Rethinking oxygen

A top-down investigation of the possible extension of oxygen concentrator use within Swedish healthcare, with regards to national and global benefits.

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Abstract

Oxygen concentrators are relatively small medical devices that concentrates oxygen from the ambient air next to the patient. They are widely used in low resource settings and in the home health care. For larger hospitals in Sweden and similar countries however, the most common oxygen source is liquid oxygen and oxygen cylinders, delivered from an off-site supplier. Liquid oxygen is often not an option in countries with scarce resources.

This study aims to explore the opportunity of extending the use of oxygen concentrators. Behind this investigation is the belief that high resource countries could benefit from ideas made for low resource settings, since the goal for both is to find sustainable and cost-efficient solutions. Furthermore the possible impact of an oxygen supply system that is transferable anywhere is substantial. Profit-driven development and advancement of oxygen concentrators could increase the availability of the device, and thereby oxygen therapy, globally.

A literature study and qualitative individual interviews were carried out in order to collect data of the subject. A top-down approach was chosen to achieve a broad presentation of the situation, i.e. interviews were held with key people from the industry. Analysis of the interviews was performed according to Graneheim and Lundman qualitative content analysis.

This study presents that the use of oxygen concentrators could be extended in the Swedish home health care, in nursing homes, and in the future maybe ambulances. For hospitals larger bulk systems appear as preferable, and there are indications that a thorough exploration of the available options should be in place. On-site production may have economical and environmental advantages, and could be a subject for future research.

Preface

In the spring of 2022 I carried out my bachelor thesis project and spent almost three months in Rwanda. I was a part of research group that worked with maternal and fetal healthcare in rural parts of the Northern Province. I visited about ten hospitals and health centers, and worked closely with a Rwandan nurse that carried out her doctorate studies in the same project as I.

The hospitals we visited were often the only hospital many of the people in the rural areas would ever visit. Some were larger with working theatres and some were small with close to no technology at all. The Rwandan country is made out of hills, and even if there are many great roads there are also many horrible ones with endless narrow turns around the mountains. The healthcare system aims to work closely to the people, hence often far away from the paved highways. No one would think it is a good idea to get a tank truck filled with highly compressed gas to the rural hospitals.

One day we were discussing medical oxygen. I did not have any prior knowledge of the shortage, and we only discussed it briefly, but it really got to me. She told me about all the lives that were lost due to the inability to provide oxygen therapy, and how faulty the supply system was. That sometimes industry cylinders were used due to the lack of clean and medical ones. Furthermore we started talking about the fact that the surrounding air actually holds enormous amount of oxygen, and how frustrating it must be to care for a patient that so desperately needs it. We discussed that it should be possible to concentrate oxygen from the surrounding air.

I thought about all the absurd amount of technology available today, that oxygen concentration cannot be that difficult. And obviously it was not. Oxygen concentrators have been available on the market for many years.

Right there this project started - *why are we producing, compressing, and transporting something that we can literally create out of thin air?*

Acronyms

COPD chronic obstructive pulmonary disease

FiO2 fraction of inspired oxygen

LOX liquid oxygen

LPM litres per minute

MT Medical Technology

NGO non-governmental organization

PSA pressure swing adsorption

VPSA vacuum pressure swing adsorption

WHO The World Health Organization

Contents

1 Introduction

1.1 Background

Medical oxygen is a vital asset for any modern health care instance, however there are many people around the world that will never access it. The SARS-CoV-19 pandemic brought the issue of the shortage into bright daylight, even though this is a problem that has been with us for many years.

Countries with unstable infrastructure and scarce resources naturally struggle to build and maintain central oxygen supply systems, to deliver liquid oxygen (LOX), and to provide hospitals with oxygen cylinders (Hill et al., 2009). An alternative that has been used for a long time is the oxygen concentrator. This is a relatively small medical device, see figure 1.1, that pulls in the ambient air, compresses and filters it, and delivers therapeutical levels of oxygen to the patient. During the recent pandemic and the thereby increased oxygen shortage many non-governmental organization (NGO)s and UNICEF highlighted the benefits of using concentrators to tackle the situation (UNICEF, 2021). In more resourceful countries they are mostly developed for home health care patients.

When oxygen concentrators are compared to other oxygen sources they are often presented as the cheaper option. Since the source is inexhaustible and does not require any deliveries form a supplier, unlike cylinders and LOX, there is also often a smaller environmental impact (World Health Organization, 2015).

UNICEF is currently operating a project to develop a powerful version of an oxygen concentrator that will be easy to maintain, that will be able to operate even in extreme heat, cold, dryness, or humidity, and that won't be interrupted by power failures (UNICEF, 2021). Meaning that there is a development of a product that eliminates the need for oxygen transportation. This could thereby be a cheaper option, with less environmental impact. However, this develop-

Figure 1.1: Oxygen concentrator in Swedish hospital.

ment is carried out by non-profit organizations for countries with less resources, while the countries that can afford it rely on systems that could never be transferred south. If the use of oxygen concentrators would be more widespread, all over the world, the development and the production would in all likelihood be quicker and cheaper. Market competition would additionally provide an opportunity for further advancement.

If oxygen concentrators are a viable choice to use further in the richer part of the world, the availability of the device would by all means increase. They could become better and cheaper. This could lead to an increased availability of oxygen therapy worldwide.

This thesis aims to examine the possibility of letting Sweden take the next step in the development and use of oxygen concentrators, by investigating the possible benefits Sweden and other resourceful countries could gain from reducing necessary infrastructure for oxygen provision.

2 Literature study

2.1 Medical oxygen and its history

Medical oxygen is according to The World Health Organization (WHO) at least 82% pure oxygen that is certified to be used for oxygen therapy, and it is thereby free from contaminations (Jha and Gaur, 2022) (World Health Organization, 2020*a*). In the early 1770s the Swedish pharmacist Karl Sheele was the first to obtain purified oxygen by experimenting with mercuric oxide and potassium nitrate. Around the same time period the British theologian-chemist Joseph Priestley had heated only mercuric oxide and found something that he did not at the time understand what it was - but this was also oxygen. In Priestley's *Experiments and Observations on Different Kinds of Air* he describes the first inhalation of the purified air:

> *'The feeling of it to my lungs was not sensibly different from that of common air; but I fancied that my breast felt peculiarly light and easy for some time afterwards. Who can tell but that, in time, this pure air may become a fashionable article in luxury. Hitherto only two mice and myself have had the privilege of breathing it.'*

Even this early in time, Priestley did speculate regarding the possibility of using the purified air for medical applications. Only a few years later, in 1783, the first medical use occurred. A young woman suffering from tuberculosis was treated with daily inhalations of oxygen, and was said to have 'very much benefited' (Priestley, 1775) (Grainge, 2004). The first record of continuous administration of oxygen is however not recorded until 1890, when a patient with pneumonia was given about 6 litres per minute (LPM) by Dr Albert Blodgett. This was done out of desperation, since Blodgett thought that the patient was doomed and he was looking for some relief to the suffering (Blodgett, 1890).

After this, the use of oxygen therapy became widespread (Grainge, 2004). Today, oxygen is an absolutely necessary medicine without substitute, that treat hypoxia[1]. For illnesses such as pneumonia, malaria, and COVID-19 it can be life-saving (World Health Organization, 2023).

2.2 Oxygen administration

When providing oxygen therapy different measurements are used in order to ensure safe and efficient treatment. Flow rate, i.e. the amount of oxygen the source is delivering, is measured by litres per minute (LPM) and fraction of inspired oxygen (FiO2) is the portion of oxygen that the patient inhales. Air has an oxygen concentration of 21 %, hence the FiO2 is without oxygen therapy is 21 % (Oxford Medical Education, 2023). During oxygen administration the FiO2 depend on the flow rate, but also respiratory rate, tidal volume, and the element, i.e. the mask or similar, used to deliver oxygen (World Health Organization, 2023).

The most common oxygen therapy within hospitals is carried out with a nasal cannula, see figure 2.1, for mildly hypoxic or non-acute patients (Oxford Medical Education, 2023). This consists of a tube that carries oxygen from the source to the patients nostrils. Typically a low flow nasal cannula is used, which provides flow rates up to 6 LPM. However, the typical use is around 2 LPM (The Handbook for Healthcare, 2022*a*) (Sharma et al., 2023). Since this type of nasal cannula delivers non-humidified air, the nasal passages can become very dry, irritated, and prone to bleeding for higher flow rates, limiting the possible delivered flow rate and FiO2 to lower levels (Sharma et al., 2023). A low flow nasal cannula typically delivers an FiO2 of 24-30 %, however there are high flow nasal cannulas which are used together with a heating and humidification system. These can deliver up to 60 LPM (Segovia et al., 2018).

