors of each bar in the graphs are similar to the colors of the flow diagrams presented in section 4.2 – each color represents a different process.
[5] The figures presented in section 5.1 group all four product systems for the same environmental impact indicator in the same graph, because the Y-axis or the unit of the results are the same. However, the discussion of the results in-text is sectioned separately based on the four product systems. This presentation may appear odd to the reader, however, there is no best way to present LCA results, and this way was thought best in this case.

GWP

The total emissions from liquid oxygen delivery are 0.494 kg CO_2eq/oxygen bed day (see Figure 12). 82% of these emissions come from production and 18% from transportation.

Fossil fuel depletion

The total fossil fuel depletion from liquid oxygen delivery accounts for 0.895 MJ surplus/oxygen bed day (Figure 13). 77% of this number is attributed to production, and 23% to transportation.

Human health categories: carcinogens, non-carcinogens, and respiratory effects

The toxicity or disease cases from liquid oxygen delivery are $6.22x10^{-8}$ CTUh in the carcinogens indicator category (Figure 14) and $2.09x10^{-7}$ CTUh in the non-carcinogens indicator category (Figure 15) per oxygen bed day. The emissions for the respiratory effects category are $2.83x10^{-4}$ PM 2.5-eq/oxygen bed day (Figure 16). In the carcinogens and non-carcinogens indicator category, oxygen production accounts for $\geq$ 90% of the results. Production accounts for 78% of results in the respiratory effects category, and transportation 22%.

Ecotoxicity

The potential affected fraction of species from liquid oxygen delivery is 15.3 CTUe (Figure 17). About 96% of this number is attributed to production and 4% to transportation.

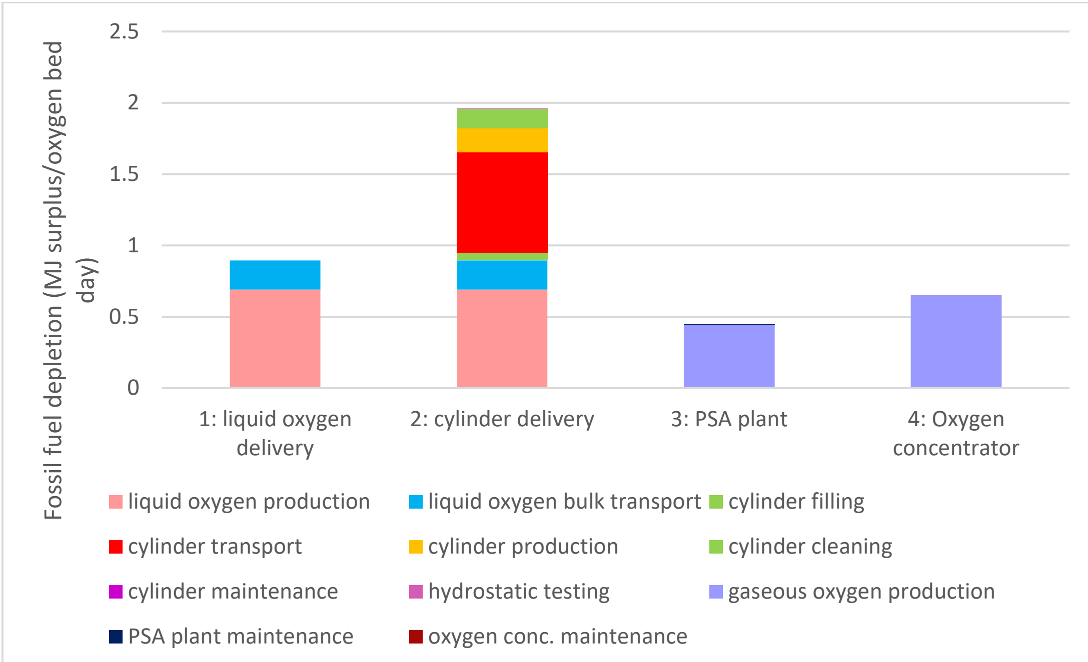

Figure 13: Results of the LCA for all four systems, for the fossil fuel depletion indicator – Cylinder transport and oxygen production are significant contributors

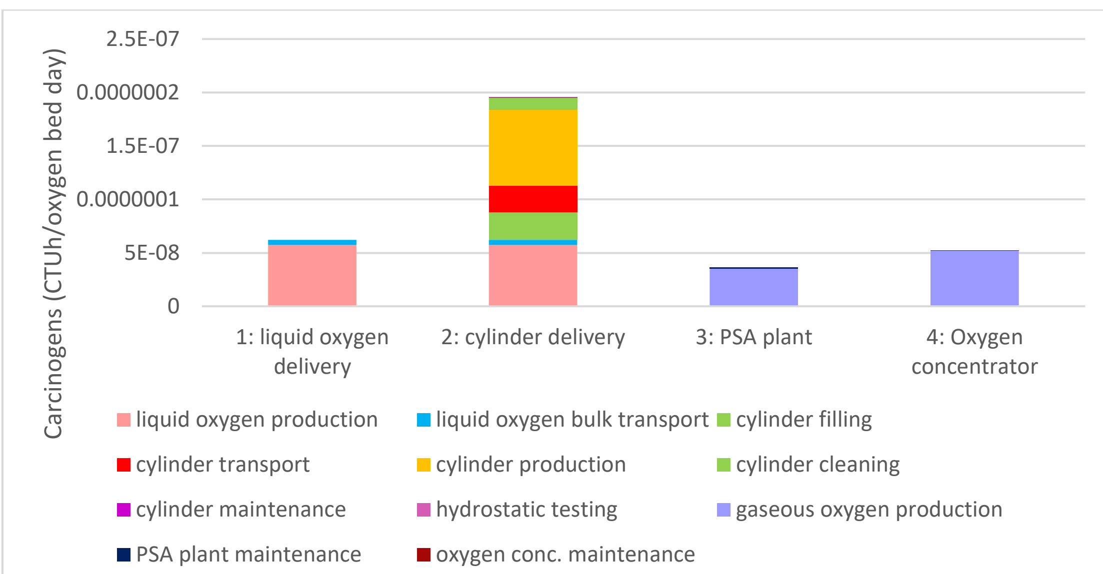

Figure 14: Results of the LCA for all four systems, for the carcinogens indicator – Cylinder production and oxygen production are significant contributors

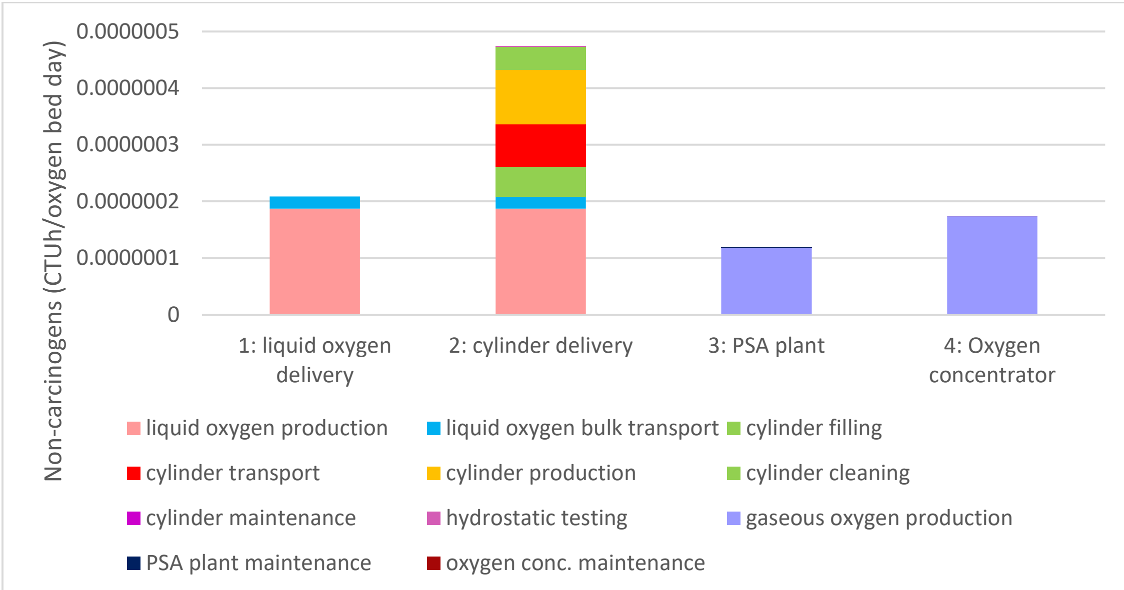

Figure 15: Results of the LCA for all four systems, for the non-carcinogens indicator – Oxygen production is a significant contributor

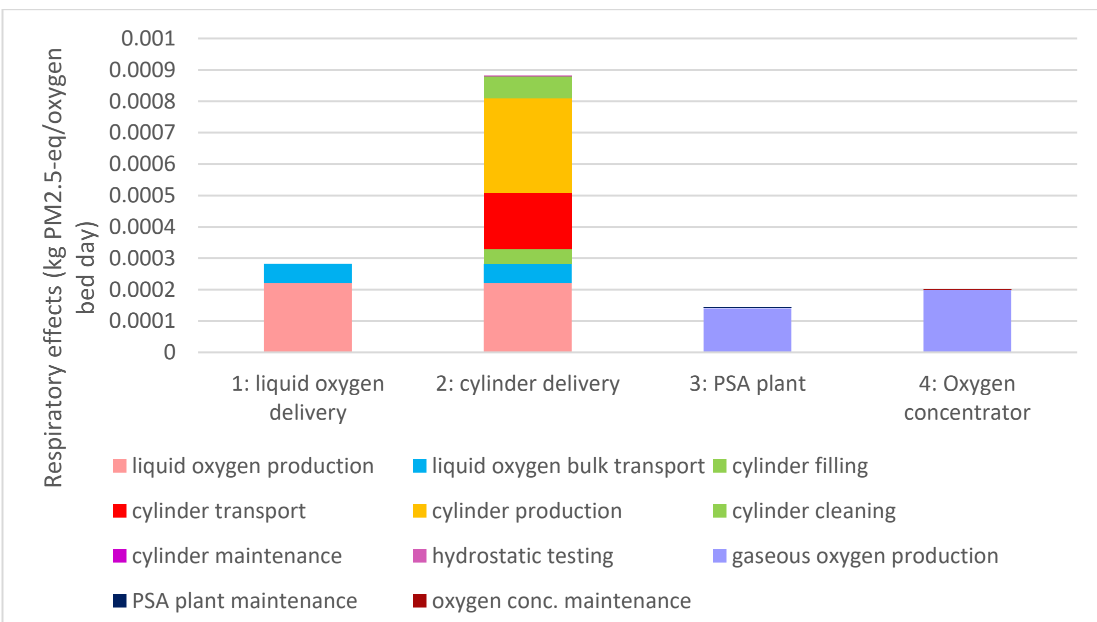

Figure 16: Results of the LCA for all four systems, for the respiratory effects indicator – Oxygen production, cylinder production, and cylinder transportation contribute significantly

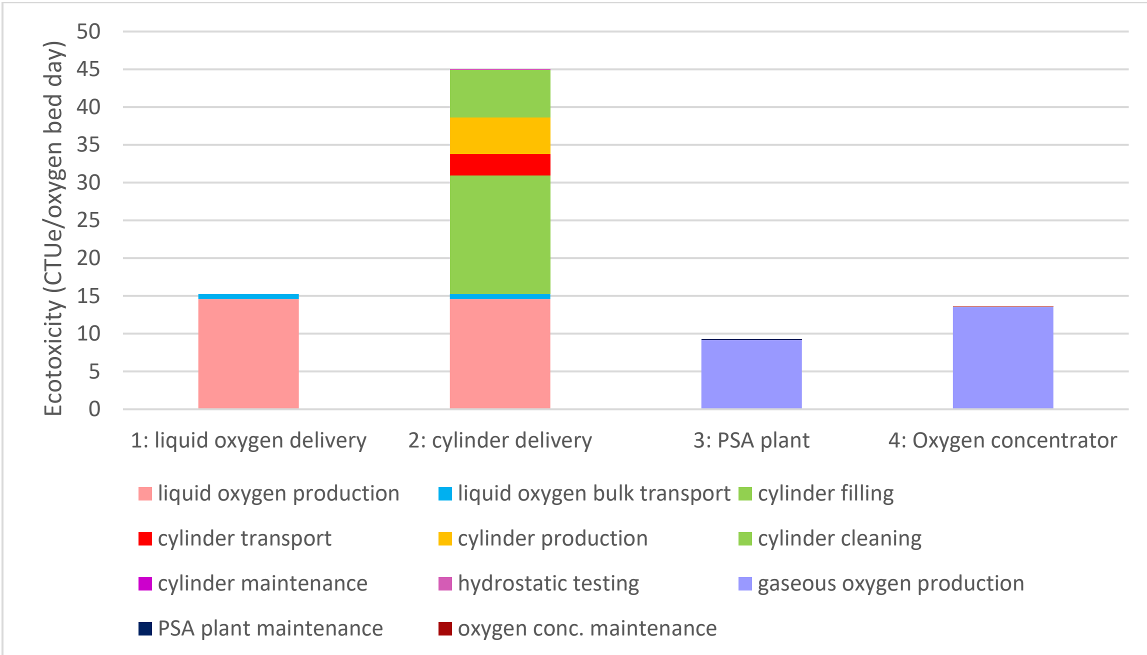

Figure 17: Results of the LCA for all four systems, for the ecotoxicity indicator – Cylinder filling and oxygen production are main contributors

5.1.2 Product system 2 – cylinder delivery

The results below are assessed as per the following life cycle stages: liquid oxygen production; transportation which includes both liquid oxygen transportation and cylinder transportation; and cylinder-related processes, which include cylinder filling, cylinder production, cylinder cleaning, cylinder maintenance, and hydrostatic testing.

The highest indicator values or hotspots are attributed to oxygen production and cylinder transportation. Of note is that cylinder production has significant contributions to the human health categories. The production of aluminum alloy used in cylinder production contributes significantly to the results. Cylinder filling also has contributions to the ecotoxicity category in particular, which can be attributed to the pump production itself. The materials used for the pump infrastructure, i.e., steel, cast-iron and copper, as well as handling copper waste from the production, drive the results up for these categories. Cylinder maintenance and hydrostatic testing account for less than 1% of the results in all impact categories assessed.

GWP

The total emissions from cylinder delivery are 1.20 kg CO_2eq/oxygen bed day (see Figure 12). 36% of these emissions come from transportation, mostly from cylinder transportation. 34% of the emissions come from oxygen production. Cylinder-related processes account for 30% of the total emissions, with cylinder cleaning, filling, and production accounting for most of the 30%.

Fossil fuel depletion

The total fossil fuel depletion from cylinder delivery accounts for 1.96 MJ surplus/oxygen bed day (see Figure 13). 46% of this number is attributed to transportation (mostly to cylinder transport), 35% to oxygen production, and 19% to cylinder-related processes.

Human health categories: carcinogens, non-carcinogens, and respiratory effects

The toxicity or disease cases from cylinder delivery are 1.96×10^{-7} CTUh in the carcinogens indicator category (see Figure 14), and 4.74×10^{-7} CTUh in the non-carcinogens indicator category (see Figure 15), per oxygen bed day. The emissions for the respiratory effects category are 8.80×10^{-4} PM 2.5-eq/oxygen bed day (see Figure 16). For all human health indicator categories, oxygen production, cylinder transport and cylinder production are the largest contributors to the results. Oxygen production contributes 25 – 29% of the total in the carcinogens and respiratory effects categories and 40% in the non-carcinogens category. Cylinder production contributes around 35% of the total in the carcinogens and respiratory effects categories', and 20% in the non-carcinogens category. Cylinder transportation also has significant contributions to human health indicator categories, with 13% contribution to the carcinogens category, 16% to the non-carcinogens category, and 20% to the respiratory effects category.

Ecotoxicity

The potential affected fraction of species from cylinder delivery are 45.0 CTUe (see Figure 17). 35% of this number is attributed to cylinder filling. Oxygen production accounts for 32% of the results.

5.1.3 Product system 3 – PSA plant

The results below are assessed as per the following life cycle stages: PSA plant operation (gaseous oxygen production) and PSA plant maintenance. The highest indicator values or hotspots are attributed to oxygen production.

GWP

The total emissions from the PSA plant are 0.261 kg CO_2eq/oxygen bed day. 99% of these emissions come from the operation, i.e., the electricity consumption of the PSA plant. Only 1% of the emissions come from maintenance.

Fossil fuel depletion

The total fossil fuel depletion from the PSA plant accounts for 0.447 MJ surplus/oxygen bed day. > 99% of this number is attributed to operation and < 1% to maintenance.

Human health categories: carcinogens, non-carcinogens, and respiratory effects

The toxicity or disease cases from the PSA plant are 3.65×10^{-8} CTUh in the carcinogens indicator category and 1.20×10^{-7} CTUh in the non-carcinogens indicator category per oxygen bed day. The emissions for the respiratory effects category are 1.40×10^{-4} PM 2.5-eq/oxygen bed day. PSA plant operations contribute ≥ 97% in all human health categories.

Ecotoxicity

The potential affected fraction of species from the PSA plant is 9.28 CTUe. > 99% of this number is attributed to plant operation and < 1% to maintenance.

5.1.4 Product system 4 – oxygen concentrator

The results below are assessed as per the following life cycle stages: oxygen concentrator operation (gaseous oxygen production) and oxygen concentrator maintenance. The highest indicator values or hotspots are attributed to oxygen production.

GWP

The total emissions from the oxygen concentrator are 0.381 kg CO_2eq/oxygen bed day. > 99% of these emissions come from operation, i.e., electricity consumption by the concentrator. < 1% of the emissions come from maintenance.

Fossil fuel depletion

The total fossil fuel depletion from the oxygen concentrator accounts for 0.653 MJ surplus/oxygen bed day. > 99% of this number is attributed to operation and < 1% to maintenance.

Human health categories: carcinogens, non-carcinogens, and respiratory effects

The toxicity or disease cases from the oxygen concentrator are 5.21×10^{-8} CTUh in the carcinogens indicator category and 1.74×10^{-7} CTUh in the non-carcinogens indicator category per oxygen bed day. The emissions for the respiratory effects category are 2.00×10^{-4} PM 2.5-eq/oxygen bed day. Oxygen concentrator operation contributes over 99% of the total in each of the human health indicator categories.

Ecotoxicity

The potential affected fraction of species from the oxygen concentrator are 13.6 CTUe. > 99% of this number is attributed to operation and < 1% to maintenance.

5.2 Calculated emissions for oxygen's life cycle

In this section, the emissions result for oxygen's life cycle of gaseous oxygen is presented – the denominator of one litre is used because this is a common unit used in medical oxygen delivery. For example, healthcare professionals administer oxygen to a patient on a litre per minute basis. Table 8 presents an emissions factor for each impact category across all four product systems – which means that the LCA results of medical oxygen's life cycle are presented per litre of oxygen gas. The table presents all results reported in section 5.1 per litre of oxygen gas. The numbers were calculated based on the following formula:

Emissions factor for liquid oxygen delivery = Reported environmental impact for each product system ÷ reference flow for the applicable product system

The result is an emissions factor, a quantitative representation of environmental impact per litre of gaseous oxygen. Liquid oxygen delivery – the baseline system has a GWP emissions factor of 1.70×10^{-4} kg CO_2eq/L of gaseous oxygen.

Table 8: LCA results for oxygen production and delivery to bedside (presented per litre of oxygen gas)

	1: Liquid oxygen delivery	**2: Cylinder delivery**	**3: PSA plant**	**4: Oxygen concentrator**
GWP (kg CO_2 eq/L)	1.70×10^{-4}	4.11×10^{-4}	8.44×10^{-5}	1.23×10^{-4}
Fossil fuel depletion (MJ surplus/L)	3.08×10^{-4}	6.74×10^{-4}	1.44×10^{-4}	2.11×10^{-4}
Carcinogens (CTUh/L)	2.14×10^{-11}	6.72×10^{-11}	1.18×10^{-11}	1.68×10^{-11}
Non-carcinogens (CTUh/L)	7.17×10^{-11}	1.63×10^{-10}	3.86×10^{-11}	5.63×10^{-11}
Respiratory effects (kg PM 2.5 eq/L)	9.72×10^{-8}	3.03×10^{-7}	4.61×10^{-8}	6.46×10^{-8}
Ecotoxicity (CTUe/L)	5.25×10^{-3}	1.55×10^{-2}	3.00×10^{-3}	4.38×10^{-3}

5.3 Scenario analysis

5.3.1 Effect of Geographic location

Medical oxygen is produced and used all over the world. Oxygen production in different locations was evaluated to see how it impacts the environment (goal two discussed in section 4.1.1). Figure 18 shows the results for GWP for liquid oxygen delivery in Ontario, Canada; Delaware, U.S.; Great Britain; and China. $\geq$ 90% of the indicator values are attributed to liquid oxygen production in each geography. Figure 19 shows the results for GWP results for gaseous oxygen production in these different locations. In this comparison, GWP results are highest in China, where electricity is sourced from fossil sources of energy and lowest in Ontario, Canada, where the electricity is sourced significantly from cleaner sources of energy (see section 4.4.1.1). It is interesting to note that Ontario's electricity grid – with an emissions factor of 0.0280 kg CO_2eq/kWh – is much cleaner than Canada's average electricity grid (which consists of Canada's 13 provinces and territories) – with an average emissions factor of 0.282 kg CO_2eq/kWh (Government of Canada, 2022)[6].

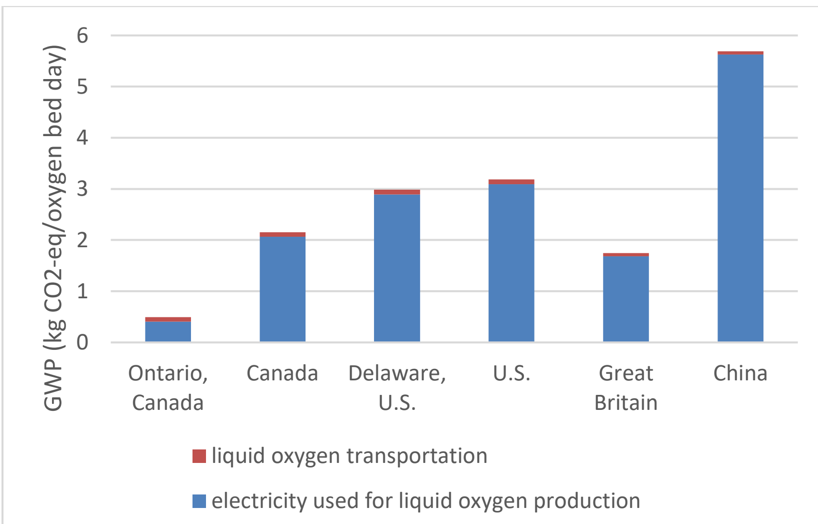

Figure 18: GWP varies depending on the geographical location of liquid oxygen delivery

[6] An average EF was calculated for Canada by adding the EFs for all provinces and territories and dividing it by 13.

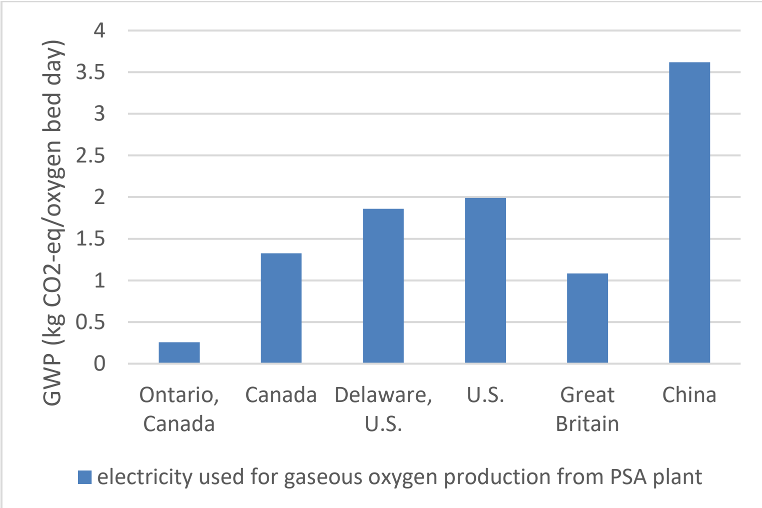

Figure 19: GWP varies depending on the geographical location of gaseous oxygen production

The results for the electricity used during liquid oxygen production were also plotted onto a graph which shows various geographies in the world and their electricity grid make-ups (Figure 20). Countries in different continents of the world and ones with low and high populations were chosen, i.e., Canada, Great Britain, the U.S., and China, representing 0.5%, 0.9%, 4%, and 18% of the world's population, respectively. The emissions factors (EFs) for the chosen countries' electricity grids were plotted onto the X-Axis of the figure (kg CO_2eq/kWh). In other words, the higher EFs represent countries, where the electricity is sourced from non-renewable sources of energy i.e., coal and oil, and the lower EFs, represent countries where the electricity is sourced from cleaner sources of energy e.g., hydroelectricity, nuclear energy etc. The results for electricity used during liquid oxygen production (using cryogenic distillation – the most common method of producing medical oxygen) for the four geographies considered in this thesis were plotted on the Y-Axis of the figure (kg CO_2eq per litre of oxygen gas). The correlation shows how the emissions factor for the electricity grid affects GHG emissions. China has a dirtier electricity grid with an emissions factor of 0.541 kg CO_2eq/kWh; therefore, the results for electricity used during oxygen production are highest at 0.00193 kg CO_2eq/L of oxygen gas. In comparison, Canada has a cleaner electricity grid with an emissions factor of 0.282 kg CO_2eq/kWh. Based on this, oxygen production electricity usage GWP results are at 0.000709 kg CO_2eq/L. Readers can use the graph to understand the average GWP impact of oxygen production based on the geographies they live in.

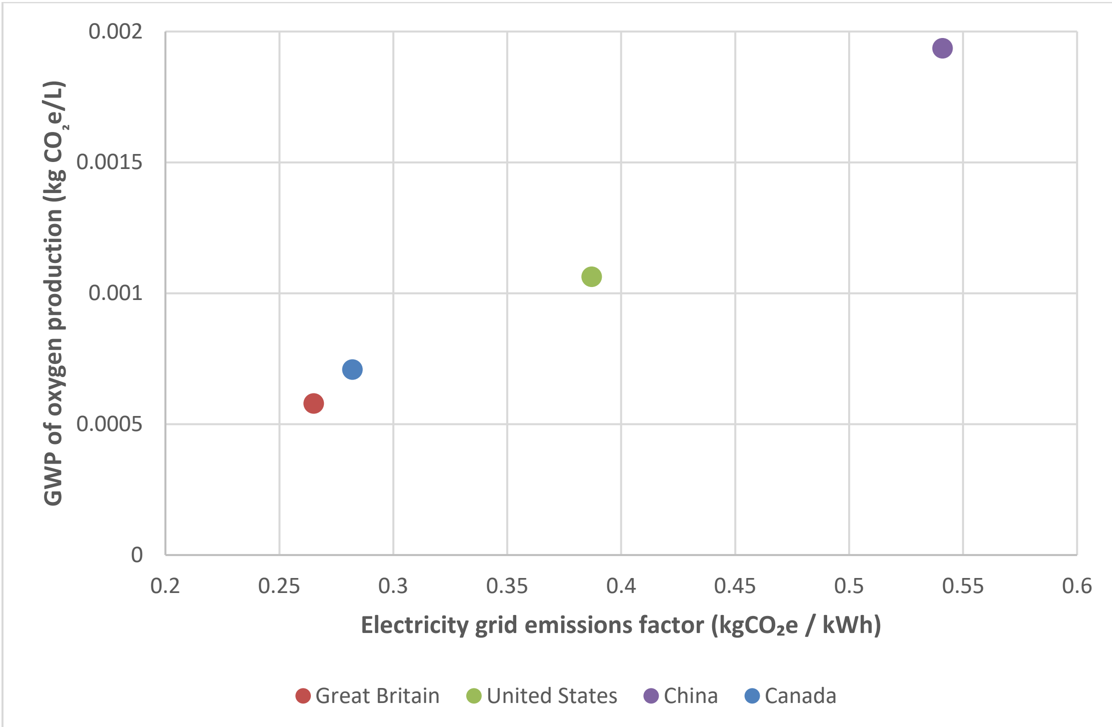

Figure 20: Emissions factors of oxygen production based on various electricity grids in the world

5.3.2 Flowrates

In the original calculations, an oxygen delivery flowrate of 2 L/min to a patient bed was used; however, in clinical practice the flow of oxygen delivered to a patient can vary significantly. Different flowrates were considered to inform oxygen use decisions and management practices from an environmental impact perspective (goal number three discussed in section 4.1.1). The LCA results are directly and linearly proportional to an increase in flowrate. For instance, if the flowrate increases from 2 L/min to 5 L/min (an increase by a factor of 2.5), the results for the environmental indicator also increase by a factor of 2.5. Figure 21 shows the flowrate comparison results for GWP for all product systems. It can be seen that a flowrate of 60 L/min, such as when required during the COVID-19 pandemic or in extreme cases, leads to a very high GWP impact (30 times that of that standard flowrate of 2 L/min used in this study). Other environmental indicator categories considered also showed the same response.

Figure 21: GWP increases linearly as flowrate increases

5.4 Sensitivity analysis

5.4.1 Co-product allocation for the ASU

Although the modelling of the ASU in this study assumes that gases other than oxygen from the cryogenic distillation process are vented to the atmosphere and there is no co-product allocation required, in practice, this would not happen. At some ASU facilities, nitrogen and argon would be co-products of the air separation process. A theoretical discussion of how the results would change if a molar-based co-product allocation is presented. If the reported GWP impacts from operating an ASU are 0.405 kg CO_2eq per oxygen bed day, then 78% of these would be allocated to nitrogen production (i.e., 0.316 kg CO_2eq/oxygen bed day), 21% to oxygen production (i.e., 0.0850 kg CO_2eq/oxygen bed day) and 0.9% to argon production (i.e., 0.00364 kg CO_2eq/day), which reduces the indicator value for oxygen by 79%. Allocation is an important step in scoping an LCA. Although this model assumes no co-products in the air separation process, in practice, it is quite different. Nitrogen and argon are also collected, stored and sold for use. Data for an entire ASU operation, including the amounts of inputs and outputs are needed to quantify the environmental indicator impacts. The modelling and results of the ASU operation can give a clear picture of the impacts, and how much are attributed to oxygen production.

5.4.2 Impact assessment method

Many different LCIA methods can be used to translate LCI data into environmental indicator impacts. In this study, TRACI 2.1 was used as a primary LCIA method and IMPACT 2002+ and USEtox 2.0 for sensitivity analysis. The values for the baseline system – liquid oxygen delivery are shown in Table 9 below. All impact assessments provide an assessment of midpoint indicators, as shown in the table. The results from the IMPACT 2002+ impact method were similar to those from the base product systems (which used the TRACI 2.1 method) for GWP and respiratory effects categories. For example, comparable results are obtained from both LCIA methods for global warming at 0.494 kg CO_2 eq and 0.483 kg CO_2 eq per oxygen bed day. The units used for analysis are different for the other impact categories, so a comparison cannot be made.

The units for human toxicity – cancer, human toxicity – non-cancer from USEtox 2.0 are in "cases", and unit for freshwater ecotoxicity in "PAF (affected fraction of species).m^3.day". These units are comparable to the CTUh and CTUe units from TRACI 2.1. Disease cases from USEtox 2.0 for human toxicity categories are similar compared to TRACI 2.1 e.g., the result for the carcinogens category in TRACI 2.1 is $6.22x10^{-8}$ CTUh, and human toxicity – cancer in USEtox 2.0 shows $5.52x10^{-8}$ cases. Of note is that freshwater ecotoxicity results in USEtox 2.0 are extremely high compared to TRACI 2.1 (see Table 9). USEtox 2.0 is a more comprehensive method compared to TRACI 2.1 and assesses a larger set of chemicals and its impacts on living species. USEtox developed human health cancer and non-cancer toxicity and freshwater ecotoxicity potentials for over 3000 substances worldwide (U.S. EPA, n.d.). In comparison, TRACI focused on chemicals of concerns in the U.S. Moreover, characterization factors in USEtox can change by more than 12 orders of magnitude amongst chemicals (Rosenbaum et al., 2008). Additionally, USEtox has interim characterization factors which makes the model uncertain, so the impact scores should be interpreted with caution (Rosenbaum et al., 2008). Each LCIA method is unique and differs in comprehensiveness of the calculated impacts on the environment. In addition, they all focus on different areas of concern, and sometimes have different characterization factors and reporting units.

Regardless of the limitations of the LCIA methods, the results of this LCA study are valid and more precise. Hence, the results can be interpreted and used with more confidence.

Table 9: Similar results obtained using TRACI 2.1 and IMPACT 2002+ impact methodologies for liquid oxygen delivery system

Environmental impact midpoint category	TRACI 2.1	IMPACT 2002+	USEtox 2.0
GWP / Global warming	0.494 kg CO_2 eq	0.483 kg CO_2 eq	Not comprehended
Respiratory effects / respiratory inorganics	2.80×10^{-4} kg PM 2.5 eq	3.50×10^{-4} kg PM 2.5 eq	Not comprehended
Fossil fuel depletion / Non-renewable energy	0.895 MJ surplus	58.7 MJ primary	Not comprehended
Carcinogens / Human toxicity – cancer	6.22×10^{-8} CTUh	6.60×10^{-3} kg C_2H_3Cl eq	5.52×10^{-8} cases
Non-carcinogens/ Human toxicity – non-cancer	2.09×10^{-7} CTUh	2.12×10^{-2} kg C_2H_3Cl eq	1.70×10^{-7} cases
Ecotoxicity / Aquatic ecotoxicity / Freshwater ecotoxicity	15.3 CTUe	154 kg TEG water	9,670 PAF.m^3.day

5.4.3 Using a different pump for cylinder filling

The energy used by a 75-kW pump with a flowrate for cylinder filling of 530 m^3/hour was calculated to be 0.314 kWh (for the cylinder delivery system). For this sensitivity analysis, a 30-kW pump with a flowrate of 132 m^3/hour gave an energy usage of 0.504 kWh. The indicator values for the cylinder filling process increases by 60%. For instance, the original GWP value for cylinder filling is 0.0368 kg CO_2eq/oxygen bed day. With this sensitivity analysis, the GWP indicator value for cylinder filling is 0.0591 kg CO_2eq. However, the overall results for the cylinder delivery system do not change by much – the original GWP value is 1.20 kg CO_2eq/oxygen bed day, and the new value is 1.22 kg CO_2eq. Cylinder filling has contributions, particularly to human health and ecotoxicity indicators, however, changing the size of the pump does not skew the results to a great degree. Deciding factors are not just the power rating of the pump but also the pressure, flowrate, and the number of hours used to fill the cylinders.