For higher flow rates different types of oxygen masks are often used. A Hudson mask can be utilized with a flow rate from 5 to 10 LPM, delivering an FiO2 of 30-40%, however these are not widely used. A Venturi mask includes a valve to precisely deliver the desired FiO2. Different valves are available with distinct colours representing the percentage of oxygen they deliver. Flow rates range from 2 up to 15 LPM, which delivers FiO2 from 24% up to 60% (Oxford

[1]Low levels of oxygen in body tissue.

Figure 2.1: Patient with nasal cannula. Graphics created with canva.com.

Table 2.1: Different flow rates and FiO2 during oxygen administration.

Medium of delivery	**Flow rate (LPM)**	**FiO2 (%)**
Nothing, i.e no oxygen therapy	0	21
Nasal cannula	2	28
Hudson mask	5-10	30-40
Venturi mask	2-15	24-60
Non-rebreather mask	15	85-90

Medical Education, 2023).

Higher FiO2 can be provided with a non-rebreather mask, for more acute patients. This mask includes a bag and a valve that prevents the patient from breathing in their exhaled breath, and can supply air with 85-90% oxygen. In order to achieve this a flow rate of 15 LPM is necessary (The Handbook for Healthcare, 2022*a*) (Oxford Medical Education, 2023). This type of treatment is only used short term (Oxford Medical Education, 2023). Long term or high flow oxygen therapy usually requires humidification in order to maintain healthy airways. To obtain this some type of humidifier is necessary, that makes the air warm and humid (The Handbook for Healthcare, 2022*a*). For an overview of a few different flow rates and FiO2 during oxygen administration, see table 2.1.

When the patient require ventilation there are non-invasive continuous positive airway pressure (CPAP) and bilevel positive airways pressure (BiPAP), and ordinary invasive ventilation (Oxford Medical Education, 2023).

2.2.1 Oxygen therapy and some relevant diseases

Humans depend on a constant supply of oxygen for survival. Normally a healthy person has an saturation level of about 97 % in their blood, and levels beneath 70% can be life threatening. To measure the oxygen saturation levels a pulse oximeter is generally used, which can indicate if supplemental oxygen is necessary. A pulse oximeter is a non-invasive medical device that attaches to the skin, usually a finger, to measure saturation. For a more precise measurement an arterial blood gas test can be used.

Swedish hospitals generally supply their patients with oxygen via a central oxygen supply system, and sometimes by using oxygen cylinders. The latter are especially relevant for transportation. The central oxygen supply system delivers oxygen directly into the treatment rooms via pipelines, and health care professionals can access it through outlets. Oxygen therapy is widely used and there are a number of conditions that can result in low oxygen saturation levels. A few examples of these are heart failure, pneumonia, asthma, chronic obstructive pulmonary disease, anaphylaxis, and blood pressure falls (Karolinska Institutet, 2021). A selection of these conditions will be further presented below.

Chronic obstructive pulmonary disease (COPD)

Patients with chronic obstructive pulmonary disease (COPD) has a progressive disease mainly affecting the lungs and the airways. There are currently hundreds of thousands in people in Sweden living with COPD, and there is no absolute cure. The diagnosis includes several different types of diseases, however they all include some type of deterioration of the respiratory system caused by inflammation. The diagnosis can differ between countries. One common condition is lung emphysema, which is when there are damage to the walls between the finest alveolar sacks. This causes the alveoli to merge and decrease in number, and the surface for gas exchange becomes a lot smaller. Bronchitis, another part of the disease, causes mucus to form in the airways, resulting in coughing. Most patients have a combination of emphysema and bronchitis (1177, Region Stockholm, 2023*b*) (The Swedish Heart Lung Foundation, 2023) (National Heart, Lung, and Blood Institute, 2022).

Treatment of COPD within the hospital varies and oxygen therapy is not always necessary (Internetmedicin, 2023). A constant low oxygen saturation is however a common result of COPD. When this occurs the patient can receive oxygen therapy in their home (1177, Region Stockholm, 2023*b*). A hospitalized patient with COPD does always require oxygen in case of an exacerbation. The patient is then given 1-2 LPM via a nasal cannula, however this flow rate can be increased if necessary (Internetmedicin, 2023).

Pneumonia

Pneumonia is an infection targeting one or both lungs, caused by bacteria, fungi, or viruses. The alveoli get inflamed and fluid or pus fill them up, which results in decreased ability to take in oxygen. It is often painful and difficult to breath, and in severe cases become hypoxic (1177, Region Stockholm, 2023*c*) (National Heart, Lung, and Blood Institute, 2023). Pneumonia can be a very serious disease. In children under 5 years of age, pneumonia account for 14 % of all deaths (2019).

For less severe cases of pneumonia no oxygen therapy is necessary, however the more dangerous cases require hospitalization and oxygen treatment (World Health Organization, 2022*b*).

COVID-19

COVID-19, caused by the coronavirus SARS-CoV-2, is an infectious disease. It often causes respiratory symptoms similar to those of a regular cold, however it can also spread further than just the lungs. In most cases the patient will get better without treatment, and in more severe cases hospitalization including oxygen therapy may be necessary (1177, Region Stockholm, 2023*a*).

2.3 Oxygen supply systems

Hospitals are supplied with medical oxygen either by deliveries of LOX or compressed oxygen cylinders from an off-site manufacturer, or they have their own on-site production using a large PSA-system or bedside oxygen concentrators. A representation of the different supply systems can be found in figure 2.2.

Hospitals have access to medical oxygen mainly through their own central oxygen supply system, which from tanks, cylinders, or their own oxygen generators, supplies the entire facility through a pipeline system. If tanks are used these

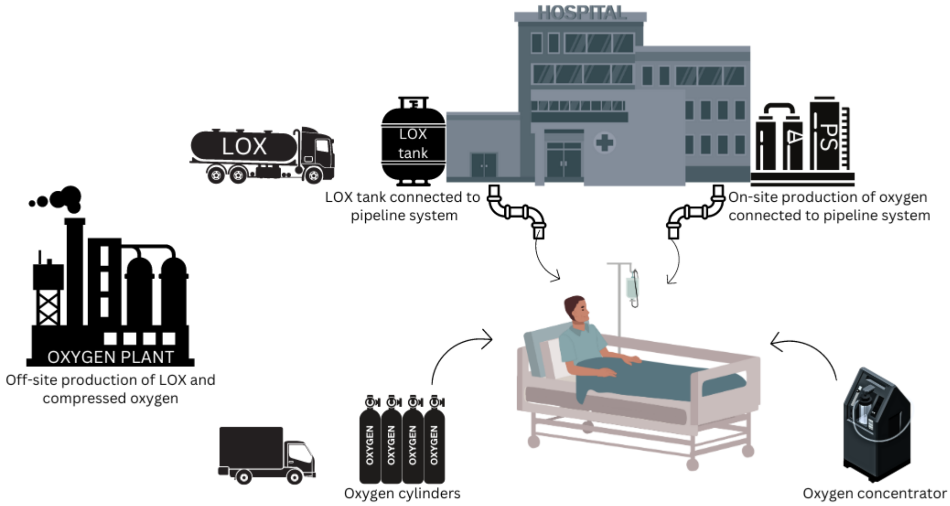

Figure 2.2: Presentation of different options of oxygen supply for hospitals. Graphics created with canva.com.

are filled with LOX by deliveries of oxygen from a manufacturing site (Linde Healthcare, 2023) (World Health Organization, 2023). Depending on the region there may be different standards that apply, however oxygen should always be handled with care. Production, transportation, utilization, and storage of medical oxygen must thereby always follow strict regulations. For on-site oxygen production or large-scale storage personnel should be present at all times, and qualified technicians should be available 24/7 for support. Independent of the method of choice, a backup oxygen supply that can deliver oxygen for at least 72 hours will always be necessary (World Health Organization, 2023).

To reach the necessary concentration of oxygen for medical applications there are different processes for separation of the components of atmospheric air (World Health Organization, 2023).

2.3.1 Cryogenic air separation

Concentrated oxygen can be produced in liquid form, i.e. held in a temperature of -183°C, and called simply liquid oxygen, often short as LOX (The Handbook for Healthcare, 2022*c*). The production of this is called cryogenic air separation, and is carried out by a third party that delivers LOX to a number of hospitals.

The process of cryogenic air separation includes:

(i) Filtering.

(ii) Compression.

(iii) Purification.

(iv) Cooling.

(v) Liquidation.

(vi) Distillation.