Supplementary content:

See Appendix B for results for the product systems, C for scenario analysis results and D for sensitivity analysis results

Chapter 6 Discussion

The study met the goal of modelling the environmental impact of the different pathways through which medical oxygen is delivered to a patient. Findings show the medical oxygen life cycle does not produce significantly high results for the indicator categories assessed, especially compared to other common daily use items. The GWP results for the baseline system (consisting of liquid oxygen production and delivery to a patient) showed 0.494 kg CO_2 eq/oxygen bed day, which translates to $1.70x10^{-4}$ kg CO_2eq per litre of gaseous oxygen. Comparatively, gaseous oxygen produced by the PSA plant has lower environmental indicator values, i.e., 48% less than the liquid oxygen delivery system. The PSA plant system yielded $8.44x10^{-5}$ kg CO_2eq per litre of gaseous oxygen. To contextualize these results, an average gasoline passenger vehicle contributes 12.6 kg CO_2eq to GWP per day – calculated from data provided by the U.S. EPA (2016). Results for GWP for the baseline system – liquid oxygen delivery are only 4% of the 12.6 kg CO_2eq. While any of the product systems are not at par with GWP results from an average passenger vehicle, it is important to know the oxygen's supply chain indicator impacts because it is a lifesaving drug used in abundance and often wasted.

While analyzing hotspots, cylinder delivery had higher values for all six impact categories. Cylinder transportation demands more nodes or transfer points in the supply chain. Moreover, empty cylinders must be cleaned periodically and returned to the trans-fill facility for re-use. These extra activities lead to additional potential environmental burdens in the oxygen supply chain. Oxygen production and cylinder transportation are key drivers for the results for all environmental impact categories assessed. The indicator impacts for oxygen production are attributed to electricity. Especially the electricity grid mix makes a considerable difference to the results.

Extrapolating the results to a 1000-bed hospital in Ontario, such as Sunnybrook Health Sciences Centre, the GWP indicator values for the liquid oxygen delivery system are 494 kg CO_2eq/day if all beds are assumed to be occupied. In comparison, GWP indicator values for the cylinder delivery, PSA plant and oxygen concentrator systems are 1,200 kg CO_2eq, 259 kg CO_2eq, and 381 kg CO_2eq per day, respectively.

6.1 Comparison to other studies

The author is aware of five studies to which results can be compared. The reported results of each study were converted to a common unit of comparison, kg CO_2eq/L of oxygen gas (Table 10). As mentioned in section 5.2, the number for liquid oxygen delivery (which includes liquid oxygen production and transportation) is calculated to be 0.000170 kg CO_2eq/L of oxygen gas.

Worldsteel, the global steel industry association for the primary industry that consumes vast amounts of oxygen, includes the analysis of oxygen in its life cycle assessment models; however, their modelling varies by region, and disaggregated results are not published. Generic data from Worldsteel were presented in a U.K. report by ResponsibleSteel (2022), a non-profit organization, and provided a GHG emissions factor for oxygen production of 0.426 tCO_2e/KNm^3 (0.426 CO_2e/Nm^3), which equates to 0.000397 kg CO_2e/L of oxygen gas. The value from ResponsibleSteel's U.K. report compares well to this study's value of 0.000579 kg CO_2e for Great Britain (for oxygen production), especially when considering steel producers typically have their ASU located on-site and would not require transport, which is included in this study's system for delivery to the hospital.

Bałys et al. (2021) present environmental indicator results of the delivery of medical oxygen to a patient in Poland. The study considers the impacts of transportation of liquid oxygen for: (1) oxygen provided to a patient in cylinders, and (2) liquid oxygen transported and stored in tanks. They also considered and the electricity impacts for on-site PSA plant operation. Contrary to the work done by Balys et al. (2021), this thesis modelled the supply chain of medical oxygen, inclusive of most ancillary activities such as infrastructure and maintenance. Bałys et al. (2021) presented their results as normalized environmental impacts, which makes it difficult to compare with our study.

Transportation impacts for "oxygen cylinders" considered by Bałys et al. (2021) are almost double "liquid oxygen in tanks". Reported results for electricity usage for "on-site oxygen production" appear to be 40% higher than "liquid oxygen in tanks." Here, the electricity usage impacts are compared to transportation impacts. This thesis accounts for electricity usage in all systems, where the impacts for cylinder delivery (product system 2) are about 140% more than the bulk liquid oxygen delivery (product system 1). Also, in this thesis, electricity usage for PSA plant operation (product system 3) leads to 36% fewer impacts than liquid oxygen production. The impact assessment method used by Balys et al. (2021), IMPACT 2002+, is European-based, which explains the difference in electricity use impacts between their study and this thesis. Although it is not conclusive, the comparison between the two studies infers that cylinder delivery adds environmental burdens to the supply chain, and that electricity grid mix can significantly affect the results.

In a commentary on the COVID-19 oxygen crisis, Bonnet et al. (2021) mention a carbon footprint of 67 kg CO_2/m^3 of liquid oxygen based on unpublished Air Liquide company data, part of which is attributed to transport. Zhong et al. (2020) present the GWP impacts of medical oxygen to be 0.70 kg CO_2e/kg, which includes the production of oxygen through an ASU and electricity for the production process, cooling water, waste heat and infrastructure. Seglenieks et al. (2021) have also critiqued GWP values associated with the production of 1 kg of medical oxygen by comparing values in Zhong et al. (2020) with numbers from the Australian Life Cycle Inventory Database Initiative v1.27 and ecoinvent v3.5 (see Table 10). According to Seglenieks et al. (2021), Zhong et al. (2020) have a “best case scenario” for the GWP of oxygen production, because the electricity needed for production comes from renewable energy. This thesis presents a better and worse-case scenario for oxygen delivery. Ontario has a clean electricity grid and results in 0.000170 kg CO_2e/L of oxygen gas. Compared to oxygen production in China, the GWP for oxygen delivery is 0.00198 kg CO_2e/L of oxygen gas. This thesis also includes contributions from transportation, which are small.

Studies published in literature have different system boundaries and consider different methods of assessment of GHG emissions, which makes it difficult to conduct a fair comparison. The reported numbers for geographies relying on non-renewable energy are one order of magnitude higher than those relying on a cleaner electricity grid (see Figure 18 and Figure 19). In particular, reported numbers for France are even one order of magnitude lower, which is reasonable given that it has a very clean electricity grid (see Figure 20). This thesis is more reliable, given that it identifies all processes and flows from cradle-to-gate, and includes most important activities in the LCA modelling, and justifies the activities which were not included.

Table 10: Comparison the results of this study to existing studies

	Life cycle stages considered	Reported GWP results	GWP results (kg CO_2 eq/L of oxygen gas)	Study based in	Comments
	In this table, P means Production and T means Transportation.				
This study	P, T	0.494 kg CO_2eq/oxygen bed day	0.000170	Ontario, Canada	Data from ecoinvent 3.8
	P, T	2.99 kg CO_2eq/oxygen bed day	0.00103	Delaware, U.S.	
	P, T	1.80 kg CO_2eq/oxygen bed day	0.000620	Great Britain	
	P, T	5.75 kg CO_2eq/oxygen bed day	0.00198	China	
Worldsteel	P	0.426 tCO_2e/KNm^3 of oxygen gas	0.000397	Unclear, although value is likely for the U.K.	Value is from Responsible Steel (2022)
Bałys et al. (2021)	T	N/A	--	--	Results not comparable
Bonnet et al. (2021)	P, T	67 kg CO_2/m^3 of liquid oxygen	0.0000779	France	unpublished Air Liquide data

Seglenieks et al. (2021)	P	1.45 kg CO_2e/kg of oxygen gas	0.00193	Australia	Data from Australian Life Cycle Inventory Database Initiative v1.27
	P	0.62 kg CO_2e/kg of oxygen gas	0.000825	Europe	Data from ecoinvent v3.5
	P	1.17 kg CO_2e (for the world)/kg of oxygen gas	0.00156	the World	
Zhong et al. (2020)	P	0.70 kg CO_2e/kg of oxygen gas	0.000931	--	--

6.2 Implications of study

Oxygen is one of the three most abundant elements in the universe (Siegel, 2020). However, the focus on sustainability in its supply chain is limited. Although the natural supply of oxygen is inexhaustible, the results show that energy, resources, and planning are incorporated into its supply chain without attention given to conserving or managing product use and the associated equipment and technology. The sections below will focus on how the results of this study can introduce sustainable practices in the medical oxygen supply chain, and aid medical gas suppliers and healthcare actors in decision-making for reducing environmental impacts. Results of the LCA can be meaningful for manufacturers of medical oxygen and industrial gas suppliers as they can see the benefits and opportunities of the different technologies. Additionally, facility administrators in hospitals can make informed decisions on which option to choose if they are looking to reduce their environmental impact.

6.2.1 Improving oxygen life cycle environmental impacts

A goal of the LCA was to evaluate how oxygen production in different geographies impact the environment which was shown through the scenario analysis. Manufacturers of medical oxygen can reduce the environmental impact of production by exploring cleaner energy alternatives, as proposed by Air Products Canada Ltd. (see Chapter 1). Modelling indicates that electricity is the dominant driver of environmental impacts, which should lead to more meaningful conversations on nations investing in clean energy for their electricity grids. Additionally, oxygen manufacturers can consider off-grid electricity, such as on-site power production using renewable energy sources. This option has its own challenges, such as high capital costs of arranging and maintaining the infrastructure for producing on-site electricity. Ultimately, what should be highlighted is the importance of electricity in contributing to environmental indicator impacts, which is also dependent on geographical factors (i.e., availability of renewable energy sources) and cost considerations.

The modelling in this thesis shows that PSA technology has lower environmental indicator results compared to cryogenic distillation. During the COVID-19 pandemic, hospitals faced medical oxygen supply chain challenges (see section 2.3.2.1). In such emergency situations, or otherwise, switching to PSA production would reduce hospitals' dependency on transported bulk liquid oxygen or oxygen gas in cylinders, although these oxygen delivery methods may still be needed occasionally. Electricity and maintenance would be factors for operating the plant efficiently and effectively on-site, since continuous electricity is required for the operation of a PSA plant. If the electricity supply fluctuates significantly, switching to PSA may not be a viable alternative. As mentioned before and as demonstrated by this example, the electricity grid mix makes a difference in environmental impacts. Locations such as Ontario, Canada would contribute less to environmental impact for a PSA plant running 24 hours a day continuously, in comparison to a location in China, where the contribution to environmental impact would be much higher from this operation (see section 5.3.1). Hospitals can also consider reliance on oxygen concentrators as a backup method of supply. In this case, availability of oxygen concentrators, their ongoing maintenance, and continuous supply of electricity would be necessary. Both cryogenic distillation and PSA technologies produce oxygen at a purity approved by WHO (see section 2.2.1), at > 99% and 93%, respectively. Medically, switching to PSA production would not affect patients. However, healthcare actors need to determine the best path forward based on patients' needs.

Additional activities such as transportation in cylinders contribute to environmental impact (as shown by cylinder delivery system results). Cylinders need to be collected, cleaned, and transported back to a trans-fill facility, which add to environmental burdens, and disrupts the supply chain. For instance, during the COVID-19 pandemic, hospitals in Toronto reported experiencing increased burdens and activity from cylinder collection and transportation (N. Dimovski, personal communication, February 23, 2022). Cylinders are required for patient transfer from one part of the hospital to another (J. Sherman, personal communication, January 13, 2022). Hospitals use cylinders as the backup method of oxygen supply – this will always be necessary. In such cases, an on-site PSA plant is capable of delivering oxygen at high pressures (> 2000 psig), which is sufficient to fill high-pressure cylinders (AirSep Corporation, 2017).

6.2.2 Reducing losses and waste

Another goal of the LCA was to inform oxygen use decisions and management practices from an environmental impact perspective. An important aspect of this is healthcare professionals accepting a lower flowrate. Another important aspect is the inadvertent waste of gas in medical oxygen's life cycle. Wasting oxygen product results in upstream environmental impact, as more oxygen needs to be produced and transported. Sustainability in manufacturing, transporting, and delivering gases has received some attention by industrial gas suppliers seeking to increase operational efficiency (Air Liquide S.A., 2022; Air Products and Chemicals, Inc., 2022; Linde plc, 2019). Medical oxygen supply chain actors can increase operational efficiency by reducing waste. Liquid oxygen is lost while loading and unloading from a storage tank to the cryogenic truck for transportation or through evaporation loss during vaporizing and storage (Chart Industries, Inc., n.d.; Guevara, 2020). Assuming 10% loss from each of the activities: loading, unloading and vaporizing liquid oxygen to gaseous oxygen, this adds 25% to the value for the GWP indicator (for liquid oxygen delivery system). While evaporation losses from storage and transportation may be harder to control, practices can be implemented to reduce losses. For instance, Guevara (2020) reports that a wrong filling process and the amount of cryogenic liquid loaded onto a transport trailer are significant variables contributing to waste in the loading of liquid oxygen.

Hospitals can better manage the use of medical gases. Research from Scotland has revealed that waste within piped nitrous oxide systems is a significant problem. In 2020, a small study in two of England’s National Health Service (NHS) hospitals revealed that piped nitrous oxide waste was around 89% or 1.5 million litres per annum (calculated from Chakera et al. (2021)). Hospitals similarly waste medical oxygen within piped oxygen systems (J. Sherman, personal communication, September 2022). Moreover, cylinder manifolds lead to losses. Further research in this area can be advanced to determine the amount of waste from piped oxygen systems, either through piping connections or cylinder manifold system. Similar to the NHS hospitals, strategies can be developed to reduce waste, such as decommissioning manifolds if necessary, identifying and escalating cylinder leaks, and reducing cylinder stock levels (Chakera et al., 2021). There are losses in storing and transporting oxygen – detailed research in mapping out the actual losses in the supply chain, including at the end use, can be used to provide more strategies for reducing loss.

6.2.3 Future work towards a sustainability-focused system

The medical oxygen supply chain needs re-adjustment considerations from suppliers, medical facilities, and other relevant entities to reduce environmental impact and build an uninterrupted, resilient, and efficient supply chain. Re-adjustment refers to “mixing and matching” the different product systems we have considered in this study. For example, what if we reduced reliance on cylinders? What if we have a liquid oxygen delivery system as the primary oxygen supply and a PSA plant or oxygen concentrator set up on-site as the backup supply? While much of the current network operates in such a way, considerations of environmental impact, reducing nodes of transfer, and reducing loss are not considered. Such deliberations can help industrial gas suppliers and the healthcare industry shift to a sustainability-focused system. A sustainability-focused system is focused on meeting SDGs, and is concerned about environmental impact, and resilience. Resilience was not the focus of this thesis but should be considered for future work.

All supply chain actors must be involved to help create a sustainability-focused health system. Industrial gas suppliers, cylinder suppliers, healthcare facilities, and international governmental and intergovernmental agencies are decision-makers at each stage of the medical oxygen supply chain, as they facilitate the flow of the gas product from the suppliers to health systems and patients.

A number of aspects of healthcare sustainability discussed in this thesis relate to environmental impacts of medical products and services and building resilience in the medical product supply chains. Industry experts, healthcare actors and policymakers are all critical in building sustainable health systems. A sustainable health system would help reduce costs by minimizing inefficiencies and waste in medical product supply chains. It would also increase the supply chain's resilience by ensuring an uninterrupted supply of products, especially during emergencies or disturbances. Additionally, SDGs such as good health and well-being (SDG 3) could be met by ensuring the consistent delivery of healthcare services to the global population. Responsible consumption and production (SDG 12) can be focal points for supply chains – through considerations of environmental impact, reducing nodes of transfer, and reducing loss in medical product supply chains. Attention to the environmental impact of health products and services would be a step forward in positive climate action (SDG 13).

The oxygen supply chain challenges discussed in section 2.3.2.1 emphasize the importance of oxygen supply chain resilience. PSA technology can be an alternative to liquid oxygen and cylinder delivery, given the challenges with liquid oxygen and cylinder delivery, storage, and maintenance issues. However, a PSA plant operation has initial set-up costs and needs an uninterrupted electrical supply. Its use as the only reliable source of oxygen supply could raise the question of the amount of oxygen needed to meet demand. Nevertheless, switching to a 100% PSA supply is worth exploring and researching. Initial studies can be done to determine if this option is feasible for hospitals, especially smaller hospitals. Hospitals in Northern Ontario may be located further from ASUs, so PSA operations may be more suitable. Inefficiencies and waste also affect supply chain resilience. Advances in switching to PSA technology can help build resilient medical gas supply chains, as there is less reliance on ease of transportation or cylinder availability.

The medical oxygen supply chain can be re-vamped for a sustainable health system. Similar detailed research on other products and services is needed to contribute to the growing knowledge of sustainable development in medicine, which involves studies on environmental impact, measuring resource waste, and discussions on resilience. Sustainability-related studies on individual products, technologies, and resources used in healthcare would inform policymakers and experts in decision-making and would meet the WHO’s goal of sustainable development in health systems.

6.3 Limitations of the study

There were limitations to the LCA study. Data was collected from secondary sources such as company and government websites and the ecoinvent database. While industry experts were also consulted regarding high-level data checks or management practices, this does not necessarily provide a comprehensive portrayal of the industry's best practices. Due to data limitations, the LCA results may have a degree of uncertainty. This thesis mainly aims to outline the supply chain of medical oxygen and add to the limited work on the environmental impacts of industrial and medical gases. Readers should use the reported results and information with caution. Also, the numbers reported in the results are accurate to not more than three significant digits. Additional digits increase uncertainty and add false precision to the results.

Certain life cycle activities were omitted during modelling (see Table 7), as these activities would be more time-consuming to model, and more expert knowledge, consultation, and manufacturer data would be needed. Oxygen is tested before delivery to a patient to ensure it meets regulatory guidelines for it to be classified as a medical gas. The equipment and materials for testing were not considered. Moreover, the waste and losses in medical oxygen's life cycle were not modelled. Results may thus not be complete for healthcare practitioners to make meaningful change at the user end, as additional activities and losses may increase the environmental impact of medical oxygen.

Chapter 7 Conclusion

This thesis focused on an important service delivery sector: healthcare. Access to healthcare is needed by the 7.8 billion global population. However, such an important sector contributes to environmental impacts, which can in turn harm public health. There is an urgency for environmental sustainability studies, with experts and policymakers increasing their awareness of this area. Additionally, resource use and resilience of health systems are essential topics to the sustainability discussion. In particular, medical oxygen, has been under scrutiny due to shortages during the COVID-19 pandemic. It is a vital healthcare product provided to a patient to achieve minimum required oxygen blood saturation. Understanding the medical oxygen supply chain, its environmental impacts, and critical resilience-related issues is thus vital in creating uninterrupted resource availability and reducing burdens on the environment.

This thesis answers the question: “What is the environmental impact of medical oxygen?” and meets the objective of quantifying the potential environmental impacts using a “bottom-up” approach such as LCA. Four product systems through which oxygen is produced and delivered to a patient were considered. The global warming potential value of medical oxygen is 1.70×10^{-4} kg CO_2eq per litre of gaseous oxygen for a North American scenario involving liquid oxygen production through cryogenic distillation, transporting the liquid oxygen to a hospital, where it is stored, gasified, and piped to patient rooms for use. This study looks at additional environmental indicator categories, apart from carbon footprint, which is the focus of most published literature. Of note is that electricity used during oxygen production is an important factor in driving the environmental indicator values. Using cylinders in the medical oxygen supply chain significantly increases the environmental impact of medical oxygen.

Recommendations from this research include further research into switching to oxygen production at a hospital site through a PSA plant, which showed lower potential environmental impacts by reducing reliance on liquid oxygen transportation and cylinder transportation and use. This research also identifies losses and inefficiencies in the supply chain, hence offering insight on how to build a resilient supply chain. A discussion on oxygen use and management practices was also presented.

This study adds to the growing body of literature on the life cycle assessment of medical oxygen. This thesis looks at the oxygen supply chain in more detail than existing studies, and comments on the supply chain resilience of medical oxygen and how industrial gas suppliers and medical facilities can use such work to study environmental impact, reduce losses and inefficiencies, and build resilient systems. The reported numbers are lower than reported in existing literature, which may be attributed to methodological and geographical considerations. This thesis aims to encourage industrial and medical experts to use the framework and conduct an LCA using primary data. Given the imminence of pressing issues such as climate change and supply chain risk, medical resources – particularly medical gases – and sustainable development should be paid more attention to create an environmentally sustainable health system.

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Appendix A
Calculations

The tables in this Appendix show all the processes across the four product systems as they were modelled using ecoinvent 3.8 and openLCA. Generally, the tables have the following columns: Flow, Amount, Calculations, and Provider. The “Flow” column shows the name of the input or output flow taken from the ecoinvent 3.8 database. The “Amount” column indicates the amount of the flow. The “Calculations” column shows the steps taken to calculate the flow amount. The “Provider” column shows the chosen process already modelled in the database and is in the following format “process | output | location.” This column contains some acronyms and phrases, which are defined as follows:

1. APOS means “Allocation at the point of substitution” which is an “attributional approach in which the responsibility over wastes (burdens) are shared between producers and sub-sequent users benefiting of the treatment processes by using valuable products generated in these” (*System Models*, 2020).
2. “U” refers to unit process, which means that it is a gate-to-gate LCA process.
3. CA-ON refers to the province of Ontario in Canada. CA-QC refers to the province of Quebec in Canada. CA-QC was chosen in cases where an Ontario-based process was not found. RoW refers to rest of the world. RoW was chosen in cases where a Canadian-based process was not found – it shows the average process calculations for available geographies in the world. GLO refers to global.
4. EURO6 refers to the standard for transportation lorries – the lorries are classified using the European emission standards, as Euro VI. The emission standards list the limits pollutant emissions for vehicles.
5. “Market for…” means a market-based process, which shows the “consumption mix of a product for a given region, accounting for the trade between the producer and consumer, and, when needed, for product losses that occur during the product’s transportation” (*System Models*, 2020).

Modelling for liquid oxygen delivery system

Liquid oxygen delivery to hospital bed | no. of oxygen bed days | ON

Flow	Amount	Calculations	Provider	References
Inputs				
oxygen, liquid	3.86 kg	Step 1: Volume of liquid oxygen needed = volume of oxygen gas needed ÷ liquid to gaseous oxygen conversion factor = 2,900 L ÷ 860 = 3.38 L Step 2: Mass of liquid oxygen needed = Volume of liquid oxygen × density of liquid oxygen = 3.38 L × 1,141 kg/m3 ÷ 1,000 L/m3 = 3.86 kg	air separation, cryogenic | oxygen, liquid | APOS, U (Ontario) - CA-ON	(Air Products and Chemicals, Inc., 2015)
transport, freight, lorry >32 metric ton, EURO6	1,000 kg*km	Mass of liquid oxygen to be transported over a unit of distance = mass of liquid oxygen × transport distance × 2 = 3.86 kg × 260 km = 1,000 kg-km	transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	(*Ecoinvent - Life Cycle Inventory Database. Version 3.8*, 2021)
Outputs				
no. of oxygen bed days_1	1 d			

Modelling of the ASU operation

air separation, cryogenic | oxygen, liquid | APOS, U (Ontario) - CA-ON

Flow	Amount	Calculations	Provider	References
Inputs				
air separation facility	1.12E-09 Item(s)	N/A – process and calculations taken from the ecoinvent 3.8 database	market for air separation facility | air	(*Ecoinvent - Life Cycle Inventory Database.*

			separation facility | APOS, U - GLO	*Version 3.8*, 2021)
Argon-40	0.024823 kg			
electricity, medium voltage	1.41848 kWh		market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	
Nitrogen	1.338691 kg			
Oxygen	0.409586 kg			
Water, cooling, unspecified natural origin	0.053885 m3			
Outputs				
oxygen, liquid	1 kg			
Water	0.02088 m3			
Water	0.033004 m3			

Modelling for cylinder delivery system
Cylinder filling and delivery to hospital | no. of oxygen bed days | ON

Flow	Amount	Calculations	Provider	References
Inputs				
oxygen, liquid	3.86 kg	same as product system 1	air separation, cryogenic | oxygen, liquid | APOS, U (Ontario) - CA-ON	
transport, freight, lorry >32 metric ton, EURO6	1,000 kg*km	same as product system 1	transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	
no. of cylinders	0.0110 Item(s)	Step 1: No. of E cylinders required per oxygen bed day = volume of oxygen gas needed ÷ volume of oxygen gas contained within one E cylinder = 2,900 L ÷ 690 L = 4.22 E cylinders Step 2: No. of E cylinders required per oxygen bed week = No. of E cylinders required per oxygen bed day × 7 = 4.22 E cylinders × 7 = 29.5 = 30 E cylinders Step 3: No. of cylinder reuses over lifetime = life of a cylinder × no. of uses in a year for 1 E cylinder = 15 years × 26 = 390 reuses/cylinder (Assume that a cylinder is used every other week - it is used for one week and re-	Aluminum cylinder production | no. of cylinders | ON	(Air Liquide Healthcare Canada, n.d.) (ABC Fire & Safety Equipment Ltd., n.d.; Government of Canada, 2019)

		filled in the second week, hence 26 uses/year) Step 4: No. of cylinders per use = no. of E cylinders ÷ no. of cylinder reuses over lifetime = 1 E cylinder ÷ 390 reuses = 0.00256 cylinders/use Step 5: No. of E cylinder uses per oxygen bed day = no. of E cylinders per use × no. of cylinder required per oxygen bed day = 0.00256 cylinders/use × (30 ÷ 7) cylinders/bed day = 0.0110 cylinders/oxygen bed day		
oxygen compressor operation	0.314 kWh	Step 1: No. of hours for oxygen compressor operation = volume of oxygen in 1 E cylinder × no. of E cylinders required per oxygen bed day ÷ flowrate = (690 L ÷ 1000 L) × (30 ÷ 7) ÷ 530 m^3/hour = 0.00558 hours (Note: Air compressor rated at flowrate of 4-1600 m^3/hour chosen with an output pressure of > 2000 psig) Step 2: Electricity required for filling cylinders for one oxygen bed day = compressor rated power × motor efficiency × no. of hours for operation = 75 kW × 75% × 0.00558 hours = 0.314 kWh (Note: Air compressor rated at 2-250 kW power chosen, motor efficiency is around 75%)	cylinder filling pressurizing operation | oxygen compressor operation | ON	(Gardner Denver, n.d.) (U.S. Department of Energy, n.d.)

transport, freight, lorry 7.5-16 metric ton, EURO6	1,540 kg*km	Step 1: Mass of empty E cylinders needed for one oxygen bed day = mass of one E cylinder × no. of E cylinders needed = 3.54 kg × (30 ÷ 7) E cylinders = 15.2 kg Step 2: Mass of oxygen gas in one E cylinder = density of the gas × volume = 1.33 kg/m3 × 690 L ÷ 1,000 L/m3 = 0.918 kg Step 3: Mass of filled cylinders = (mass of oxygen gas in one E cylinder + mass of one E cylinder) × no. of E cylinders needed = (0.918 kg + 3.54 kg) × (30 ÷ 7) E cylinders = 19.1 kg Step 4: Mass of oxygen cylinders to be transported over a unit of distance = (mass of filled cylinders × transport distance) + (mass of empty cylinders × transport distance) = (15.2 kg × 45 km) + (19.1 kg × 45 km) = 1,540 kg-km	transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, U - RoW	(Air Liquide Healthcare Canada, n.d.) (Air Products and Chemicals, Inc., 2015)
no. of cleaned cylinders	0.429 Item(s)	No. of cleaned cylinders = no. of cylinders required per oxygen bed day × 10% = (30 ÷ 7) × 10% = 0.429 cylinders/oxygen bed day (Assume that 10% of the cylinders per oxygen bed day require cleaning)	cylinder cleaning | no. of cleaned cylinders | ON	(A. Siddhantakar, personal communication, Sept. 2022)
no. of maintained cylinders	0.00237 Item(s)	Step 1: Cylinder maintenance sessions over lifetime = no. of maintenance sessions over lifetime for 1 E cylinder × no. of cylinders required per	cylinder maintenance | no. of maintained cylinders | ON	(Compressed Gas Association, Inc., 2019)

		oxygen bed day = 3 × (30 ÷ 7) = 12.9 = 13 maintenance sessions (Note: cylinder maintenance happens every 5 years, and the lifetime of a cylinder is 15 years) Step 2: No. of maintained cylinders per oxygen bed day = cylinder maintenance sessions ÷ lifetime = 13 sessions ÷ (15 years × 365 days) = 0.00237 cylinders/oxygen bed day		
no. of tested cylinders	0.00164 Item(s)	Step 1: Cylinder hydrostatic test sessions over lifetime = no. of test sessions over lifetime for 1 E cylinder × no. of cylinders required per oxygen bed day = 2 × (30 ÷ 7) = 8.57 = 9 test sessions (Note: hydrostatic testing happens every 12 years, and the lifetime of a cylinder is 15 years - assume that a cylinder is tested twice in its life) Step 2: No. of tested cylinders per oxygen bed day = cylinder test sessions ÷ lifetime = 9 sessions ÷ (15 years × 365 days) = 0.00164 cylinders/oxygen bed day	hydrostatic testing | no. of tested cylinders | ON	(U.S. Government Publishing Office, 2018)
Output				
no. of oxygen bed days_2	1 d			

Modelling for cylinder production

Aluminum cylinder production | no. of cylinders | ON

Flow	Amount	Calculations	Provider	References
Inputs		N/A – process and calculations taken from the ecoinvent 3.8 database		
alkyd paint, white, without solvent, in 60% solution state	0.043285668 kg		market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without solvent, in 60% solution state | APOS, U - RoW	
aluminium alloy, AlMg3	2.07903064 kg		market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | APOS, U - GLO	
electricity, low voltage	0.277470628 MJ		market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	
electricity, medium voltage	0.277470628 MJ		market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	

heat, district or industrial, natural gas	1.101086612 MJ	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | APOS, U - CA-QC	
heat, district or industrial, other than natural gas	0.740934535 MJ	market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | APOS, U - CA-QC	
hot water tank factory	1.60E-07 Item(s)	market for hot water tank factory | hot water tank factory | APOS, U - GLO	
tap water	4.933699634 kg	market for tap water | tap water | APOS, U - CA-QC	
welding, arc, aluminium	0.061731217 m	market for welding, arc, aluminium | welding, arc, aluminium | APOS, U - GLO	
Outputs			
no. of cylinders	1 Item(s)		
waste aluminium	2.07903064 kg	market for waste aluminium | waste	

			aluminium | APOS, U - GLO	
wastewater, from residence	0.0049337 m3		market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	
Water	7.40E-04 m3			

Modelling for cylinder filling operation
cylinder filling pressurizing operation | oxygen compressor operation | ON

Flow	Amount	Calculations	Provider	References
Inputs		N/A – process and calculations taken from the ecoinvent 3.8 database		
electricity, low voltage	0.277326458 kWh		market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	
lubricating oil	5.13E-04 kg		market for lubricating oil | lubricating oil | APOS, U - RoW	
water pump, 22kW	7.81E-06 Item(s)		market for water pump, 22kW | water pump, 22kW | APOS, U - GLO	
Output				

oxygen compressor operation	1 MJ			
waste mineral oil	5.13E-04 kg		market for waste mineral oil | waste mineral oil | APOS, U - RoW	

Modelling for cylinder cleaning

cylinder cleaning | no. of cleaned cylinders | ON

Flow	Amount	Calculations	Provider	References
Inputs				
electricity, low voltage	1.19 kWh	Step 1: Electricity = electricity required for water pump + electricity required for air compressor + electricity required by rolling machine = (22 kW water pump × 75% motor efficiency × 1 hour operation) + (10 kW air compressor × 75% motor efficiency × 1 hour operation) + (3 kW rolling machine × 75% motor efficiency × 1 hour operation) = 26.3 kWh * Step 2: Electricity required for 1 cleaned cylinder = total electricity ÷ no. of cylinders washed over 1 hour = 26.3 kWh ÷ 22 cylinders = 1.19 kWh/cylinder	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	based on author's knowledge (Flexo Wash Leading Cleaning Solutions, n.d.)
heat, district or industrial, natural gas	0.503 MJ	Heat required for warm water = specific heat of water × mass of water × change in temperature = 4,184 J/kg-K × 4.8 kg × (313 K - 288 K) = 0.503 MJ (Note: 313 K = 40 °C, 288 K = 15 °C)	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | APOS, U - CA-QC	based on author's knowledge

soap	0.0193 kg	Step 1: Dishwashing detergent ratio = 1 tablespoon of liquid detergent to 1 gallon of water = (14.8 mL × 1.03 g/mL) ÷ (3,790 mL) = 0.00402 g/mL or 0.00402 kg/L Step 2: Total washing detergent required = 0.00402 kg/L × 4.8 L = 0.0193 kg (4.8 L is the amount of water required for washing 1 E cylinder)	market for soap | soap | APOS, U - GLO	(Luxfer Cylinders, n.d.)
water, completely softened	4.8 kg	Water required = volume of 1 E cylinder = 4.8 L or 4.8 kg	market for water, completely softened | water, completely softened | APOS, U - US	
Outputs				
no. of cleaned cylinders	1 Item(s)			
wastewater, from residence	0.0048 m3	Wastewater amount = amount of water for washing = 4.8 L or 0.0048 m^3	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	

Notes:
* Cylinder cleaning: Water pump is used for pumping water for washing; air compressor is used for providing air for drying; rolling machine is a conveyor belt onto which the cylinders are rolled while the pump sprays water

Modelling for cylinder maintenance

cylinder maintenance | no. of maintained cylinders | ON

Flow	Amount	Calculations	Provider	References
Inputs				
alkyd paint, white, without solvent, in 60% solution state	0.0433 kg	<u>Step 1:</u> Paint required for 1 E cylinder = Surface area of 1 E cylinder = 2 × π × radius^2 + 2 × π × radius × height = (3.14 × 2^2) + (2 × 3.14 × 2 × 29) = 390 inch^2 (or 0.251 m^2) (Note: 1 E cylinder has dimensions of 4 × 29 inches. The formula for the surface area of a normal cylindrical shape is assumed for the oxygen cylinder) <u>Step 2:</u> Paint required for 1 E cylinder = 1.6 kg/9.29 m^2 × 0.251 m^2 = 0.0433 kg	market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without solvent, in 60% solution state | APOS, U - RoW	(*Paint Calculator*, n.d.)
dichloromethane	0.217 kg	Paint remover required for 1 E cylinder = 5.02 kg/5.81 m^2 of paint remover × 0.251 m^2 = 0.217 kg paint remover or dichloromethane	market for dichloromethane | dichloromethane | APOS, U - RoW	(TotalBoat, n.d.)
transport, freight, lorry 3.5-7.5 metric ton, EURO6	70.8 kg*km	Mass of 1 E cylinder transported over a unit of distance = mass of 1 empty cylinder × transport distance × 2 = 3.54 kg × 20 km = 70.8 kg-km	transport, freight, lorry 3.5-7.5 metric ton, EURO6 | transport, freight, lorry 3.5-7.5 metric ton, EURO6 | APOS, U - RoW	
Outputs				
no. of maintained cylinders	1 Item(s)			

waste paint	0.0433 kg	Waste paint (estimated) = paint required for 1 E cylinder = 0.0433 kg (Assume that paint and corrosion removed from cylinder would be = fresh paint required for 1 cylinder)	market for waste paint | waste paint | APOS, U - RoW	