Surrounding air is drawn into the plant, and through these steps converted into storable liquid oxygen (Linde CryoPlants Ltd, 2023). This paper will not go into further details regarding the different steps. Oxygen in this state of aggregation is however extremely compressed. One litre of liquid oxygen is equal to about 800 litres of gas, hence this system is highly space efficient.

Since the temperature can cause frostbite, it should always be handled with caution (The Handbook for Healthcare, 2022*c*). When storing or transporting LOX there will always be some degree of heat leakage and surface evaporation, i.e. loss of product. In some cases this loss can be as big as 5 % per day. When setting up a LOX generator there is generally long term (20 years) planning involved for financial reasons, and constant maintenance by personnel with specialized training is absolutely necessary (World Health Organization, 2023).

2.3.2 Pressure swing adsorption (PSA)

Another way to generate large quantities of medical oxygen, typically on-site, is with pressure swing adsorption (PSA) plants. One model available on the Swedish market, dimensions 1421 mm x 970 mm x 2015 mm, can produce up to 25 Nm/h free oxygen (95 %) delivery, i.e. 422 LPM (Atlas Copco, 2023). Just like with cryogenic air separation, the purified oxygen can supply the hospital directly via a pipeline system. It is also possible to use the plant to fill cylinders (World Health Organization, 2020*b*). The purification takes place through a number of steps:

(i) Surrounding air is drawn in through a an intake filter to remove gross particles.

(ii) The air undergoes compression. This step results in increased temperature.

(iii) A heat exchanger cools down the compressed air.

(iv) The compressed air enters sieve beds that contain zeolite. Zeolite is a mineral that adsorbs nitrogen at high pressures, and is thereby vital for the air separation process. The passage through these sieve beds yields the concentrated oxygen.

(v) Oxygen with a purity of 93 $\pm$ 3 % is stored in a reservoir. When the pressure is released, the zeolite releases the nitrogen out of the device. To keep the oxygen concentration continuos, two sieve beds are thereby used (World Health Organization, 2015) (World Health Organization, 2020*b*).

In order to prevent malfunction of the plants an extensive maintenance system needs to be established, with dependence on staff with specialized training (World Health Organization, 2020*b*). These plants do also require long term financial planning.

There are similar systems available that use vacuum instead of pressure, vacuum pressure swing adsorption (VPSA), and also a combination of PSA and VSA. PSA is however the most popular choice (World Health Organization, 2023).

2.3.3 Oxygen cylinders

Oxygen cylinders are cylinders filled with high-pressure medical oxygen. The containers are generally made of steel alloys or aluminium, with a valve on top that controls the outflow of oxygen (Ismail and Bansal, 2022). Looking at one major distributor in Sweden, volumes ranges from 1.1 litres, intended for home use, up to 50 litres, weighing from 2.5 kg to 88 kg. The smallest version has a diameter of 101 mm and a height of 70 mm, one cylinder with a volume of 5 litres measures 143 mm i diameter and 616 mm from top to bottom. The largest version can be up to 1750 mm tall, with a diameter of 220 mm. A summary of some common cylinder sizes is presented in table 2.2. However, the most common cylinders in hospitals are 3-5 litres of volume (Linde Healthcare, 2022).

Since the oxygen is under high pressure, the actual volume of oxygen can be calculated by multiplying with the gauge pressure (bar) (Ismail and Bansal,

Table 2.2: Oxygen cylinder sizes and weights (Linde Healthcare, 2022).

Size (litres)	**Height (mm)**	**Weight (kg)**
1.1	70	2.5
3	558-568	4.7
5	616	7.7
10	1072-1116	14.2

2022). To calculate how many hours an oxygen cylinder will last, the following formula is used:

$$\frac{Cylinder\ volume\ in\ litres \cdot pressure\ in\ bar}{LPM \cdot 60} \tag{2.1}$$

E.g., a 5 litre oxygen cylinder with 120 bar pressure will last a 2 LPM patient 5 hours (Karolinska Institutet, 2021).

Ensuring safety when handling oxygen cylinders is vital. Even if oxygen itself is not flammable, air with an increased concentration of oxygen will significantly increase the risk of fire if presence of heat or a spark. The product should thereby always be kept away from any source of heat and flammable objects. The compressed oxygen may cause spontaneous reaction if in contact with materials like fat, oil, and alcohol because of their flammable properties. I.e. caution needs to be taken when cleaning the cylinders, and regular disinfection solutions containing alcohol or ammonium should not be used. The product should also not be exposed to temperatures above 50°C. For use close to an MRI there are special cylinders available, since many of the materials in a regular cylinder will be drawn into the magnetic field with intense force (Linde Healthcare, 2014). When moving oxygen cylinders, independent of the distance, the appropriate equipment should be used, such as a truck, handcart, or forklift made for the purpose (Linde Healthcare, 2013). If the cylinder is dropped and breaks, the high-pressure oxygen may flow out and cause the bottle to become a highly dangerous projectile.

The hazardous nature of oxygen cylinders makes it necessary to always use a warning sign outside of rooms where these are present, and one sign should be hung on the entrance of the entire institution. For patients using oxygen cylinders in their home, a sign should be placed on the front door. In case of a fire all oxygen cylinders must be moved, or the fire fighters should be informed (The Handbook for Healthcare, 2022*c*).

Because of the danger present during use of high pressure cylinders, there are countries that have prohibited the bedside use of these (World Health Organization, 2023).

2.3.4 Medical gas pipeline system

To deliver medical oxygen, and other medical gases, within the hospital from the LOX tanks, the PSA plant, or sometimes the oxygen cylinders, to the patient the most common arrangement is a medical gas pipeline system. The pipes are typically made out of non-arsenic copper specially manufactured for medical use. Additionally the system consists of regulators, line valve assemblies, isolation (safety) valves, alarms and control panels, and wall outlets. Alarms and control panels are utilized for safety reasons. Trained personnel should always carry out surveillance over the pressure in the pipes.

These highly intricate systems require personnel with expertise to maintain and monitor during the entire life cycle of the pipelines. Every pipeline system is also uniquely constructed for its facility (World Health Organization, 2023).

2.3.5 Transportation

For LOX and cylinders that are made or filled at a production site, delivery is naturally an additional part of the system. Transportation of LOX is carried out using large tank trucks. According to Swedish law LOX and compressed oxygen are types of dangerous goods, in this case since it *”may cause or intensify fire”*, and since it is oxidizing. This means that a leakage may lead to combustible materials easily catching fire and burn intensely, and materials that are non-combustible in air with normal amounts of oxygen may become flammable. Furthermore a started fire may result in explosions (MSB, 2023*a*) (MSB, 2023*b*). The law states that all transportation of dangerous goods should be carried out with caution and protective measure in order to prevent, avert, and limit the risk of harming people or causing damage to the environment or property. Organizations that perform transportation of dangerous goods should have at least one security advisor, whose role is to prevent damage. Further the authorities should perform surveillance to ensure that these laws are being obeyed (Sveriges Riksdag, 2006).

2.3.6 Oxygen concentrators

Oxygen concentrators are relatively small medical devices that generates concentrated oxygen from the surrounding air, directly next to the patient. Just like some larger plants, oxygen concentrators utilizes PSA technology. Ambient air is drawn into the device, and air with therapeutical levels of oxygen is stored shortly in a reservoir before delivered to the patient at a chosen flow rate (World Health Organization, 2015). Concentrators are in the Swedish context generally used for patients that need oxygen therapy on a daily basis within their homes, however it is also a current solution for hospitals in countries with scarcer resources and infrastructure. Most of the concentrators deliver relatively low flow rates, typically up to 10 LPM. Yet there are models available that can deliver as much as 30 LPM, intended for use within the hospital, reported by the World Health Organization in February 2023 (World Health Organization, 2023). Stationary models often have wheels and are thereby relatively easy to maneuver, and the portable devices are small enough to carry around. Oxygen concentrators are electrically powered, so an electrical cord or a battery is always necessary.

Oxygen concentrators do not require personnel besides health care professionals, however technicians should be available for support. Furthermore, the mobile nature of the oxygen concentrators makes them possible to replace if malfunctioning. Some maintenance is however necessary, but this does not need to be carried out by a specialized technician (World Health Organization, 2023). For flow rates of 2 LPM and less humidification may not be necessary, since the air delivered is at room temperature (World Health Organization, 2015).

The limited flow rate that an oxygen concentrator can deliver compared to central systems or cylinders implies that there are situations when oxygen concentrators are not enough, e.g. air-oxygen blenders to acquire lower concentrations of oxygen. Neonatal resuscitation require 30 % oxygen, otherwise they are prone to oxygen toxicity. According to the World Health Organization's specification of oxygen concentrators from 2015 the air-oxygen blenders that are used to deliver lower oxygen concentration *"usually require a high-pressure oxygen source (typically 300–450 kPa)"*, which oxygen concentrators cannot do. However it is possible to work around this problem if oxygen concentrators are the only source of pure oxygen. Anaesthesia is another context that traditionally depend on high-pressure oxygen, yet this is presented to be possible with oxygen concentrators when designed for it (World Health Organization, 2015).

There are oxygen concentrators designed to deliver oxygen to multiple patients simultaneously, with individual flow rates (World Health Organization, 2015).

The gross particle filter needs to be cleaned regularly in order to function properly. This can easily be carried out by any personnel, and no technical education or specialized training is necessary. The filter should only be removed, washed, dried, and put back in the device. A mild detergent and water is sufficient for the cleaning procedure. This should be carried out weekly, or more often in particularly dusty or dirty environments. Further maintenance is only required yearly for most models of oxygen concentrators. This includes checking oxygen output with an oxygen analyser, and controlling the air pressure both internally and externally. For the latter a pressure gauge is necessary. These maintenance procedures should be carried out by a trained technician (World Health Organization, 2015).

All environments with heightened concentrations of oxygen increases the danger in case of a fire. When handling oxygen concentrators, this is vital to remember. Thereby electrical cords and outlets need to be kept maintained, and flammable objects should be kept at a distance. Hence the device should not be exposed to oil, grease, alcohol, and similar products (World Health Organization, 2015). In contrast to when using oxygen cylinders, no warning signs are necessary for rooms with oxygen concentrators since there is no increased level of oxygen when the device is turned off (The Handbook for Healthcare, 2022*c*).

Current use

In Sweden oxygen concentrators are used by patients that need oxygen therapy on a daily basis. For use within the patients home there are stationary devices that operate with electricity from a power outlet, and for mobility there are battery dependent models. For the latter the batteries are rechargeable. The oxygen concentrators should be chosen to fit the individual needs of the patient (The Handbook for Healthcare, 2022*b*).

In low resource settings oxygen concentrators are often used within the hospitals, since the availability of other options are scarce. Since these hospitals may have problems with power interruptions, additional features are requested to ensure proper functioning. If oxygen concentrators would consume less energy a car battery or solar panels could be sufficient. Internal rechargeable batteries are also an option even for stationary devices, that can either work as short-term back up or long-term options. Hospitals in these environments may also be dustier than others, hence the gross particle filter will need cleaning more frequently. Different manufacturers require varying maintenance procedures of the filter, some need cleaning and some should be replaced. The cleanable alternatives can cause problems since they may be inserted while still wet, and thereby damaging the device. Replaceable filters need to constantly be purchased, which means new filters need to be available. To ensure this suggestions have been made regarding a universal filter, or off-the-shelf options. For environments with high temperatures some oxygen concentrator models are prone to overheating, yet there are also models that work well even in hot conditions (World Health Organization, 2022*a*).

In certain low resource settings where research has been carried out regarding oxygen concentrators compared to cylinders, many health care professionals have pointed out the economical benefits of oxygen concentrators (World Health Organization, 2022*a*). The World Health Organization's guidelines for rational use of oxygen include the invitation to use oxygen concentrators for patients that only demand low flow treatment (World Health Organization, 2023).

Oxygen concentrators are also used outside of healthcare. E.g. military aircrafts are using PSA oxygen concentrators to supply oxygen-rich breathing gas (Eaton, 2023).

2.4 Current availability of oxygen

High income countries have generally had reliable supplies of medical oxygen. Even though medical oxygen is a central part of healthcare it has however been a scarce resource in low- and middle-income countries, even long before the COVID-19 pandemic. But during the pandemic the shortage of medical oxygen reached even resourceful countries. Patients in California was held at an oxygen saturation just above 90% to prevent oxygen exhaustion, and other states also reported struggles to provide enough medical oxygen for their patients (Patil, 2021) (Advisory Board, 2021). For locations where this problem always has been present the situation suddenly became a lot worse.

The oxygen supply system that operate in Sweden an similar countries has never been an option in countries that lack proper infrastructure. Different alternatives have thereby been used, most widely transportation of individual oxygen cylinders. Thorough research has been carried out regarding oxygen concentrators versus oxygen cylinders. To be noted is however that the costs may vary between countries. An article published already in 1987 reviews the shortage of medical oxygen in Nepal, since the country did not hold their own medical gas production. Even if the performance of an oxygen concentrator was highly limited, it was mentioned as a viable substitute to oxygen cylinders. The other option for Nepal to be able to provide oxygen therapy for ill patients was at the time to import cylinders from India (Swar, 1987). In 1991 a cost analysis was carried out in Papa New Guniea, comparing compressed medical oxygen to oxygen concentrators. The capital, Port Moresby, did have their own production of LOX. However, the inadequate infrastructure made it necessary for the more rurally placed hospitals to depend on oxygen cylinders. The costs analysis present savings from 25% to 75% when using oxygen concentrators instead of oxygen cylinders (Dobson, 1991). Research from 2001 again concludes how oxygen concentrators often is a favourable option in low resource settings, looking at both costs and logistics, compared to transporting cylinders (Dobson, 2001). In an article from 2021 UNICEF describes that oxygen concentrators can be used to offer oxygen therapy in challenging settings, and that they have played an important role during the COVID-19 pandemic (UNICEF, 2021). Further research has also been carried out that accepts oxygen concentrators as a viable choice in low-resource settings, and instead focuses on providing electricity for the concentrators by using solar panels (Duke et al., 2021).

2.4.1 Economic analysis of the current systems

Little research has been carried out regarding the costs of central oxygen systems, however there are many articles presenting the fact that oxygen concentrators are cheaper than cylinders where these are the only options. One economical analysis comparing oxygen cylinders, LOX tanks, and on-site PSA production in Poland from 2021 shows a large difference in costs for the different systems. However, in the assessment only hospitals using LOX systems was surveyed, and compared to facts given by PSA manufacturers and cylinder providers. For oxygen cylinders the costs for leasing the cylinders and the transportation of these was considered, leaving this as the far more expensive alternative. For LOX stored in tanks by the hospitals the assessment considered purchase and installation of the tank and the necessary accessories, and transportation of oxygen. Further the spare and maintenance costs was assumed as 5% of the cost of the delivered oxygen. Comparing LOX to oxygen cylinder deliveries, the expenses for LOX was almost 1/10. PSA on-site production only included costs for installation, maintenance, and electricity, leaving this as the far cheaper alternative- almost 1/4th of the price of LOX (Balys et al., 2021).

One Swedish study from 1998 compares the costs of LOX and oxygen concentrators for oxygen therapy in the patient's home. During a six month period the cost for LOX ended up at $4950, where $2200 was the cost for the oxygen and $3340 was the cost for rent, freight, and depreciation. For the same period the total cost for oxygen concentrators was $1310 (Andersson et al., 1998). Both arrangements included similar costs for maintenance and healthcare services. With adjustments for inflation and converted into SEK the LOX would in 2023 cost approximately 105,115 SEK and oxygen concentrators approximately 27,800 SEK for the six month period.

2.5 Aims

Oxygen is a vital but scarce resource in many countries, and during the recent pandemic the shortage was a present concern globally. However there are few questions that have been asked regarding the oxygen supply in the richer part of the world, and very little research is available regarding the cost of LOX. There does however seem to be many possible aspects regarding oxygen concentrators, everywhere. This indicates that there might be reasons the expand the use of oxygen concentrators in a country like Sweden, since the literature presents this as an often cheaper option that eliminates the need for transportation. For suppliers an expanded use would mean an increased market and thereby possible profit to gain. Furthermore this would most likely improve the performance of the product, and long-term there could be more and better oxygen concentrators available.

To investigate how medical oxygen is supplied and used within Swedish healthcare, and to examine if there is a possibility that an extended use of oxygen concentrators could be beneficial, the following study was carried out. The research questions of this study were:

(I) To examine and evaluate the current situation for different medical oxygen supply systems in Sweden, including the positive and negative aspects of the current systems. This aspect is investigated in order to gain a deep understanding of how oxygen is used today, and how people with the right expertise experience it, in order to make a brief evaluation.

(II) To more deeply explore how oxygen concentrators are used today, with regards to performance and user experience. Further this should present how the development of the device is proceeding in Sweden.

(III) To investigate if there is an opportunity to increase the use of oxygen concentrators in Sweden, and in that case where this extended use would be beneficial.

(IV) To examine future possibilities for use and development of oxygen concentrators within Sweden, with regards to national and global benefits.