Modelling for cylinder hydrostatic testing

hydrostatic testing | no. of tested cylinders | ON

Flow	Amount	Calculations	Provider	References
Inputs				
electricity, low voltage	5.44 kWh	Step 1: No. of hours for hydrostatic system pump operation = volume of water filled ÷ flowrate + time for pressurizing = 106 L ÷ 21 L/min + 30 min = 35.0 min or 0.584 hours (Note: Pump rated at flowrate of 21 L/min chosen with an output pressure of >3600 psig; assume that the test system is pressurized for 30 min) Step 2: Electricity required for pressurizing the test system = pump rated power × motor efficiency × no. of hours for operation = 9.32 kW × 75% × 0.584 hours = 5.44 kWh (Note: Pump rated at 12.5 hp or 9.32 kW power chosen, motor efficiency is around 75%)	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	(Hydro Technology Systems Inc., n.d.; MD Highjet Pump & Systems, n.d.)
transport, freight, lorry 3.5-7.5 metric ton, EURO6	70.8 kg*km	Mass of 1 E cylinder transported over a unit of distance = mass of 1 empty cylinder × transport distance × 2 = 3.54 kg × 20 km = 70.8 kg-km	transport, freight, lorry 3.5-7.5 metric ton, EURO6 | transport, freight, lorry	

			3.5-7.5 metric ton, EURO6 | APOS, U - RoW	
water, completely softened	106 kg	Water required for the hydrostatic test = amount of water filled in 1 E cylinder + amount of water filled in the test jacket = 4.8 L + 101 L = 106 L or 106 kg	market for water, completely softened | water, completely softened | APOS, U - US	(calculated based on volume of cylinder and test jacket)
Outputs				
no. of tested cylinders	1 Item(s)			
wastewater, from residence	0.106 m^3	Wastewater amount = amount of water for the hydrostatic test = 106 L or 0.106 m^3	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	

Modelling for PSA plant system

Oxygen gas delivery from PSA plant to hospital bed | no. of oxygen bed days | ON

Flow	Amount	Calculations	Provider	References
Inputs				
oxygen gas_3	3.10 m^3	Volume of oxygen gas needed for one oxygen bed day = reference flow for product systems 3 and 4 = 3,097 L or 3.10 m^3	Oxygen gas production from PSA plant | oxygen gas | ON	
Output				
no. of oxygen bed days_3	1 d			

Modelling for oxygen gas production from PSA plant

Oxygen gas production from PSA plant | oxygen gas | ON

Flow	Amount	Calculations	Provider	References
Inputs				
electricity, medium voltage	2850 kWh	Electricity used per day = energy usage of PSA plant × maximum flowrate of PSA plant × time = 1.22 kWh/Nm^3 × 97.3 Nm^3/hour × 24 hours/day = 2,850 kWh	market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	(AirSep Corporation, 2017)
maintenance, PSA plant	0.000137 Item(s)	No. of plants needed per day = 1 plant ÷ life cycle of plant = 1 plant ÷ (20 years × 365 days/year) = 0.000137 plants per day (Note: the life of a PSA plant is 20 years)	PSA plant maintenance | maintenance, PSA plant | ON	(Kohlheb et al., 2021)
Outputs				

oxygen gas_3	2510 m3	Step 1: convert Nm^3/hour to m^3/hour: Combined gas law = $P_1V_1/T_1 = P_2V_2/T_2$ Since pressure does not change, the formula can be simplified: $V_1/T_1 = V_2/T_2$ $V_1 = 97.3 \times 294\ K \div 273\ K = 105\ m^3$/hour (Note: 294 K = 21 °C, 273 K = 0 °C) Step 2: Maximum capacity of the PSA plant = 105 m^3/hour × 24 hours/day = 2,510 m^3 per day		based on author's knowledge
Water, CA	12.0 m3	Step 1: divide air into its various components - 78% nitrogen, 21% oxygen, 0.9% argon and 0.1% water vapor by volume Volume of air required = volume of oxygen produced by PSA plant per day ÷ 21% = 2,510 m^3 ÷ 21% = 12,000 m^3 Step 2: Volume of water discharged from PSA plant operation = 0.1% × 12,000 m^3 = 12.0 m^3		

Modelling for PSA plant maintenance

PSA plant maintenance | maintenance, PSA plant | ON

Flow	Amount	Calculations	Provider	References
Inputs				
air filter, in exhaust air valve	176 Item(s)	Step 1: Life of a PSA plant = 20 years × 365 days/year × 24 hours/day = 175,000 hours Step 2: No. of filters over lifetime = 175,000 hours ÷ 2,000 hours/filter = 88 filters Since there are two types of filters, the above no. is multiplied by two = 176 filters/lifetime** (Note: A filter should be changed every 2,000 hours)	market for air filter, in exhaust air valve | air filter, in exhaust air valve | APOS, U - GLO	(Kohlheb et al., 2021) (Chicago Pneumatic, n.d.)
ultrafiltration module	22 Item(s)	No. of air-oil separators needed over lifetime = 175,000 hours ÷ 8,000 hours/separator = 22 air-oil separators** (Note: An air-oil separator should be changed every 8,000 hours)	market for ultrafiltration module | ultrafiltration module | APOS, U - GLO	(Chicago Pneumatic, n.d.)
zeolite, powder	2790 kg	Step 1: Convert oxygen flowrate to mass basis: 105 m^3 per hour × 1.33 kg/m^3 = 139 kg per hour (Note: 105 m^3 is the per hour output of the chosen PSA plant)	market for zeolite, powder | zeolite, powder | APOS, U - GLO	

		Step 2: Mass of adorbent ratio = 0.1 kg oxygen per hour per 1 kg of adsorbent Based on the above, total mass of zeolite needed over lifetime = (139 kg oxygen per hour ÷ 0.1 kg/hr/1 kg adsorbent) × 2 = 2,790 kg (Note: Zeolite is assumed to be replaced every 10 years)		(Ashcraft & Swenton, n.d.)
Outputs				
maintenance, PSA plant	1 Item(s)			
used air filter in exhaust air valve	198 Item(s)	Waste air filter items = used filters + used air-oil separators = 176 + 22 = 198 items	treatment of used air filter, in exhaust air valve | used air filter in exhaust air valve | APOS, U - RoW	
waste zeolite	2790 kg	waste zeolite = mass of used zeolite = 2790 kg	treatment of waste zeolite, inert material landfill | waste zeolite | APOS, U - RoW	

Notes:
PSA plant has the following components (World Health Organization, 2020):

• Air compressor with air dryer and pre-filters with automatic drains*;

• Filters**:
- pre-filter (>5 micron);
- coalescing filter (0.1 micron); and,
- coal filter (coal tower, alternatively activated carbon filter).

• oxygen generator unit;

• oxygen analyser for medical application;

• oxygen tank (receiver/buffer tank) with bacterial outlet filter.

*The air compressor can be oil-free or filtered oil-injected or oil-lubricated rotary screw type (World Health Organization, 2020). An oil-free compressor was assumed for the above calculations.
**Pre-filters are air filters (used for removing dust and foreign particles from air); coalescing filters are air-oil separators and remove water and aerosols from air (assumed to be an ultrafiltration module in the modelling); and coal filters are assumed to be air filters (used for removing impurities) in the above calculations.

Modelling for oxygen concentrator system

Oxygen gas delivery from oxygen concentrator to patient | no. of oxygen bed days | ON

Flow	Amount	Calculations	Provider	References
Inputs				
oxygen gas_4	3.10 m3	Volume of oxygen gas needed for one oxygen bed day = reference flow for product systems 3 and 4 = 3,097 L or 3.10 m^3	Oxygen gas production from oxygen concentrator | oxygen gas | ON	
Output				
no. of oxygen bed days_4	1 d			

Modelling for oxygen gas production from oxygen concentrator

Oxygen gas production from oxygen concentrator | oxygen gas | ON

Flow	Amount	Calculations	Provider	References
Inputs				
electricity, medium voltage	19.3 kWh	<u>Step 1:</u> convert 0.48 m^3/hour to Nm^3/hour: Combined gas law = $P_1V_1/T_1 = P_2V_2/T_2$ Since pressure does not change, the formula can be simplified: $V_1/T_1 = V_2/T_2$ $V_1 = 0.48 \times 273$ K ÷ 294 K = 0.447 Nm^3/hour (Note: 8 L/min = 0.48 m^3/hour; and 294 K = 21 °C, 273 K = 0 °C) <u>Step 2:</u> Electricity used per day = energy usage of oxygen concentrator × maximum flowrate of oxygen concentrator × time = 1.8 kWh/Nm^3 × 0.447 Nm^3/hour × 24 hours/day = 19.3 kWh	market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	based on author's knowledge (J. Klein, personal communication, November 24, 2021)

maintenance, oxygen concentrator	0.000548 Items(s)	No. of units needed per oxygen bed day = 1 oxygen concentrator ÷ life cycle of concentrator = 1 ÷ (5 years × 365 days/year) = 0.000548 oxygen concentrator items per oxygen bed day (Note: the life of an oxygen concentrator is 5 years)	Oxygen concentrator maintenance | maintenance, oxygen concentrator | ON	(Ridl, 2013)
Output				
oxygen gas_4	11.5 m3	Maximum capacity of the oxygen concentrator = 8 L/min ÷ 1000 L/m^3 × 60 min/hour × 24 hours/day = 11.5 m^3 per day		

Modelling for oxygen concentrator maintenance

Oxygen concentrator maintenance | maintenance, oxygen concentrator | ON

Flow	Amount	Calculations	Provider	References
Inputs				
air filter, in exhaust air valve	3 Item(s)	No. of filters over lifetime = 5 years ÷ 2 years/filter = 2.5 = 3 filters (Note: An air filter should be changed every 2 years)	market for air filter, in exhaust air valve | air filter, in exhaust air valve | APOS, U - GLO	(Oxygen Always, 2018)
tap water	240 kg	Water required for filter cleaning = 4 L × 5 years × 12 times/year = 240 L or 240 kg (Assume that 4 L of water is used per wash. Filter is washed once every month)	market for tap water | tap water | APOS, U - CA-QC	
Outputs				
maintenance, oxygen concentrator	1 Item(s)			
used air filter in exhaust air valve	3 Item(s)	Waste filter items = used filters = 3 items	treatment of used air filter, in exhaust air valve | used air filter	

			in exhaust air valve | APOS, U - RoW	
wastewater, from residence	0.24 m3	Wastewater amount = amount of water for washing = 240 kg = 240 L or 0.0048 m^3	treatment of wastewater, from residence, capacity 1.1E10l/year | wastewater, from residence | APOS, U - RoW	

Appendix B

Results

Results for product system 1 - liquid oxygen delivery

GWP

Contribution			Process	Amount (kg CO2 eq)
100.00%			Liquid oxygen delivery to hospital bed | no. of oxygen bed days | ON	0.49424
	81.91%		air separation, cryogenic | oxygen, liquid | APOS, U (Ontario) - CA-ON	0.40484
		81.19%	market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	0.40128
		0.72%	market for air separation facility | air separation facility | APOS, U - GLO	0.00356
	18.09%		transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	0.08939
		2.75%	market for road | road | APOS, U - GLO	0.01361
		1.83%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - RoW	0.00905
		0.45%	market for lorry, 16 metric ton | lorry, 16 metric ton | APOS, U - RoW	0.00221
		0.30%	market for maintenance, lorry 16 metric ton | maintenance, lorry 16 metric ton | APOS, U - RoW	0.00149
		0.29%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - ZA	0.00145
		0.25%	market for road maintenance | road maintenance | APOS, U - RoW	0.00123
		0.19%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - IN	0.00096
		0.08%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - CO	0.00039
		0.06%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - BR	0.00031
		0.01%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - PE	2.54E-05

		0.00%	market for brake wear emissions, lorry | brake wear emissions, lorry | APOS, U - GLO	0
		0.00%	market for road wear emissions, lorry | road wear emissions, lorry | APOS, U - GLO	0
		0.00%	market for tyre wear emissions, lorry | tyre wear emissions, lorry | APOS, U - GLO	0

Fossil fuel depletion

Contribution			Process	Amount (MJ surplus)
100.00%			Liquid oxygen delivery to hospital bed | no. of oxygen bed days | ON	0.89512
	77.22%		air separation, cryogenic | oxygen, liquid | APOS, U (Ontario) - CA-ON	0.69121
		76.92%	market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	0.68849
		0.30%	market for air separation facility | air separation facility | APOS, U - GLO	0.00272
	22.78%		transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	0.20391
		14.61%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - RoW	0.13077
		4.90%	market for road | road | APOS, U - GLO	0.04383
		1.26%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - IN	0.01129
		0.61%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - CO	0.00542
		0.59%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - BR	0.00527
		0.27%	market for maintenance, lorry 16 metric ton | maintenance, lorry 16 metric ton | APOS, U - RoW	0.00239
		0.26%	market for lorry, 16 metric ton | lorry, 16 metric ton | APOS, U - RoW	0.00232
		0.15%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - ZA	0.00135

		0.10%	market for road maintenance | road maintenance | APOS, U - RoW	0.00091
		0.04%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - PE	0.00036
		0.00%	market for brake wear emissions, lorry | brake wear emissions, lorry | APOS, U - GLO	0
		0.00%	market for road wear emissions, lorry | road wear emissions, lorry | APOS, U - GLO	0
		0.00%	market for tyre wear emissions, lorry | tyre wear emissions, lorry | APOS, U - GLO	0

Carcinogens

Contribution			Process	Amount (CTUh)
100.00%			Liquid oxygen delivery to hospital bed | no. of oxygen bed days | ON	6.22E-08
	92.38%		air separation, cryogenic | oxygen, liquid | APOS, U (Ontario) - CA-ON	5.74E-08
		88.33%	market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	5.49E-08
		4.05%	market for air separation facility | air separation facility | APOS, U - GLO	2.52E-09
	7.62%		transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	4.74E-09
		3.04%	market for road | road | APOS, U - GLO	1.89E-09
		2.89%	market for lorry, 16 metric ton | lorry, 16 metric ton | APOS, U - RoW	1.80E-09
		0.68%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - RoW	4.25E-10
		0.42%	market for maintenance, lorry 16 metric ton | maintenance, lorry 16 metric ton | APOS, U - RoW	2.60E-10
		0.29%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - ZA	1.78E-10
		0.13%	market for road maintenance | road maintenance | APOS, U - RoW	8.01E-11

		0.06%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - IN	3.83E-11
		0.05%	market for tyre wear emissions, lorry | tyre wear emissions, lorry | APOS, U - GLO	2.91E-11
		0.03%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - CO	1.88E-11
		0.01%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - BR	8.55E-12
		0.01%	market for brake wear emissions, lorry | brake wear emissions, lorry | APOS, U - GLO	5.23E-12
		0.00%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - PE	1.29E-12
		0.00%	market for road wear emissions, lorry | road wear emissions, lorry | APOS, U - GLO	0

Non-carcinogens

Contribution			Process	Amount (CTUh)
100.00%			Liquid oxygen delivery to hospital bed | no. of oxygen bed days | ON	2.09E-07
	89.83%		air separation, cryogenic | oxygen, liquid | APOS, U (Ontario) - CA-ON	1.87E-07
		88.01%	market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	1.84E-07
		1.83%	market for air separation facility | air separation facility | APOS, U - GLO	3.81E-09
	10.17%		transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	2.12E-08
		3.46%	market for tyre wear emissions, lorry | tyre wear emissions, lorry | APOS, U - GLO	7.23E-09
		2.61%	market for brake wear emissions, lorry | brake wear emissions, lorry | APOS, U - GLO	5.46E-09
		1.57%	market for lorry, 16 metric ton | lorry, 16 metric ton | APOS, U - RoW	3.27E-09
		0.99%	market for road | road | APOS, U - GLO	2.07E-09

		0.48%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - RoW	1.01E-09
		0.29%	market for maintenance, lorry 16 metric ton | maintenance, lorry 16 metric ton | APOS, U - RoW	6.09E-10
		0.24%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - ZA	4.92E-10
		0.13%	market for road maintenance | road maintenance | APOS, U - RoW	2.66E-10
		0.04%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - IN	8.85E-11
		0.02%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - CO	4.16E-11
		0.01%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - BR	3.06E-11
		0.00%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - PE	2.85E-12
		0.00%	market for road wear emissions, lorry | road wear emissions, lorry | APOS, U - GLO	0

Respiratory effects

Contribution			Process	Amount (kg PM2.5 eq)
100.00%			Liquid oxygen delivery to hospital bed | no. of oxygen bed days | ON	0.00028
	77.60%		air separation, cryogenic | oxygen, liquid | APOS, U (Ontario) - CA-ON	0.00022
		75.61%	market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	0.00021
		1.99%	market for air separation facility | air separation facility | APOS, U - GLO	5.57E-06
	22.40%		transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	6.27E-05
		7.63%	market for road | road | APOS, U - GLO	2.14E-05
		3.88%	market for tyre wear emissions, lorry | tyre wear emissions, lorry | APOS, U - GLO	1.09E-05

		3.19%	market for brake wear emissions, lorry | brake wear emissions, lorry | APOS, U - GLO	8.94E-06
		2.92%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - RoW	8.19E-06
		1.68%	market for road wear emissions, lorry | road wear emissions, lorry | APOS, U - GLO	4.71E-06
		1.05%	market for lorry, 16 metric ton | lorry, 16 metric ton | APOS, U - RoW	2.95E-06
		0.67%	market for road maintenance | road maintenance | APOS, U - RoW	1.87E-06
		0.59%	market for maintenance, lorry 16 metric ton | maintenance, lorry 16 metric ton | APOS, U - RoW	1.65E-06
		0.23%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - IN	6.49E-07
		0.20%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - ZA	5.72E-07
		0.11%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - CO	3.02E-07
		0.06%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - BR	1.58E-07
		0.01%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - PE	2.23E-08

Ecotoxicity

Contribution			Process	Amount (CTUe)
100.00%			Liquid oxygen delivery to hospital bed | no. of oxygen bed days | ON	15.27103
	95.64%		air separation, cryogenic | oxygen, liquid | APOS, U (Ontario) - CA-ON	14.60553
		93.63%	market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	14.29844
		2.01%	market for air separation facility | air separation facility | APOS, U - GLO	0.30709
	4.36%		transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	0.6655