3 Methodology

A study of oxygen use and oxygen generation was carried out by using information from governmental healthcare organizations, large suppliers for medical oxygen, and the World Health Organization. Further a literature study of previous research was carried out by searching through Google Scholar and Web of Science. The following key words were used: oxygen concentrators, LOX, liquid oxygen, oxygen therapy, medical oxygen, oxygen cylinder, cryogenic air, PSA, VPSA, oxygen supply.

To answer research question (I) to (III) qualitative individual interviews with key people from the industry were carried out. All subjects were chosen to contribute with their own expertise and thereby present a unique angle of the topic, in order to obtain a top-down overview. They were all also able to present their part of the industry, to make a full presentation of the oxygen chain possible. Contact with different respondents was established throughout the project, and those who agreed to participate were interviewed. The interviews were constructed to fit the individual respondent. The contacted respondents and if they agreed to be interviewed or not can be found in table 3.1.

The chosen perspective was top-down, i.e. the choice of representative interviewees in order to collect data that can represent a larger picture of the subject (Sabatier, 1986). According to Sabatier (1986), this choice of interview respondents may indicate a unilateral picture of the situation. The aim of the research was however to find people that together could provide the broadest perspective available, to reduce the risk of neglecting certain stakeholders and avoiding said problem.

To answer research question (IV) an analysis of future potentials and the possible markets was carried out. This will be presented further in section 3.2

3.1 Industry analysis using interviews

A semi-structured interview method was chosen. The questions were thought to be asked in an open manner, which according to Jacobsen (2002) invites to further develop the discussion. According to Skärvad and Lundahl (2016) the semi-structured format makes it possible obtain high flexibility and well developed answers. It also grants the opportunity to ask relevant follow-up questions. The structure was however further towards unstructured on the semi-structured spectrum, which is very common for this type of research according to Alvehus (2013).

This method of interviewing often creates a clear idea of what the respondent is trying to say, with less misunderstanding, and further a more reliable data collection (Alvehus, 2013). The questions were not standardized for all the respondents, which Skärvad and Lundahl (2016) argues makes it possible to customize the interview to the respondent and the situation, which was highly relevant for this study.

3.1.1 The interview guide

A unique interview guide was created for every respondent, however the aim was to follow the same structure, corresponding to the aims of the study. The interview guides consisted of pre-formed questions including probing questions regarding:

- The oxygen sources the interviewee was familiar with, and how these were used.
- The positive and negative aspects of the oxygen sources used.
- Risks, training, and costs.
- Oxygen concentrators and their opinion regarding an extended use of these.
- Opportunities, limitations, and risks related to an extended use of oxygen concentrators.
- The adjustments necessary for an extended use of oxygen concentrators.

Table 3.1: Contacted interview respondents.

Contacted respondent	Agreed to be interviewed
Medical gas expert from one of Sweden's main medical gas suppliers	No, after first agreeing they stopped responding.
Medical gas expert from one of Sweden's largest hospitals	Yes
Nurse with oxygen therapy expertise for both home and in hospital care	Yes
Ambulance nurse and MT coordinator at Ambulance care in Greater Stockholm Ltd	Yes
Oxygen concentrator expert from one of Sweden's main oxygen concentrator suppliers	Yes
Swedish Physician. Founder of a children's hospital in Sierra Leone, that uses oxygen concentrators	Yes

Every interview was followed by an evaluation of the content, which resulted in some changes of those questions that was asked every interviewee. This changes mainly included better customization of the questions towards the respondent. Every interview lead to a deeper understanding of the subject for the author, resulting in the interviews becoming slightly more advanced with regards to the subject during the course of the study. The interview questions can be found in Appendix A.

3.1.2 Recruiting respondents

The respondents were chosen to find information and perspectives that was missing in the available research. The literature study did not reveal any depth to how the current oxygen supply system in Swedish healthcare operates, and if it is planning to develop or change. People that were found relevant to interview were thereby experts from different parts of the industry. The goal was to get a thorough insight in the entire oxygen supply system, and the viewpoints and opinions from those with expertise and experience. Experts from varying professions in the industry were contacted, see table 3.1.

Respondents were recruited by email and phone contact initially. The medical gas expert from the gas supplier was contacted before the project started, and participated in discussion regarding the project. The gas expert from the hospital was a colleague from a previous employment. The nurse with oxygen therapy expertise is also an author for the Swedish Handbook of Healthcare, and was thereby found and contacted during the literature study. To come in contact with the ambulance nurse and the oxygen concentrator expert the respective company was initially contacted. After an explanation of the project these respondents were then recommended by the person of contact at the companies. During the interview with the oxygen concentrator expert the respondent brought up the physician during in the conversation i.e. snowball sampling. The snowball sampling method was otherwise avoided in order to reach a broader perspective. Alvehus (2013) argues that snowball sampling may cause the researcher to interview people within the same network.

When reaching out to the respondent a short presentation of the project was attached, and a more thorough description followed when interest was shown. Before the interview the respondent was given the interview guide. For the respondents that were not necessarily familiar with oxygen concentrators a short power point presentation with information of these was also sent, all via email. The presentation was constructed to prepare the respondent if they wished to. All respondents signed a consent form, where they also expressed if they wished to be anonymous or not, and if they agreed to be recorded or not.

All respondents agreed to be recorded, and only one wished to be anonymous. For consistency, all respondents are thereby anonymous in this report.

3.1.3 Motivation behind selection of respondents

Since the field of central oxygen supply systems is rather technically intricate and requires a certain degree of knowledge in order to explore, an expert in this field was chosen to interview. This expert was interviewed to further develop the understanding for central oxygen supply systems and oxygen cylinders, and how a Swedish hospital works around them. Investigation was carried out regarding the everyday handling, maintenance, difficulties and favouring features of the current oxygen supply in the hospital. The interview also aimed to explore the thoughts and opinions an expert in this field could have regarding this project, and what difficulties, challenges, or opportunities they could foresee.

This expert also provided a more technical perspective, in contrast to the perspective of healthcare professionals.

For another angle of the everyday use of medical oxygen one interview was held with an Ambulance Nurse who was also Medical Technology (MT) Coordinator for the ambulance care. This respondent was chosen to further understand the oxygen use in ambulatory healthcare, since ambulances and hospitals operate rather differently. This respondent could provide thorough explanations regarding both oxygen delivery, handling, and oxygen therapy with their perspective as both nurse and MT-coordinator.

To further review the oxygen supply in Swedish health care an oxygen therapy expert, i.e. a nurse with this expertise, was interviewed. The goal of this interview was to gain a full picture of the day-to-day work with oxygen, and the perspective from a person working very close to the patients. Furthermore this interview was carried out to deepen the understanding of the current systems of oxygen supply within the hospital and the home health care.

Another interview was held with an expert in the field of oxygen concentrators. Even if this field is heavily researched, it is arguable that a local expert is absolutely necessary in order to make this research comprehensive enough. This expert was able to give timely information regarding Sweden's current development in the field. This interview was also be able to bring forward unique insights regarding this project from an important perspective. Additionally this interviewee had previous experience as a nurse, and thereby still partly represented a health professional perspective.

Due to the background of this study one interview was chosen to be held with a person with experience from a low resource setting, where oxygen concentrators are used. This respondent had utilized Swedish oxygen concentrators in rural hospitals in Sierra Leone. This physician could provide a unique perspective since they had experience from both the Swedish hospitals, hospitals with scarce resources, and they worked with oxygen concentrators.

3.1.4 The interview setting

All interviews were held privately, either in a room or digitally. Three interviews were held in the respondents workplace. This was convenient and it also increased the comfort for the respondents (Jacobsen, 2002). One other interview was carried out digitally, and one was held in the respondent's home. The respondents were informed that the interview would last for about one hour.

However, no time limit was given, and the respondent could thereby decide for how long they wished to proceed.

The first choice was always to meet in person, nevertheless this was not always possible. For digital meetings Zoom was used.

All interviews were recorded using an iPhone. The interviews were carried out between June and August 2023. The length of the interviews ranged from 43 minutes to 1 hours 9 minutes, with a median of 55 minutes and a mean of 56 minutes.

3.1.5 Interview analysis

All interviews were transcribed verbatim. Microsoft Office Word was used to automatically transcribe all recordings, and the transcripts were afterwards corrected manually. Jacobsen (2002) expresses the importance of transcribing to make commenting, searching, and navigating possible within the interview. The interviews were then reduced in order to make the data comprehensible. This included highlighting the relevant answers and thereby compressing the data, according to Alvehus (2013). The answers that were determined as relevant were those that had relation to the research questions and the research purpose (Alvehus, 2013). The analysis was thereafter carried out according to qualitative content analysis, based on the Graneheim and Lundman method (Graneheim and Lundman, 2002).

The transcripts were coded, and thereafter the codes were categorized. These categories were then assembled in larger categories, presenting sub-categories with similarities. Finally, a theme was composed based on all included categories and subcategories.

Lastly the interview data was used as basis for argumentation. The choice to use interviews for collection of data beyond the available literature was based on the wish to further find information, perspectives, and thoughts of the area of research (Rennstam and Wästerfors, 2015).

To easily refer to the respondents during the analysis a title was chosen for most of the respondents, these can be found in table 3.2.

3.1.6 Interview ethics

Qualitative interviews as part of the method indicates that ethical aspects need to be considered, and all interviews was carried out with some requirements

Table 3.2: Titles of the interview respondents during the analysis.

Respondent	**Title**
Medical gas expert from one of Sweden's largest hospitals	Gas expert
Nurse with oxygen therapy expertise for both at home at in hospital care	Oxygen nurse
Ambulance nurse and MT coordinator at Ambulance care in Greater Stockholm Ltd	Ambulance nurse
Oxygen concentrator expert from one of Sweden's main oxygen concentrator supplier	Oxygen concentrator expert
Swedish Physician. Founder of a children's hospital in Sierra Leone, that uses oxygen concentrators	(title did not appear necessary)

according to Jacobsen (2002):

Informed consent

All respondents participated voluntarily, and they were all asked if they wished to participate, and if they had the possibility to. They were all well informed regarding the topic both orally and in writing, and they all read and signed an informed consent form.

Privacy

All interviewees could choose to be anonymous if they wished to. During this research there was a risk of sensitive information being discussed. The project was carried out with the aim to be discreet regarding this, and the transcripts did not include any sensitive information.

Correct reproduction of the answers

To ensure correct reproduction further the interviews were recorded and transcribed, as mentioned earlier. All interview respondents were represented in the same manner as they agreed to. This included not extracting and distorting answers, and the respondents were given the opportunity to read what was written based on their interviews. If they wished to they could clarify, alter, or remove anything that was based on their responses.

3.2 Future potentials

After the potential of oxygen concentrators or different versions of on-site oxygen generating systems was established a design process and an evaluation of the new ideas was carried out. The design thinking process was performed including a discussion regarding future possibilities. The process of design thinking was chosen to be carried out according to a widely established system, presented in schools like Stanford University (Hasso Plattner Institute of Design at Stanford, n.d.). To examine the value of the ideas IDEO's three circles was utilized: *desirability, feasibility, and viability*. This system is also adopted by many to prototype business ideas (IDEO U, n.d.).

3.2.1 Design thinking process

The design thinking process includes five steps:

(i) Empathize

(ii) Define

(iii) Ideate

(iv) Prototype

(v) Test

However, since this is just a chapter of the project the process only reached the ideate step.

Empathize

The *empathize* step includes understanding the people and the context of the possible design, to comprehend what is important for the end user. This step is what was carried out during the interview study.

Define

The collected data was later used to find the users' problems and needs, hence the opportunity for innovation. The goal of this step was to create a problem statement.

Ideate

The next step of the process was to use creativity the address the problem, i.e. finding solutions to the found problem (Hasso Plattner Institute of Design at Stanford, n.d.).

3.2.2 Desirability, feasibility, and viability

In order to evaluate if a business may succeed or not it is important to consider the right aspects. Desirability, feasibility, and viability is often a good guide to find these. These imply as follows (IDEO U, n.d.):

Desirability

Are there stakeholders that desire the product, and is this product unique? If a production is carried through, will it make sense for buyers to purchase it?

Feasibility

Is it feasible to produce this product or to carry out the idea? Is the technology available, and does this appear as possible in the foreseeable future?

Viability

Will the business around this product or idea be possible to run sustainably? Is it financially possible? What else has to be in place in order for this to work?

3.3 Delimitations

In order to make this project possible to finalize within the time frame, certain delimitations have been chosen. This thesis aims to give a brief overview of multiple aspect of the issue, to possibly encourage further exploration in different directions and in more detail. If the subject had been more researched previously, there would have been reasons to choose topics within the subject that could have been explored in more depth. Furthermore this project does not wish to perform any comprehensive analysis of costs, to keep it on the subject of biomedical engineering. However indications regarding where a cost analysis could be beneficiary is relevant. Intricate technicalities regarding oxygen concentration or generation will also not be reviewed.

The design process in this project was limited and not the main goal of the research. The interviews were carried out with regards to the aims of the study and not with regards to a new innovation, hence there are questions that were not asked that could have been relevant for a new design. Further this project did not aim to present a fully developed solution, but rather to speculate regarding possible future innovations and opportunities.

4 Interview findings

4.1 Interview findings

An overview of the theme, categories and subcategories that emerged from the qualitative data collection can be found in table 4.1.

4.2 The oxygen supply system

4.2.1 Swedish hospital

The medical gas expert provided a comprehensive report on how a large Swedish hospital provides oxygen to it's patients.

Stockholm's hospitals get LOX delivered from one medical gas supplier 80km outside of the city about once every week, however the frequency of deliveries may vary. The transportation is carried out using tank trucks, and handled by the supplier. The hospitals store LOX in their own tanks at the facility. These tanks then supplies the entire hospital with oxygen of about 99.99% purity through a pipeline system. At this facility two LOX tanks are used, one of 10,000 litres and one of 6,000 litres. The plan is to soon utilize two 10,000 litre tanks instead. Before the pandemic only one LOX tank was installed.

To transform the oxygen from liquid to gas when entering the pipes an evaporator is used, and an additional system is utilized to ensure the correct pressure output. The pipeline system is made out of copper or stainless steel. To guarantee safety there are regulations for pressurized pipes, and the pipeline system holds pressure switches, pressure monitors, and emergency valves. Since medical oxygen is of pharmaceutical grade, the entire system is a type of pharmaceutical packaging and should always be kept in perfect condition.

In this large hospital, there are a number responsible parties:

(i) Supplier of medical oxygen.

(ii) Owner and administrator.

(iii) Producer and user of the central gas system, i.e. the hospital.

(iv) An operating organisation.

(v) Independent inspection provider.

The operating organization and the hospital have different responsibilities regarding the inspection of the system, and some may be outsourced to the supplier. This includes daily examinations of, among other things, the tanks and the pressure output system. Less frequent maintenance includes exercising all valves and gas outputs, and exchanging o-rings. Additionally inspection of the pressure monitors and the pressure switches, and servicing the emergency valves, should also be carried out. Finally there is a yearly inspection carried out by an independent party.

Since this comprehensive maintenance system requires many hours from trained personnel it is very costly. There is thereby thorough risk management performed in order to decrease these expenses, i.e. parts of the supplier's recommendations for how to keep the central liquid oxygen system is not carried out.

The only electricity necessary for the system is for the control systems and the alarms. The flow of oxygen does not require any electricity. As backup oxygen cylinders are used.

Cylinders with compressed oxygen are utilized within the hospitals mainly for transportation, i.e. they can follow the patient through the hospital. This institution has a department that delivers the oxygen cylinders to wherever they are needed within the facility. The cylinders are provided by the same supplier as the liquid oxygen. The supplier delivers full, sealed, cleaned, and maintained cylinders, and picks them up for refill. All cylinders are also possible to track.

The gas expert reported that no calculated costs were available for the entire oxygen system in relation to the number of patients. They did however also express that this sort of analysis was possible to carry out.

Some costs for LOX from one Swedish gas supplier was provided[1]. The price for one kilogram was currently 2 SEK. The storage tanks were paid monthly: 4,000 SEK for 10,000 litres, and 6,000 SEK for 20,000 litres. Note that the recent increase in electricity prices in Sweden may have increased these costs. Furthermore the energy consumption at this manufacturing site was presented to be 0.98 kWhm for 1 nm^3 of LOX, and 1 nm^3 = 1.311 kg. A presentation of these numbers can be found in table 4.2.

Most of the respondents highlighted the increased demand of oxygen during the recent pandemic, and the gas expert reported that their hospital had installed a new liquid oxygen tank to meet the need.

4.2.2 Ambulance

The ambulance nurse and medical technology coordinator contributed with a thorough description of the medical oxygen system for their ambulances.

Ambulances utilizes cylinders with compressed oxygen, which are provided by the same supplier as for the hospitals in the area. All cylinders are maximum 5 litres, and they are either in a rack in the car, or placed in a backpack for flexible use. The cylinders in the car are attached to a small pipeline system, which delivers oxygen through a wall outlet just like in the hospital. Depending on the model of the ambulance, the cylinders may or may not be within reach for the healthcare professional when they are placed next to the patient. If a cylinder is emptied it is thereby sometimes necessary to unbuckle in order to switch to a full oxygen cylinder. Some ambulance models do also not have an alarm for when the oxygen is exhausted.