		1.40%	market for brake wear emissions, lorry | brake wear emissions, lorry | APOS, U - GLO	0.21328
		1.10%	market for lorry, 16 metric ton | lorry, 16 metric ton | APOS, U - RoW	0.1674
		0.78%	market for road | road | APOS, U - GLO	0.11851
		0.45%	market for tyre wear emissions, lorry | tyre wear emissions, lorry | APOS, U - GLO	0.06852
		0.24%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - RoW	0.03737
		0.17%	market for maintenance, lorry 16 metric ton | maintenance, lorry 16 metric ton | APOS, U - RoW	0.0257
		0.11%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - ZA	0.01665
		0.08%	market for road maintenance | road maintenance | APOS, U - RoW	0.01148
		0.02%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - IN	0.0033
		0.01%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - CO	0.0016
		0.01%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - BR	0.00098
		0.00%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - PE	0.00011
		0.00%	market for road wear emissions, lorry | road wear emissions, lorry | APOS, U - GLO	0

Results for product system 2 - cylinder delivery

GWP

Contribution			Process	Amount (kg CO2 eq)
100.00%			Cylinder delivery to hospital bed | no. of oxygen bed days | ON	1.19666
	33.83%		air separation, cryogenic | oxygen, liquid | APOS, U (Ontario) - CA-ON	0.40484
	28.64%		transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, U - RoW	0.34277
		2.86%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - RoW	0.03418
		1.75%	market for road | road | APOS, U - GLO	0.0209
		1.66%	market for lorry, 16 metric ton | lorry, 16 metric ton | APOS, U - RoW	0.01983
		1.11%	market for maintenance, lorry 16 metric ton | maintenance, lorry 16 metric ton | APOS, U - RoW	0.01332
		0.77%	market for road maintenance | road maintenance | APOS, U - RoW	0.00919
		0.46%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - ZA	0.00548
		0.30%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - IN	0.00364
		0.12%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - CO	0.00149
		0.10%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - BR	0.00117
		0.01%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - PE	9.59E-05
		0.00%	market for brake wear emissions, lorry | brake wear emissions, lorry | APOS, U - GLO	0
		0.00%	market for road wear emissions, lorry | road wear emissions, lorry | APOS, U - GLO	0
		0.00%	market for tyre wear emissions, lorry | tyre wear emissions, lorry | APOS, U - GLO	0
	17.68%		Aluminum cylinder production | no. of cylinders | ON	0.21155

		17.09%	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | APOS, U - GLO	0.20447
		0.25%	market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without solvent, in 60% solution state | APOS, U - RoW	0.00302
		0.09%	market for hot water tank factory | hot water tank factory | APOS, U - GLO	0.00112
		0.08%	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | APOS, U - CA-QC	0.00098
		0.08%	market for waste aluminium | waste aluminium | APOS, U - GLO	0.00093
		0.06%	market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | APOS, U - CA-QC	0.00066
		0.02%	market for welding, arc, aluminium | welding, arc, aluminium | APOS, U - GLO	0.00021
		0.01%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	6.70E-05
		0.01%	market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	6.21E-05
		0.00%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	2.96E-05
		0.00%	market for tap water | tap water | APOS, U - CA-QC	1.09E-05
	9.01%		cylinder cleaning | no. of cleaned cylinders | ON	0.10778
		4.00%	market for soap | soap | APOS, U - GLO	0.04792
		3.38%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	0.04041
		1.45%	market for heat, district or industrial, natural gas | heat, district or	0.01741

			industrial, natural gas | APOS, U - CA-QC		
		0.09%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	0.00112
		0.08%	market for water, completely softened | water, completely softened | APOS, U - US	0.00093
	7.47%		transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	0.08939
	3.08%		cylinder filling pressurizing operation | oxygen compressor operation | ON - CA-ON	0.03681
		2.07%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	0.02476
		0.85%	market for water pump, 22kW | water pump, 22kW | APOS, U - GLO	0.01022
		0.09%	market for waste mineral oil | waste mineral oil | APOS, U - RoW	0.00104
		0.07%	market for lubricating oil | lubricating oil | APOS, U - RoW	0.00078
	0.22%		cylinder maintenance | no. of maintained cylinders | ON	0.00258
		0.15%	market for dichloromethane | dichloromethane | APOS, U - RoW	0.00176
		0.05%	market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without solvent, in 60% solution state | APOS, U - RoW	0.00065
		0.01%	transport, freight, lorry 3.5-7.5 metric ton, EURO6 | transport, freight, lorry 3.5-7.5 metric ton, EURO6 | APOS, U - RoW	9.04E-05
		0.01%	market for waste paint | waste paint | APOS, U - RoW	8.18E-05
	0.08%		hydrostatic testing | no. of tested cylinders | ON	0.00094
		0.06%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	0.00071

		0.01%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	9.47E-05
		0.01%	market for water, completely softened | water, completely softened | APOS, U - US	7.81E-05
		0.01%	transport, freight, lorry 3.5-7.5 metric ton, EURO6 | transport, freight, lorry 3.5-7.5 metric ton, EURO6 | APOS, U - RoW	6.26E-05

Fossil fuel depletion

Contribution			Process	Amount (MJ surplus)
100.00%			Cylinder delivery to hospital bed | no. of oxygen bed days | ON	1.96087
	35.70%		transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, U - RoW	0.69999
		25.20%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - RoW	0.49413
		3.43%	market for road | road | APOS, U - GLO	0.06734
		2.18%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - IN	0.04265
		1.09%	market for maintenance, lorry 16 metric ton | maintenance, lorry 16 metric ton | APOS, U - RoW	0.02144
		1.06%	market for lorry, 16 metric ton | lorry, 16 metric ton | APOS, U - RoW	0.02079
		1.05%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - CO	0.0205
		1.02%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - BR	0.01992
		0.34%	market for road maintenance | road maintenance | APOS, U - RoW	0.00676
		0.26%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - ZA	0.00509
		0.07%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - PE	0.00136
		0.00%	market for brake wear emissions, lorry | brake wear emissions, lorry | APOS, U - GLO	0

		0.00%	market for road wear emissions, lorry | road wear emissions, lorry | APOS, U - GLO	0
		0.00%	market for tyre wear emissions, lorry | tyre wear emissions, lorry | APOS, U - GLO	0
	35.25%		air separation, cryogenic | oxygen, liquid | APOS, U (Ontario) - CA-ON	0.69121
	10.40%		transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	0.20391
	8.73%		Aluminum cylinder production | no. of cylinders | ON	0.17115
		8.25%	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | APOS, U - GLO	0.1617
		0.16%	market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without solvent, in 60% solution state | APOS, U - RoW	0.00311
		0.13%	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | APOS, U - CA-QC	0.00248
		0.07%	market for waste aluminium | waste aluminium | APOS, U - GLO	0.00138
		0.06%	market for hot water tank factory | hot water tank factory | APOS, U - GLO	0.00116
		0.05%	market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | APOS, U - CA-QC	0.00094
		0.01%	market for welding, arc, aluminium | welding, arc, aluminium | APOS, U - GLO	0.00012
		0.01%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	0.00011
		0.01%	market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	0.00011

		0.00%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	2.76E-05
		0.00%	market for tap water | tap water | APOS, U - CA-QC	9.64E-06
	6.84%		cylinder cleaning | no. of cleaned cylinders | ON	0.13404
		3.46%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	0.0679
		2.25%	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | APOS, U - CA-QC	0.04414
		1.02%	market for soap | soap | APOS, U - GLO	0.02002
		0.05%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	0.00104
		0.05%	market for water, completely softened | water, completely softened | APOS, U - US	0.00094
	2.87%		cylinder filling pressurizing operation | oxygen compressor operation | ON - CA-ON	0.05628
		2.12%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	0.04161
		0.49%	market for water pump, 22kW | water pump, 22kW | APOS, U - GLO	0.00963
		0.26%	market for lubricating oil | lubricating oil | APOS, U - RoW	0.00502
		0.00%	market for waste mineral oil | waste mineral oil | APOS, U - RoW	1.61E-05
	0.14%		cylinder maintenance | no. of maintained cylinders | ON	0.00282
		0.10%	market for dichloromethane | dichloromethane | APOS, U - RoW	0.00195
		0.03%	market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without solvent, in 60% solution state | APOS, U - RoW	0.00067

		0.01%	transport, freight, lorry 3.5-7.5 metric ton, EURO6 | transport, freight, lorry 3.5-7.5 metric ton, EURO6 | APOS, U - RoW	0.00018
		0.00%	market for waste paint | waste paint | APOS, U - RoW	2.31E-05
	0.08%		hydrostatic testing | no. of tested cylinders | ON	0.00148
		0.06%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	0.00119
		0.01%	transport, freight, lorry 3.5-7.5 metric ton, EURO6 | transport, freight, lorry 3.5-7.5 metric ton, EURO6 | APOS, U - RoW	1.20E-04
		0.00%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	8.82E-05
		0.00%	market for water, completely softened | water, completely softened | APOS, U - US	7.98E-05

Carcinogens

Contribution			Process	Amount (CTUh)
100.00%			Cylinder delivery to hospital bed | no. of oxygen bed days | ON	1.96E-07
	36.20%		Aluminum cylinder production | no. of cylinders | ON	7.08E-08
		35.70%	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | APOS, U - GLO	6.98E-08
		0.22%	market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without solvent, in 60% solution state | APOS, U - RoW	4.33E-10
		0.17%	market for hot water tank factory | hot water tank factory | APOS, U - GLO	3.26E-10
		0.04%	market for waste aluminium | waste aluminium | APOS, U - GLO	7.54E-11
		0.03%	market for welding, arc, aluminium | welding, arc, aluminium | APOS, U - GLO	5.38E-11

		0.01%	market for tap water | tap water | APOS, U - CA-QC	2.14E-11
		0.01%	market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | APOS, U - CA-QC	1.56E-11
		0.01%	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | APOS, U - CA-QC	1.40E-11
		0.01%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	1.38E-11
		0.01%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	1.22E-11
		0.00%	market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	8.50E-12
	29.37%		air separation, cryogenic | oxygen, liquid | APOS, U (Ontario) - CA-ON	5.74E-08
	13.32%		cylinder filling pressurizing operation | oxygen compressor operation | ON - CA-ON	2.61E-08
		10.97%	market for water pump, 22kW | water pump, 22kW | APOS, U - GLO	2.15E-08
		2.31%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	4.51E-09
		0.03%	market for lubricating oil | lubricating oil | APOS, U - RoW	6.55E-11
		0.01%	market for waste mineral oil | waste mineral oil | APOS, U - RoW	1.37E-11
	12.56%		transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, U - RoW	2.46E-08
		8.23%	market for lorry, 16 metric ton | lorry, 16 metric ton | APOS, U - RoW	1.61E-08
		1.49%	market for road | road | APOS, U - GLO	2.91E-09
		1.19%	market for maintenance, lorry 16 metric ton | maintenance, lorry 16 metric ton | APOS, U - RoW	2.33E-09

		0.82%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - RoW	1.61E-09
		0.34%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - ZA	6.72E-10
		0.31%	market for road maintenance | road maintenance | APOS, U - RoW	5.97E-10
		0.07%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - IN	1.45E-10
		0.04%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - CO	7.11E-11
		0.03%	market for tyre wear emissions, lorry | tyre wear emissions, lorry | APOS, U - GLO	6.06E-11
		0.02%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - BR	3.23E-11
		0.01%	market for brake wear emissions, lorry | brake wear emissions, lorry | APOS, U - GLO	1.09E-11
		0.00%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - PE	4.89E-12
		0.00%	market for road wear emissions, lorry | road wear emissions, lorry | APOS, U - GLO	0
	5.91%		cylinder cleaning | no. of cleaned cylinders | ON	1.16E-08
		3.77%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	7.36E-09
		1.68%	market for soap | soap | APOS, U - GLO	3.28E-09
		0.27%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	5.24E-10
		0.13%	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | APOS, U - CA-QC	2.48E-10
		0.07%	market for water, completely softened | water, completely softened | APOS, U - US	1.43E-10
	2.42%		transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	4.74E-09

		0.97%	market for road | road | APOS, U - GLO	1.89E-09
		0.92%	market for lorry, 16 metric ton | lorry, 16 metric ton | APOS, U - RoW	1.80E-09
		0.22%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - RoW	4.25E-10
		0.13%	market for maintenance, lorry 16 metric ton | maintenance, lorry 16 metric ton | APOS, U - RoW	2.60E-10
		0.09%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - ZA	1.78E-10
		0.04%	market for road maintenance | road maintenance | APOS, U - RoW	8.01E-11
		0.02%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - IN	3.83E-11
		0.01%	market for tyre wear emissions, lorry | tyre wear emissions, lorry | APOS, U - GLO	2.91E-11
		0.01%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - CO	1.88E-11
		0.00%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - BR	8.55E-12
		0.00%	market for brake wear emissions, lorry | brake wear emissions, lorry | APOS, U - GLO	5.23E-12
		0.00%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - PE	1.29E-12
		0.00%	market for road wear emissions, lorry | road wear emissions, lorry | APOS, U - GLO	0
	0.12%		cylinder maintenance | no. of maintained cylinders | ON	2.41E-10
		0.05%	market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without solvent, in 60% solution state | APOS, U - RoW	9.34E-11
		0.04%	market for dichloromethane | dichloromethane | APOS, U - RoW	8.64E-11
		0.03%	market for waste paint | waste paint | APOS, U - RoW	5.30E-11
		0.00%	transport, freight, lorry 3.5-7.5 metric ton, EURO6 | transport, freight, lorry	8.15E-12

			3.5-7.5 metric ton, EURO6 | APOS, U - RoW	
	0.10%		hydrostatic testing | no. of tested cylinders | ON	1.91E-10
		0.07%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	1.29E-10
		0.02%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	4.43E-11
		0.01%	market for water, completely softened | water, completely softened | APOS, U - US	1.20E-11
		0.00%	transport, freight, lorry 3.5-7.5 metric ton, EURO6 | transport, freight, lorry 3.5-7.5 metric ton, EURO6 | APOS, U - RoW	5.64E-12

Non-carcinogens

Contribution			Process	Amount (CTUh)
100.00%			Cylinder delivery to hospital bed | no. of oxygen bed days | ON	4.74E-07
	39.52%		air separation, cryogenic | oxygen, liquid | APOS, U (Ontario) - CA-ON	1.87E-07
	20.21%		Aluminum cylinder production | no. of cylinders | ON	9.59E-08
		19.59%	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | APOS, U - GLO	9.29E-08
		0.21%	market for waste aluminium | waste aluminium | APOS, U - GLO	9.77E-10
		0.14%	market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without solvent, in 60% solution state | APOS, U - RoW	6.72E-10
		0.11%	market for welding, arc, aluminium | welding, arc, aluminium | APOS, U - GLO	5.14E-10
		0.11%	market for hot water tank factory | hot water tank factory | APOS, U - GLO	5.13E-10

		0.02%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	9.39E-11
		0.02%	market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | APOS, U - CA-QC	8.09E-11
		0.01%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	4.75E-11
		0.01%	market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	2.84E-11
		0.00%	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | APOS, U - CA-QC	1.09E-11
		0.00%	market for tap water | tap water | APOS, U - CA-QC	1.03E-11
	15.84%		transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, U - RoW	7.51E-08
		6.19%	market for lorry, 16 metric ton | lorry, 16 metric ton | APOS, U - RoW	2.93E-08
		3.18%	market for tyre wear emissions, lorry | tyre wear emissions, lorry | APOS, U - GLO	1.51E-08
		2.40%	market for brake wear emissions, lorry | brake wear emissions, lorry | APOS, U - GLO	1.14E-08
		1.15%	market for maintenance, lorry 16 metric ton | maintenance, lorry 16 metric ton | APOS, U - RoW	5.46E-09
		0.80%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - RoW	3.82E-09
		0.67%	market for road | road | APOS, U - GLO	3.18E-09
		0.42%	market for road maintenance | road maintenance | APOS, U - RoW	1.98E-09
		0.39%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - ZA	1.86E-09
		0.07%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - IN	3.35E-10

		0.03%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - CO	1.57E-10
		0.02%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - BR	1.16E-10
		0.00%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - PE	1.08E-11
		0.00%	market for road wear emissions, lorry | road wear emissions, lorry | APOS, U - GLO	0
	11.08%		cylinder filling pressurizing operation | oxygen compressor operation | ON - CA-ON	5.26E-08
		7.33%	market for water pump, 22kW | water pump, 22kW | APOS, U - GLO	3.48E-08
		3.70%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	1.76E-08
		0.04%	market for lubricating oil | lubricating oil | APOS, U - RoW	2.09E-10
		0.01%	market for waste mineral oil | waste mineral oil | APOS, U - RoW	2.55E-11
	8.53%		cylinder cleaning | no. of cleaned cylinders | ON	4.05E-08
		6.04%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	2.87E-08
		1.64%	market for soap | soap | APOS, U - GLO	7.78E-09
		0.75%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	3.56E-09
		0.06%	market for water, completely softened | water, completely softened | APOS, U - US	2.79E-10
		0.04%	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | APOS, U - CA-QC	1.94E-10
	4.47%		transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	2.12E-08
	0.18%		hydrostatic testing | no. of tested cylinders | ON	8.41E-10

		0.11%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	5.02E-10
		0.06%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	3.01E-10
		0.00%	market for water, completely softened | water, completely softened | APOS, U - US	2.36E-11
		0.00%	transport, freight, lorry 3.5-7.5 metric ton, EURO6 | transport, freight, lorry 3.5-7.5 metric ton, EURO6 | APOS, U - RoW	1.48E-11
	0.17%		cylinder maintenance | no. of maintained cylinders | ON	7.84E-10
		0.08%	market for waste paint | waste paint | APOS, U - RoW	3.63E-10
		0.05%	market for dichloromethane | dichloromethane | APOS, U - RoW	2.54E-10
		0.03%	market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without solvent, in 60% solution state | APOS, U - RoW	1.45E-10
		0.00%	transport, freight, lorry 3.5-7.5 metric ton, EURO6 | transport, freight, lorry 3.5-7.5 metric ton, EURO6 | APOS, U - RoW	2.14E-11

Respiratory effects

Contribution			Process	Amount (kg PM2.5 eq)
100.00%			Cylinder delivery to hospital bed | no. of oxygen bed days | ON	0.00088
	34.33%		Aluminum cylinder production | no. of cylinders | ON	0.0003
		33.66%	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | APOS, U - GLO	0.0003
		0.30%	market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without solvent, in 60% solution state | APOS, U - RoW	2.65E-06

		0.15%	market for hot water tank factory | hot water tank factory | APOS, U - GLO	1.35E-06
		0.12%	market for waste aluminium | waste aluminium | APOS, U - GLO	1.03E-06
		0.04%	market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | APOS, U - CA-QC	3.51E-07
		0.04%	market for welding, arc, aluminium | welding, arc, aluminium | APOS, U - GLO	3.27E-07
		0.02%	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | APOS, U - CA-QC	1.39E-07
		0.00%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	4.38E-08
		0.00%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	4.17E-08
		0.00%	market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	3.28E-08
		0.00%	market for tap water | tap water | APOS, U - CA-QC	1.44E-08
	24.70%		air separation, cryogenic | oxygen, liquid | APOS, U (Ontario) - CA-ON	0.00022
	20.27%		transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, U - RoW	0.00018
		3.73%	market for road | road | APOS, U - GLO	3.28E-05
		3.52%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - RoW	3.10E-05
		3.01%	market for lorry, 16 metric ton | lorry, 16 metric ton | APOS, U - RoW	2.65E-05
		2.58%	market for tyre wear emissions, lorry | tyre wear emissions, lorry | APOS, U - GLO	2.27E-05

		2.12%	market for brake wear emissions, lorry | brake wear emissions, lorry | APOS, U - GLO	1.86E-05
		1.68%	market for maintenance, lorry 16 metric ton | maintenance, lorry 16 metric ton | APOS, U - RoW	1.48E-05
		1.58%	market for road maintenance | road maintenance | APOS, U - RoW	1.39E-05
		1.12%	market for road wear emissions, lorry | road wear emissions, lorry | APOS, U - GLO	9.82E-06
		0.28%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - IN	2.45E-06
		0.25%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - ZA	2.16E-06
		0.13%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - CO	1.14E-06
		0.07%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - BR	5.96E-07
		0.01%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - PE	8.41E-08
	7.96%		cylinder cleaning | no. of cleaned cylinders | ON	7.01E-05
		4.31%	market for soap | soap | APOS, U - GLO	3.79E-05
		3.00%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	2.64E-05
		0.28%	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | APOS, U - CA-QC	2.47E-06
		0.20%	market for water, completely softened | water, completely softened | APOS, U - US	1.72E-06
		0.18%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	1.58E-06
	7.13%		transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	6.27E-05

	5.29%		cylinder filling pressurizing operation | oxygen compressor operation | ON - CA-ON	4.66E-05
		3.37%	market for water pump, 22kW | water pump, 22kW | APOS, U - GLO	2.96E-05
		1.84%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	1.62E-05
		0.09%	market for lubricating oil | lubricating oil | APOS, U - RoW	7.59E-07
		0.00%	market for waste mineral oil | waste mineral oil | APOS, U - RoW	2.26E-08
	0.23%		cylinder maintenance | no. of maintained cylinders | ON	1.99E-06
		0.16%	market for dichloromethane | dichloromethane | APOS, U - RoW	1.37E-06
		0.06%	market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without solvent, in 60% solution state | APOS, U - RoW	5.71E-07
		0.01%	transport, freight, lorry 3.5-7.5 metric ton, EURO6 | transport, freight, lorry 3.5-7.5 metric ton, EURO6 | APOS, U - RoW	4.64E-08
		0.00%	market for waste paint | waste paint | APOS, U - RoW	3.70E-09
	0.09%		hydrostatic testing | no. of tested cylinders | ON	7.73E-07
		0.05%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	4.62E-07
		0.02%	market for water, completely softened | water, completely softened | APOS, U - US	1.45E-07
		0.02%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	1.33E-07
		0.00%	transport, freight, lorry 3.5-7.5 metric ton, EURO6 | transport, freight, lorry 3.5-7.5 metric ton, EURO6 | APOS, U - RoW	3.22E-08

Ecotoxicity

Contribution			Process	Amount (CTUe)
100.00%			Cylinder delivery to hospital bed | no. of oxygen bed days | ON	45.02777
	34.80%		cylinder filling pressurizing operation | oxygen compressor operation | ON - CA-ON	15.66788
		27.08%	market for water pump, 22kW | water pump, 22kW | APOS, U - GLO	12.19416
		7.69%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	3.46142
		0.03%	market for lubricating oil | lubricating oil | APOS, U - RoW	0.01161
		0.00%	market for waste mineral oil | waste mineral oil | APOS, U - RoW	0.0007
	32.44%		air separation, cryogenic | oxygen, liquid | APOS, U (Ontario) - CA-ON	14.60553
	13.89%		cylinder cleaning | no. of cleaned cylinders | ON	6.25216
		12.54%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	5.64813
		1.20%	market for soap | soap | APOS, U - GLO	0.54082
		0.08%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	0.03661
		0.03%	market for water, completely softened | water, completely softened | APOS, U - US	0.01498
		0.03%	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | APOS, U - CA-QC	0.01161
	10.86%		Aluminum cylinder production | no. of cylinders | ON	4.89207
		10.55%	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | APOS, U - GLO	4.75207
		0.12%	market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without solvent,	0.05628

			in 60% solution state | APOS, U - RoW	
		0.09%	market for waste aluminium | waste aluminium | APOS, U - GLO	0.04046
		0.05%	market for hot water tank factory | hot water tank factory | APOS, U - GLO	0.02443
		0.02%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	0.00937
		0.01%	market for welding, arc, aluminium | welding, arc, aluminium | APOS, U - GLO	0.00365
		0.00%	market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	0.00221
		0.00%	market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | APOS, U - CA-QC	0.00152
		0.00%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	0.00097
		0.00%	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | APOS, U - CA-QC	0.00065
		0.00%	market for tap water | tap water | APOS, U - CA-QC	0.00046
	6.25%		transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, U - RoW	2.81491
		3.33%	market for lorry, 16 metric ton | lorry, 16 metric ton | APOS, U - RoW	1.50038
		0.99%	market for brake wear emissions, lorry | brake wear emissions, lorry | APOS, U - GLO	0.44462
		0.51%	market for maintenance, lorry 16 metric ton | maintenance, lorry 16 metric ton | APOS, U - RoW	0.23038
		0.40%	market for road | road | APOS, U - GLO	0.18207

		0.32%	market for tyre wear emissions, lorry | tyre wear emissions, lorry | APOS, U - GLO	0.14285
		0.31%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - RoW	0.14122
		0.19%	market for road maintenance | road maintenance | APOS, U - RoW	0.08563
		0.14%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - ZA	0.0629
		0.03%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - IN	0.01246
		0.01%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - CO	0.00604
		0.01%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - BR	0.0037
		0.00%	market for diesel, low-sulfur | diesel, low-sulfur | APOS, U - PE	0.00042
		0.00%	market for road wear emissions, lorry | road wear emissions, lorry | APOS, U - GLO	0
	1.48%		transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	0.6655
	0.23%		hydrostatic testing | no. of tested cylinders | ON	0.10382
		0.22%	market for electricity, low voltage | electricity, low voltage | APOS, U - CA-ON	0.09886
		0.01%	market for wastewater, from residence | wastewater, from residence | APOS, U - RoW	0.00309
		0.00%	market for water, completely softened | water, completely softened | APOS, U - US	0.00127
		0.00%	transport, freight, lorry 3.5-7.5 metric ton, EURO6 | transport, freight, lorry 3.5-7.5 metric ton, EURO6 | APOS, U - RoW	0.0006
	0.06%		cylinder maintenance | no. of maintained cylinders | ON	0.02591
		0.03%	market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without solvent,	0.01215

			in 60% solution state | APOS, U - RoW	
		0.02%	market for waste paint | waste paint | APOS, U - RoW	0.00818
		0.01%	market for dichloromethane | dichloromethane | APOS, U - RoW	0.00471
		0.00%	transport, freight, lorry 3.5-7.5 metric ton, EURO6 | transport, freight, lorry 3.5-7.5 metric ton, EURO6 | APOS, U - RoW	0.00087

Results for product system 3 - PSA plant

GWP

Contribution				Process	Amount (kg CO2 eq)
100.00%				Oxygen gas delivery from PSA plant to hospital bed | no. of oxygen bed days | ON	0.26124
	100.00%			oxygen gas production from PSA plant | oxygen gas | ON	0.26124
		98.77%		market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	0.25804
		1.23%		PSA plant maintenance | maintenance, PSA plant | ON	0.0032
			0.91%	market for zeolite, powder | zeolite, powder | APOS, U - GLO	0.00237
			0.31%	market for ultrafiltration module | ultrafiltration module | APOS, U - GLO	0.00082
			0.00%	market for air filter, in exhaust air valve | air filter, in exhaust air valve | APOS, U - GLO	1.16E-05
			0.00%	treatment of waste zeolite, inert material landfill | waste zeolite | APOS, U - RoW	2.42E-06
			0.00%	treatment of used air filter, in exhaust air valve | used air filter in exhaust air valve | APOS, U - RoW	7.54E-07

Fossil fuel depletion

Contribution				Process	Amount (MJ surplus)
100.00%				Oxygen gas delivery from PSA plant to hospital bed | no. of oxygen bed days | ON	0.4465

	100.00%			oxygen gas production from PSA plant | oxygen gas | ON	0.4465
		99.15%		market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	0.44272
		0.85%		PSA plant maintenance | maintenance, PSA plant | ON	0.00378
			0.61%	market for zeolite, powder | zeolite, powder | APOS, U - GLO	0.00273
			0.23%	market for ultrafiltration module | ultrafiltration module | APOS, U - GLO	0.00102
			0.00%	market for air filter, in exhaust air valve | air filter, in exhaust air valve | APOS, U - GLO	1.77E-05
			0.00%	treatment of waste zeolite, inert material landfill | waste zeolite | APOS, U - RoW	1.01E-05
			0.00%	treatment of used air filter, in exhaust air valve | used air filter in exhaust air valve | APOS, U - RoW	9.23E-08

Carcinogens

Contribution				Process	Amount (CTUh)
100.00%				Oxygen gas delivery from PSA plant to hospital bed | no. of oxygen bed days | ON	3.65E-08
	100.00%			oxygen gas production from PSA plant | oxygen gas | ON	3.65E-08
		96.66%		market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	3.53E-08

		3.34%		PSA plant maintenance | maintenance, PSA plant | ON	1.22E-09
			3.22%	market for zeolite, powder | zeolite, powder | APOS, U - GLO	1.18E-09
			0.12%	market for ultrafiltration module | ultrafiltration module | APOS, U - GLO	4.41E-11
			0.00%	market for air filter, in exhaust air valve | air filter, in exhaust air valve | APOS, U - GLO	8.53E-13
			0.00%	treatment of waste zeolite, inert material landfill | waste zeolite | APOS, U - RoW	1.69E-13
			0.00%	treatment of used air filter, in exhaust air valve | used air filter in exhaust air valve | APOS, U - RoW	1.01E-14

Non-carcinogens

Contribution				Process	Amount (CTUh)
100.00%				Oxygen gas delivery from PSA plant to hospital bed | no. of oxygen bed days | ON	1.20E-07
	100.00%			oxygen gas production from PSA plant | oxygen gas | ON	1.20E-07
		98.82%		market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	1.18E-07
		1.18%		PSA plant maintenance | maintenance, PSA plant | ON	1.41E-09
			1.02%	market for zeolite, powder | zeolite, powder | APOS, U - GLO	1.22E-09
			0.15%	market for ultrafiltration module | ultrafiltration module | APOS, U - GLO	1.84E-10

			0.00%	market for air filter, in exhaust air valve | air filter, in exhaust air valve | APOS, U - GLO	3.03E-12
			0.00%	treatment of used air filter, in exhaust air valve | used air filter in exhaust air valve | APOS, U - RoW	3.18E-13
			0.00%	treatment of waste zeolite, inert material landfill | waste zeolite | APOS, U - RoW	2.50E-13

Respiratory effects

Contribution				Process	Amount (kg PM2.5 eq)
100.00%				Oxygen gas delivery from PSA plant to hospital bed | no. of oxygen bed days | ON	0.00014
	100.00%			oxygen gas production from PSA plant | oxygen gas | ON	0.00014
		97.93%		market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	0.00014
		2.07%		PSA plant maintenance | maintenance, PSA plant | ON	2.88E-06
			1.63%	market for zeolite, powder | zeolite, powder | APOS, U - GLO	2.27E-06
			0.42%	market for ultrafiltration module | ultrafiltration module | APOS, U - GLO	5.87E-07
			0.01%	market for air filter, in exhaust air valve | air filter, in exhaust air valve | APOS, U - GLO	1.14E-08
			0.00%	treatment of waste zeolite, inert material landfill | waste zeolite | APOS, U - RoW	2.72E-09

			0.00%	treatment of used air filter, in exhaust air valve | used air filter in exhaust air valve | APOS, U - RoW	1.79E-09

Ecotoxicity

Contribution				Process	Amount (CTUe)
100.00%				Oxygen gas delivery from PSA plant to hospital bed | no. of oxygen bed days | ON	9.28216
	100.00%			oxygen gas production from PSA plant | oxygen gas | ON	9.28216
		99.05%		market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	9.19432
		0.95%		PSA plant maintenance | maintenance, PSA plant | ON	0.08784
			0.83%	market for zeolite, powder | zeolite, powder | APOS, U - GLO	0.07745
			0.11%	market for ultrafiltration module | ultrafiltration module | APOS, U - GLO	0.01015
			0.00%	market for air filter, in exhaust air valve | air filter, in exhaust air valve | APOS, U - GLO	0.00015
			0.00%	treatment of used air filter, in exhaust air valve | used air filter in exhaust air valve | APOS, U - RoW	7.32E-05
			0.00%	treatment of waste zeolite, inert material landfill | waste zeolite | APOS, U - RoW	1.23E-05

Results for product system 4 - oxygen concentrator

GWP

Contribution				Process	Amount (kg CO2 eq)
100.00%				Oxygen gas delivery from oxygen concentrator to patient | no. of oxygen bed days | ON	0.3809
	100.00%			Oxygen gas production from oxygen concentrator | oxygen gas | ON	0.3809
		99.95%		market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	0.38069
		0.05%		Oxygen concentrator maintenance | maintenance, oxygen concentrator | ON	0.00021
			0.05%	market for air filter, in exhaust air valve | air filter, in exhaust air valve | APOS, U - GLO	0.00017
			0.01%	treatment of wastewater, from residence, capacity 1.1E10l/year | wastewater, from residence | APOS, U - RoW	1.93E-05
			0.00%	treatment of used air filter, in exhaust air valve | used air filter in exhaust air valve | APOS, U - RoW	9.94E-06
			0.00%	market for tap water | tap water | APOS, U - CA-QC	7.07E-06

Fossil fuel depletion

Contribution				Process	Amount (MJ surplus)
100.00%				Oxygen gas delivery from oxygen concentrator to patient | no. of oxygen bed days | ON	0.65346
	100.00%			Oxygen gas production from oxygen concentrator | oxygen gas | ON	0.65346

		99.96%		market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	0.65317
		0.04%		Oxygen concentrator maintenance | maintenance, oxygen concentrator | ON	0.00029
			0.04%	market for air filter, in exhaust air valve | air filter, in exhaust air valve | APOS, U - GLO	0.00026
			0.00%	treatment of wastewater, from residence, capacity 1.1E10l/year | wastewater, from residence | APOS, U - RoW	1.80E-05
			0.00%	market for tap water | tap water | APOS, U - CA-QC	6.28E-06
			0.00%	treatment of used air filter, in exhaust air valve | used air filter in exhaust air valve | APOS, U - RoW	1.22E-06

Carcinogens

Contribution				Process	Amount (CTUh)
100.00%				Oxygen gas delivery from oxygen concentrator to patient | no. of oxygen bed days | ON	5.21E-08
	100.00%			Oxygen gas production from oxygen concentrator | oxygen gas | ON	5.21E-08
		99.93%		market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	5.21E-08
		0.07%		Oxygen concentrator maintenance | maintenance, oxygen concentrator | ON	3.57E-11
			0.03%	market for tap water | tap water | APOS, U - CA-QC	1.39E-11
			0.02%	market for air filter, in exhaust air valve | air filter,	1.26E-11

				in exhaust air valve | APOS, U - GLO	
			0.02%	treatment of wastewater, from residence, capacity 1.1E10l/year | wastewater, from residence | APOS, U - RoW	9.01E-12
			0.00%	treatment of used air filter, in exhaust air valve | used air filter in exhaust air valve | APOS, U - RoW	1.34E-13

Non-carcinogens

Contribution				Process	Amount (CTUh)
100.00%				Oxygen gas delivery from oxygen concentrator to patient | no. of oxygen bed days | ON	1.74E-07
	100.00%			Oxygen gas production from oxygen concentrator | oxygen gas | ON	1.74E-07
		99.93%		market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	1.74E-07
		0.07%		Oxygen concentrator maintenance | maintenance, oxygen concentrator | ON	1.17E-10
			0.04%	treatment of wastewater, from residence, capacity 1.1E10l/year | wastewater, from residence | APOS, U - RoW	6.12E-11
			0.03%	market for air filter, in exhaust air valve | air filter, in exhaust air valve | APOS, U - GLO	4.50E-11
			0.00%	market for tap water | tap water | APOS, U - CA-QC	6.73E-12
			0.00%	treatment of used air filter, in exhaust air valve | used air filter in exhaust air valve | APOS, U - RoW	4.19E-12