It was further reported that they used oxygen for many patients, and that nebulizers and suction also was driven by medical oxygen. It was however also explained that the use of oxygen as therapy and the flow rates had decreased a lot during their career, due to the highlighted risk of oxygen toxicity. They also said that intubation was a lot less common now compared to earlier.

Electricity was presented to not be necessary for the system, and the only maintenance carried out was an inspection of the pipes annually. The maximum possible output for oxygen in most ambulances was expressed to be 15 LPM.

Costs for medical oxygen for five months during 2023, including a breakdown of the costs, was provided. For one ambulance the total cost for oxygen

[1] Personal communication with one of Sweden's main gas manufacturers

was 7000 SEK, which included delivery of the oxygen[2]. For price breakdown see table 4.3.

4.2.3 Home health care

The oxygen concentrator expert and the oxygen nurse gave an extensive explanation of how oxygen is used within the home health care.

Patients that require oxygen within their home are almost always provided with one stationary oxygen system and one portable oxygen system. The portable system is meant to make it possible for the patient to leave their home. For all stationary systems the oxygen source is placed within the patients home, with a long, plastic, armoured tube attached that delivers the oxygen. The portable system is smaller with a shorter tube. The oxygen source is decided together with the patient, to see what option is appropriate for their condition. The available options are LOX, compressed oxygen cylinders, and oxygen concentrators.

Patients that use LOX are provided with their own tank to keep in their home. If the LOX is used at home the patient can attach the delivery tube directly to it. For portable use the patient can fill a type of thermos directly from the tank, to carry with them when leaving their home. The oxygen concentrator expert and the current oxygen nurse did express that LOX is a very expensive system, which has resulted in fewer medical clinics currently offering this option for home healthcare patients.

Compressed oxygen cylinders are another options for continuous home healthcare. Delivery is provided directly to the patients home, and they can use the cylinders inside and outside. The prescribing medical clinic pays rent for the oxygen cylinders for every 24 hours that they are kept.

Oxygen concentrators are widely used within the Swedish home healthcare, and the oxygen nurse reported that this was considered to be the most cost efficient choice. For the hospital where the interviewee was employed, oxygen concentrators were thereby the first choice for all patients that needed oxygen in their home. The respondents reported flow rates in the range from 0.1 LPM up to 9 LPM. The patients that use oxygen concentrators are provided one stationary device to use at home, that is larger and connected to a power source. The stationary options that the respondents were familiar with were not possible to use outdoors. The portable option can be brought anywhere. The portable concen-

[2]Information provided by Ambulance care in Greater Stockholm Ltd

trator from the oxygen concentrator expert's brand could be as small as 2.3kg, and comes with a rechargeable battery. Some models do not deliver a continuous flow, meaning that the patient is required to trigger the flow of oxygen with a breath through the nose. The oxygen provided by the oxygen concentrators are 90-96% pure oxygen.

It was further reported that patients that require a higher flow rate than 9 LPM could have multiple oxygen concentrators connected. According to the oxygen nurse there had been a situation where they had received a flow rate of 27 LPM with this method.

Most models of oxygen concentrators require regular cleaning of their gross particle filter. This procedure was expressed to be easy enough to often be left for the patients to carry out every 14th day. The respondent did also announce that there are models that do not require any maintenance at all. During use all oxygen concentrators make a humming noise.

4.2.4 Nursing homes

It was reported that nursing homes without central oxygen supply systems had bought oxygen concentrators in order to provide oxygen therapy to their patients.

4.2.5 Low resource setting with oxygen concentrators

The physician and founder of a children's hospital in Sierra Leone explained the use of oxygen in Sierra Leone. Depending on the resources at the different hospitals the availability of oxygen sources varied. In the more rural areas, where they were working, they told that there were some oxygen cylinders present but nowhere to refill them. They further explained that other facilities did use cylinders and had access to refill, however this was not an option for everybody. The respondent reported that oxygen concentrators was the only source of oxygen at their hospital, and at all hospitals they had previously worked in the area. Additionally it was explained that they used ordinary medical devices that was available on the global market.

The oxygen concentrator expert reported that the company that they were employed at had contributed with oxygen concentrators to low-resource settings during the COVID-19 pandemic, due to the widespread shortage of oxygen.

4.3 A widely established system

4.3.1 LOX and pipelines - a system without competitor

Nothing negative was brought forward regarding the central oxygen supply system. Throughout all interviews when asked about positive and negative aspects of central oxygen supply many respondents struggled to find anything to compare it to except cylinders. It was highlighted that this was a system that had 'always' been used, and there had not been reasons to question it. A number of the respondents mentioned how superior the pipeline system was to cylinders, bringing forward that the appreciated aspect of the pipelines was the accessibility to oxygen. One respondent compared the gas arrangement to water, meaning tap water and oxygen outlets provide an equal service.

> *...either you choose to carry gas cylinders, or the pipes carry the gas. If I put it like this, the question could also be, 'why do you have running water?' Either you go to the well with a bucket, or you have a tap.* (Gas expert)

The gas experted highlighted that the current central oxygen system maintains great surveillance over the oxygen, i.e. when the production is outsourced the supplier is responsible for maintaining great oxygen quality. Further they reported that the hospital very rarely encountered any problems with their oxygen system, and compared to cylinders the pipelines were outstanding. The oxygen nurse expressed that it was very positive that the pipeline system provided a free flow of oxygen, and that it was quiet and easy to work with. The outlets on the wall was in their facility placed at an ergonomic height for connection and flow rate adjustments, which was mentioned as very positive.

The pipeline oxygen system at the hospital was described as safe and without a history of accidents. However it was mentioned that maintenance may sometimes be inadequate and that gas pipes sometimes run in close proximity to electrical cords. It was also expressed that gas systems always have small leakage, yet this was not described as a dangerous. Gas pipes would in most cases run outside of the walls in case of problem or leakage, the gas expert further explained.

The risk of running out of LOX was mentioned, especially in relation to the recent pandemic. According to one respondent there had been medical oxygen suppliers at the time that warned that all oxygen may actually run out. Another respondent brought forward the fact that in case of an situation where deliveries would not be possible, the hospitals would not get any new oxygen.

4.3.2 Cylinders in the hospital and the ambulance, an OK system

Cylinders with compressed oxygen was for the hospital environment described as inferior to the pipeline system, yet they were a needed substitute to make mobility possible during oxygen therapy. The fact that compressed oxygen cylinders can deliver high flow rates was mentioned as a positive property.

All respondents seemed well aware of the possible risks of handling oxygen cylinders, some did however witness about inadequate safety measures. One respondent reported that the deliveries of oxygen cylinders was included in the price, however this was not always known due to miscommunication. They had thereby for a period of time carried out the transportation themselves, without fulfilling the safety requirements. Further it was expressed that all personnel at the ambulance station handled the oxygen, and even if they had training to do so it was described as poor. Additionally it was brought forward that the departments that had a higher focus on oxygen therapy discussed the risks related to oxygen and cylinders more than other departments.

For the ambulance the current oxygen system built around cylinders was still referred to as uncomplicated, simple, and reliable. However, there was also a problem mentioned regarding the fact that oxygen cylinders are an exhaustible source. For the ambulances that did not have an alarm for empty oxygen cylinders this was described as very problematic, since the healthcare professionals then sometimes noticed the lack of oxygen only when the patients saturation decreased. The oxygen nurse did also highlight the fact that oxygen cylinders require surveillance, since the oxygen may run out.

> *"For example here in the waiting room there are no oxygen outlets in the walls, so there are patients that may not feel well that we'll bring an oxygen cylinder for. (..) But there is always a risk that it will become empty, so more monitoring is demanded.* (Oxygen nurse)

The oxygen in ambulances was mentioned as a 'large cost'. Suction driven by oxygen from the cylinders was described as a terrible waste, since the suction sometimes used more oxygen than the patient.

4.3.3 Oxygen concentrators in the hospital seems far away

The gas expert explained that oxygen concentrators do not meet the same level of purity that LOX does, hence there might be a lot of medical equipment in the hospital that would not work as intended with lower oxygen concentrations. They also expressed that overall it might be simpler to outsource the oxygen production than using concentrators. Further they indicated that oxygen concentrators would create an abundance of medical devices, and that a faulty concentrator could be dangerous for the patient.