Respiratory effects

Contribution				Process	Amount (kg PM2.5 eq)
100.00%				Oxygen gas delivery from oxygen concentrator to patient | no. of oxygen bed days | ON	0.0002
	100.00%			Oxygen gas production from oxygen concentrator | oxygen gas | ON	0.0002
		99.89%		market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	0.0002
		0.11%		Oxygen concentrator maintenance | maintenance, oxygen concentrator | ON	2.29E-07
			0.08%	market for air filter, in exhaust air valve | air filter, in exhaust air valve | APOS, U - GLO	1.69E-07
			0.01%	treatment of wastewater, from residence, capacity 1.1E10l/year | wastewater, from residence | APOS, U - RoW	2.71E-08
			0.01%	treatment of used air filter, in exhaust air valve | used air filter in exhaust air valve | APOS, U - RoW	2.36E-08
			0.00%	market for tap water | tap water | APOS, U - CA-QC	9.37E-09

Ecotoxicity

Contribution				Process	Amount (CTUe)
100.00%				Oxygen gas delivery from oxygen concentrator to patient | no. of oxygen bed days | ON	13.56896
	100.00%			Oxygen gas production from oxygen concentrator | oxygen gas | ON	13.56896

		99.97%		market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	13.56483
		0.03%		Oxygen concentrator maintenance | maintenance, oxygen concentrator | ON	0.00413
			0.02%	market for air filter, in exhaust air valve | air filter, in exhaust air valve | APOS, U - GLO	0.00224
			0.01%	treatment of used air filter, in exhaust air valve | used air filter in exhaust air valve | APOS, U - RoW	0.00097
			0.00%	treatment of wastewater, from residence, capacity 1.1E10l/year | wastewater, from residence | APOS, U - RoW	0.00063
			0.00%	market for tap water | tap water | APOS, U - CA-QC	0.0003

Appendix C

Scenario Analysis

Oxygen production in different geographies					
Product systems 1 and 2					
	RFC states*	**Great Britain**	**China**	**Canada - average**	**US - average**
GWP					
Process	Amount (kg CO2 eq)				
air separation, cryogenic | oxygen, liquid | APOS, U	2.898	1.688	5.633	2.066	3.099
market for electricity, medium voltage | electricity, medium voltage | APOS, U	*2.895*	*1.684*	*5.629*	*2.063*	*3.095*
transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	0.089	0.060	0.060	0.089	0.089
Total: Liquid oxygen delivery to hospital bed | no. of oxygen bed days	**2.988**	**1.748**	**5.693**	**2.156**	**3.188**
Fossil fuel depletion					
Process	Amount (MJ surplus)				
air separation, cryogenic | oxygen, liquid | APOS, U	2.519	3.544	5.633	2.374	3.983
market for electricity, medium voltage |	*2.516*	*3.542*	*1.027*	*2.371*	*3.981*

electricity, medium voltage | APOS, U					
transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	0.204	0.137	0.137	0.204	0.204
Total: Liquid oxygen delivery to hospital bed | no. of oxygen bed days	**2.723**	**3.682**	**5.770**	**2.578**	**4.187**
Carcinogens					
Process	Amount (CTUh)				
air separation, cryogenic | oxygen, liquid | APOS, U	1.84E-07	7.73E-08	2.63E-07	1.51E-07	1.91E-07
market for electricity, medium voltage | electricity, medium voltage | APOS, U	*1.81E-07*	*7.47E-08*	*2.61E-07*	*1.49E-07*	*1.89E-07*
transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	4.74E-09	3.19E-09	3.19E-09	4.74E-09	4.74E-09
Total: Liquid oxygen delivery to hospital bed | no. of oxygen bed days	**1.89E-07**	**8.05E-08**	**2.67E-07**	**1.56E-07**	**1.96E-07**
Non-carcinogens					
Process	Amount (CTUh)				

air separation, cryogenic | oxygen, liquid | APOS, U	5.76E-07	3.51E-07	8.40E-07	4.74E-07	7.12E-07
market for electricity, medium voltage | electricity, medium voltage | APOS, U	*5.72E-07*	*3.47E-07*	8.36E-07	*4.70E-07*	*7.08E-07*
transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	2.12E-08	1.43E-08	1.43E-08	2.12E-08	2.12E-08
Total: Liquid oxygen delivery to hospital bed | no. of oxygen bed days	**5.97E-07**	**3.66E-07**	**8.54E-07**	**4.95E-07**	**7.33E-07**

Respiratory effects					
Process	Amount (kg PM2.5 eq)				
air separation, cryogenic | oxygen, liquid | APOS, U	2.89E-03	4.00E-04	4.74E-03	1.65E-03	6.33E-03
market for electricity, medium voltage | electricity, medium voltage | APOS, U	*2.88E-03*	*3.94E-04*	*4.74E-03*	*1.64E-03*	*6.32E-03*
transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	6.27E-05	4.22E-05	4.22E-05	6.27E-05	6.27E-05

Total: Liquid oxygen delivery to hospital bed | no. of oxygen bed days	**2.95E-03**	**4.42E-04**	**4.78E-03**	**1.71E-03**	**6.39E-03**

Ecotoxicity					
Process	Amount (CTUe)				
air separation, cryogenic | oxygen, liquid | APOS, U	24.336	15.796	30.144	22.761	27.807
market for electricity, medium voltage | electricity, medium voltage | APOS, U	*24.029*	*15.489*	*29.837*	*22.454*	*27.500*
transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	0.666	0.896	0.896	0.666	0.666
Total: Liquid oxygen delivery to hospital bed | no. of oxygen bed days	**25.001**	**16.692**	**31.040**	**23.426**	**28.473**

Product system 3					
	RFC states*	**Great Britain**	**China**	**Canada - average**	**US - average**
GWP					
Process	Amount (kg CO2 eq)				
market for electricity, medium voltage | electricity, medium voltage | APOS, U	1.861	1.083	3.620	1.326	1.990
PSA plant maintenance | maintenance, PSA plant	0.003	0.003	0.003	0.003	0.003
Total: Oxygen gas delivery from PSA plant to hospital bed | no. of oxygen bed days	**1.865**	**1.086**	**3.623**	**1.330**	**1.993**
Fossil fuel depletion					
Process	Amount (MJ surplus)				
market for electricity, medium voltage | electricity, medium voltage | APOS, U	1.618	2.277	0.660	1.525	2.560
PSA plant maintenance | maintenance, PSA plant	0.004	0.004	0.004	0.004	0.004
Total: Oxygen gas delivery from PSA plant to hospital bed | no. of oxygen bed days	**1.622**	**2.281**	**0.664**	**1.528**	**2.564**
Carcinogens					
Process	Amount (CTUh)				

market for electricity, medium voltage | electricity, medium voltage | APOS, U	1.17E-07	4.81E-08	1.68E-07	9.58E-08	1.21E-07
PSA plant maintenance | maintenance, PSA plant	1.22E-09	1.22E-09	1.22E-09	1.22E-09	1.22E-09
Total: Oxygen gas delivery from PSA plant to hospital bed | no. of oxygen bed days	**1.18E-07**	**4.93E-08**	**1.69E-07**	**9.70E-08**	**1.22E-07**

Non-carcinogens					
Process	Amount (CTUh)				
market for electricity, medium voltage | electricity, medium voltage | APOS, U	3.68E-07	2.23E-07	5.38E-07	3.02E-07	4.55E-07
PSA plant maintenance | maintenance, PSA plant	1.41E-09	1.41E-09	1.41E-09	1.41E-09	1.41E-09
Total: Oxygen gas delivery from PSA plant to hospital bed | no. of oxygen bed days	**3.69E-07**	**2.25E-07**	**5.39E-07**	**3.03E-07**	**4.56E-07**

Respiratory effects					
Process	Amount (kg PM2.5 eq)				
market for electricity, medium voltage | electricity,	1.85E-03	2.60E-04	3.05E-03	1.06E-03	4.07E-03

medium voltage | APOS, U					
PSA plant maintenance | maintenance, PSA plant	2.88E-06	2.88E-06	2.88E-06	2.88E-06	2.88E-06
Total: Oxygen gas delivery from PSA plant to hospital bed | no. of oxygen bed days	**1.85E-03**	**2.63E-04**	**3.05E-03**	**1.06E-03**	**4.07E-03**

Ecotoxicity					
Process	Amount (CTUe)				
market for electricity, medium voltage | electricity, medium voltage | APOS, U	15.451	9.960	19.186	14.438	17.683
PSA plant maintenance | maintenance, PSA plant	0.088	0.088	0.088	0.088	0.088
Total: Oxygen gas delivery from PSA plant to hospital bed | no. of oxygen bed days	**15.539**	**10.048**	**19.274**	**14.526**	**17.771**

*RFC states refer to US states served by the regional entity ReliabilityFirst Corporation, which is responsible for providing power to states in Easter U.S.

Comparison of different flowrates of oxygen delivery to patient						
Flowrate	**GWP (kg CO2 eq)**	**Fossil fuel depletion (MJ surplus)**	**Carcinogens (CTUh)**	**Non-carcinogens (CTUh)**	**Respiratory effects (kg PM2.5 eq)**	**Ecotoxicity (CTUe)**
1 - liquid oxygen delivery						
0.5 L/min	0.124	0.224	1.55E-08	5.22E-08	7.00E-05	3.818
2 L/min	0.494	0.895	6.22E-08	2.09E-07	2.80E-04	15.271
5 L/min	1.236	2.238	1.55E-07	5.22E-07	7.00E-04	38.178
10 L/min	2.471	4.476	3.11E-07	1.04E-06	1.40E-03	76.355
60 L/min	14.827	26.854	1.87E-06	6.26E-06	8.40E-03	458.131
2 - cylinder delivery						
0.5 L/min	0.299	0.490	4.89E-08	1.19E-07	2.20E-04	11.257
2 L/min	1.197	1.961	1.96E-07	4.74E-07	8.80E-04	45.028
5 L/min	2.992	4.902	4.89E-07	1.19E-06	2.20E-03	112.569
10 L/min	5.983	9.804	9.78E-07	2.37E-06	4.40E-03	225.139
60 L/min	35.900	58.826	5.87E-06	1.42E-05	2.64E-02	1350.833
3 - PSA plant						
0.5 L/min	0.065	0.112	9.13E-09	2.99E-08	3.50E-05	2.321
2 L/min	0.261	0.447	3.65E-08	1.20E-07	1.40E-04	9.282
5 L/min	0.653	1.116	9.13E-08	2.99E-07	3.50E-04	23.205
10 L/min	1.306	2.233	1.83E-07	5.98E-07	7.00E-04	46.411
60 L/min	7.837	13.395	1.10E-06	3.59E-06	4.20E-03	278.465
4 - oxygen concentrator						
0.5 L/min	0.095	0.163	1.30E-08	4.36E-08	5.00E-05	3.392
2 L/min	0.381	0.653	5.21E-08	1.74E-07	2.00E-04	13.569
5 L/min	0.952	1.634	1.30E-07	4.36E-07	5.00E-04	33.922
10 L/min	1.905	3.267	2.61E-07	8.72E-07	1.00E-03	67.845
60 L/min	11.427	19.604	1.56E-06	5.23E-06	6.00E-03	407.069

Appendix D

Sensitivity analysis

Using the IMPACT 2002+ LCIA method						
1 - liquid oxygen delivery						
	GW (kg CO2 eq)	**Non-renewable energy (MJ primary)**	**Carcinogens (kg C2H3Cl eq)**	**Non-carcinogens (kg C2H3Cl eq)**	**Respiratory inorganics (kg PM2.5 eq)**	**Aquatic ecotoxicity (kg TEG water)**
air separation, cryogenic | oxygen, liquid | APOS, U (Ontario) - CA-ON	0.395	57.174	6.10E-03	1.88E-02	2.80E-04	141.985
transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	0.088	1.526	5.00E-04	2.39E-03	7.27E-05	12.175
Total: Liquid oxygen delivery to hospital bed | no. of oxygen bed days | ON	**0.483**	**58.700**	**6.60E-03**	**2.12E-02**	**3.50E-04**	**154.159**

2 - cylinder delivery						
	GW (kg CO2 eq)	**Non-renewable energy (MJ primary)**	**Carcinogens (kg C2H3Cl eq)**	**Non-carcinogens (kg C2H3Cl eq)**	**Respiratory inorganics (kg PM2.5 eq)**	**Aquatic ecotoxicity (kg TEG water)**
air separation, cryogenic | oxygen, liquid |	0.395	57.174	6.10E-03	1.88E-02	2.80E-04	141.985

APOS, U (Ontario) - CA-ON						
transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, U - RoW	0.337	5.323	2.36E-03	7.02E-03	2.20E-04	35.929
Aluminum cylinder production | no. of cylinders | ON	0.201	3.274	1.12E-02	1.53E-02	3.60E-04	179.376
cylinder cleaning | no. of cleaned cylinders | ON	0.102	6.034	2.19E-03	7.68E-03	8.85E-05	28.779
transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	0.088	1.526	5.00E-04	2.39E-03	7.27E-05	12.175
cylinder filling pressurizing operation | oxygen compressor operation | ON - CA-ON	0.036	3.524	2.00E-03	6.89E-03	5.41E-05	16.900
cylinder maintenance | no. of maintained cylinders | ON	0.002	0.029	1.33E-05	2.84E-05	2.88E-06	0.377

hydrostatic testing | no. of tested cylinders | ON	0.001	0.099	2.45E-05	1.20E-04	9.53E-07	0.815
Total: Cylinder delivery to hospital bed | no. of oxygen bed days | ON	**1.162**	**76.982**	**2.43E-02**	**5.82E-02**	**1.08E-03**	**416.335**

3 - PSA plant

	GW (kg CO2 eq)	Non-renewable energy (MJ primary)	Carcinogens (kg C2H3Cl eq)	Non-carcinogens (kg C2H3Cl eq)	Respiratory inorganics (kg PM2.5 eq)	Aquatic ecotoxicity (kg TEG water)
market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	0.252	36.733	3.83E-03	1.19E-02	1.80E-04	90.657
PSA plant maintenance | maintenance, PSA plant | ON	0.003	0.043	1.10E-04	2.60E-04	3.75E-06	6.420
Total: Oxygen gas delivery from PSA plant to hospital bed | no. of oxygen bed days | ON	**0.255**	**36.776**	**3.95E-03**	**1.21E-02**	**1.80E-04**	**97.076**

4 - oxygen concentrator

	GW (kg CO2 eq)	Non-renewable energy (MJ primary)	Carcinogens (kg C2H3Cl eq)	Non-carcinogens (kg C2H3Cl eq)	Respiratory inorganics (kg PM2.5 eq)	Aquatic ecotoxicity (kg TEG water)

market for electricity, medium voltage | electricity, medium voltage | APOS, U - CA-ON	0.371	54.194	5.66E-03	1.75E-02	2.60E-04	133.750
Oxygen concentrator maintenance | maintenance, oxygen concentrator | ON	0.000	0.003	7.62E-06	1.51E-05	2.79E-07	0.128
Total: Oxygen gas delivery from oxygen concentrator to patient | no. of oxygen bed days | ON	**0.372**	**54.198**	**5.66E-03**	**1.75E-02**	**2.60E-04**	**133.878**

Using a smaller compressor (or pump) for cylinder filling

Air compressor rated at flowrate of 132 m^3/hour and a power of 30 kW chosen with an output pressure of > 2000 psig; motor efficiency is around 75%

Step 1: No. of hours for oxygen compressor operation = volume of oxygen in 1 E cylinder × no. of E cylinders required per oxygen bed day ÷ flowrate = (690 L ÷ 1000 L) × (30 ÷ 7) ÷ 132 m^3/hour = 0.0224 hours

Step 2: Electricity required for filling cylinders for one oxygen bed day = compressor rated power × motor efficiency × no. of hours for operation = 75 kW × 75% × 0.0224 hours = 0.504 kWh

	GWP (kg CO2 eq)	**Fossil fuel depletion (MJ surplus)**	**Carcinogens (CTUh)**	**Non-carcinogens (CTUh)**	**Respiratory effects (kg PM2.5 eq)**	**Ecotoxicity (CTUe)**
air separation, cryogenic | oxygen, liquid | APOS, U	0.405	0.691	5.74E-08	1.87E-07	2.20E-04	14.606

(Ontario) - CA-ON						
transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | APOS, U - RoW	0.343	0.700	2.46E-08	7.51E-08	1.80E-04	2.815
Aluminum cylinder production | no. of cylinders | ON	0.212	0.171	7.08E-08	9.59E-08	3.00E-04	4.892
cylinder cleaning | no. of cleaned cylinders | ON	0.108	0.134	1.16E-08	4.05E-08	7.01E-05	6.252
transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | APOS, U - RoW	0.089	0.204	4.74E-09	2.12E-08	6.27E-05	0.666
cylinder filling pressurizing operation | oxygen compressor operation | ON - CA-ON	**0.059**	**0.090**	**4.18E-08**	**8.44E-08**	**7.48E-05**	**25.164**
cylinder maintenance | no. of maintained cylinders | ON	0.003	0.003	2.41E-10	7.84E-10	1.99E-06	0.026

hydrostatic testing | no. of tested cylinders | ON	0.001	0.001	1.91E-10	8.41E-10	7.73E-07	0.104
Total: Cylinder delivery to hospital bed | no. of oxygen bed days | ON	**1.219**	**1.995**	**2.11E-07**	**5.06E-07**	**9.10E-04**	**54.523**