> *”You will end up with so much equipment. The risk of one patient being without oxygen will be big. I think the risk increases, due to broken equipment. The way we have it works very well, with very little issues.”* (Gas expert)

It was also expressed by the oxygen nurse that oxygen concentrators may cause problems with heat and noise. However many mentioned that oxygen concentrators could work as a back up option in all environments, and that oxygen concentrators would mean less risks in case of a fire.

4.4 There demand for improved oxygen concentrators

4.4.1 Oxygen concentrators- a cheaper and inexhaustible oxygen source for the home health care patients

Patients with oxygen therapy in their home was the only environment where an comparison of LOX, cylinders, and oxygen concentrators had taken place.

LOX was presented as a very well functioning system for home healthcare patients due to space efficiency and the fact that it provides oxygen silently. The oxygen concentrator expert witnessed that many patients appreciated LOX. It was however highlighted as an awfully expensive alternative for the home healthcare, which had resulted in a large decrease in LOX subscriptions.

Oxygen cylinders was presented as a somewhat cheaper option compared to LOX, however it was not as smooth. For patients with oxygen cylinders or LOX a problem that was put forward was the possible anxiety of running out of oxygen. It was explained that it is common to worry about deliveries being late or not showing up at all, and the patients have to calculate their use and account for holidays when deliveries are not possible. Further the patients also have to be home to receive their oxygen. These circumstances was explained as a common source of anxiety, leading to many patients keeping an abundance of oxygen in their home. This in turn would lead to increased costs for the medical clinic, since the rent is paid per day.

> *"...is a lot of anxiety for the patient regarding the wait for deliveries of oxygen. There is Christmas, New Years, Midsummer.. A lot of holidays, 'is my calculated oxygen going to be enough?' (...) This leads to many patients hoarding cylinders in their home, which in turns becomes an enormous expense for the hospital"* (Oxygen concentrator expert)

Furthermore it was described that the portable use of compressed oxygen cylinders meant that the patient had to carry a lot of oxygen with them when leaving their home for a longer period of time. In addition oxygen cylinders are not safe to leave in a car during warm weather, hence the patient becomes obligated to bring them, one respondent reported.

When describing the use of oxygen concentrators within the patients home it was repeatedly highlighted that these patients never had to worry about their oxygen running out. The small size and the widespread availability of power outlets in the Swedish society was mentioned as making the use of portable oxygen concentrators safe and simple. The oxygen concentrator expert reported that a great development of oxygen concentrators had taken place during the last ten years, which had, among other things, resulted in the smaller sizes available. Another respondent did however express their patients sometimes asked about the development in the area, considering it to be slow. Due to the recent surge en electricity prices it was also expressed that the energy consumption was a problem for some patients with oxygen concentrators in their home.

A problem that was presented both for in the use of portable and stationary oxygen concentrators was the fact that they are not quiet. It was explained that some patients feel embarrassed about having a humming device with them in public, and that it could also be disturbing at home. The stationary models were also described as heavy and difficult to move. The oxygen nurse explained that moving a stationary concentrator meant that you had to walk bent down to reach it.

Regarding the current availability and use of oxygen concentrators the respondents stated that the maximum flow rate was too low, which limited the patient group that could benefit from them. Oxygen therapy at home was reported to be used mostly by COPD patients, however patients with pulmonary fibrosis was also mentioned. The latter was explained as more oxygen demanding, leaving them currently dependent on oxygen cylinders or parallel connected oxygen concentrators.

> *"Pulmonary fibrosis is a patient group that is difficult to treat, they demand very large amounts of oxygen. To accommodate these patients with oxygen they get these large oxygen tubes, or there have been situations where we have connected multiple oxygen concentrators to deliver more oxygen. (..) There are concentrators with higher flow rates (..) that I have said for many years that we need (..) that is one of my wishes. "* (Oxygen concentrator expert)

The oxygen nurse described the oxygen concentrators they used as stable and reliable, with little maintenance needs.

4.4.2 Could oxygen concentrators be a viable option for the ambulance?

From the low-resource setting point of view it was expressed that an expanded use of oxygen concentrators would be very positive. They explained that they experienced that corporations follow profit, with little interest countries with scarce resources. Thereby a further development and availability of oxygen concentrators could mean more that their access to oxygen concentrators would increase. The oxygen concentrator expert highlighted that an increased demand would definitely spur further development of the device. They also brought forward that a more widespread use would be a great opportunity for the manufacturer, since the market would increase. Speculations regarding increased efficiency and decreased energy consumption during use was also mentioned.

The ambulance nurse expressed that oxygen concentrators would be very interesting to look at as an alternative for the ambulances, given that they would perform as necessary. They highlighted that it is easy to forget that ambient air holds 21%, and that it would make sense to use that. The oxygen nurse also put forward the fact that we buy air.

> *"..when you think about how they produce oxygen, that we buy in cylinders and for the large containers that we access through the wall, it is actually kind of silly that they kind of collect air and sell it"* (Oxygen nurse)

An opportunity further mentioned was the possibility to decrease costs compared to using compressed oxygen cylinders. Additionally it was expressed that it would be very positive for the ambulance to work with a non-exhaustible oxygen source. Regarding design, compatibility with other equipment, and the user experience of the health professionals nothing negative was brought up when asked for. Their only concern was weight, however they reasoned that oxygen concentrators may actually weigh less than compressed oxygen cylinders.

4.4.3 A wish list to the manufacturers

A summary of these findings are presented in table 4.4.

All respondents that had worked with oxygen concentrators expressed a few shortcomings in the current design. As previously mentioned many requested a more silent alternative, to avoid embarrassment for patients with portable concentrators and to reduce noise disturbance in general. It was also repeatedly mentioned that higher flow rates than what was widely available on the market was desirable both for the current situation and for a possible expansion of the oxygen concentrator use. Further it was put forward the less energy consumption would be optimal, mainly to decrease costs. Some kind of backup battery for power interruptions was also brought up as something that would increase safety. The respondents also requested smaller and lighter devices, generally referring to the stationary option. Measures that would facilitate easier transportation was suggested as something that would make handling of the device easier. One respondent had a concrete proposal regarding a pull up handle, similar to those on a suitcase, suggesting that this would make transportation a lot smoother. Another ergonomic improvement would be a remote control for adjustment of the flow rate, and to somehow reduce the need to bend down to the concentrator to change the flow rate.

For the low-resource setting they expressed that an indicator for when the filter needed cleaning would be a great addition to the design, as well as an oxygen concentration meter. The latter was expressed that it would be very resourceful in order to determine the condition of the oxygen concentrator. The founder of the children's hospital described the oxygen concentrators as prone to breaking, requesting a more robust design in general.

Table 4.1: Theme, categories, and their subcategories

Theme	**Category**	**Subcategory**
Are there alternatives to LOX?	The supply of oxygen	• Swedish hospital • Ambulance • Home health care • Nursing home • Low resource setting with oxygen concentrators
	A widely established system	• LOX and pipelines - a system without competitor • Cylinders in the hospital and the ambulance, an OK system • Oxygen concentrators in the hospital seems far away
	The demand for improved oxygen concentrators	• Oxygen concentrators - a cheaper and inexhaustible oxygen source for home health care patients • Could oxygen concentrators be a viable option for the ambulance? • Wishlist for future oxygen concentrators

Table 4.2: Costs and energy consumption. Information provided by one of Sweden's main gas manufacturers.

LOX volume (kg)	Cost (SEK)
1	2
LOX tank (litres)	**Monthly cost (SEK)**
10,000	4,000
20,000	6,000

Table 4.3: Costs for medical oxygen within the ambulatory healthcare[2]. Please note that the price for the 3 litre oxygen cylinders recently increased due to a new model with digital manometer.

Cylinder size	Rental cost, 24h (SEK)	Refill cost (SEK)
5	0.22	52.26
3	1.44	149.33
Time period	**Number of missions**	**Total cost (SEK)**
5 months	1500	7000

Table 4.4: Target specifications for oxygen concentrators, identified from the interview findings. If no other indication, this table refers to stationary oxygen concentrators.

Target	Motivation
Lower noise level.	Avoid embarrassment in public (portable). Reduce disturbance in general.
Higher flow rate.	Make treatment of patients that need higher flow rates possible.
Less energy consumption.	Decrease costs.
Backup in case of power interruptions.	Increase safety.
Smaller devices.	Make easier to move.
Lighter devices.	Make easier to move.
Add handle.	Make easier to move.
Add remote control.	Make flow rate changes easier.
Add indicator for filter cleaning.	Make maintenance easier.
Add oxygen concentration meter.	Facilitate verification of functionality.
Make more robust.	Increase life length in dusty environments.

5 Discussion

A comparison of the oxygen supply systems that has been discussed in this research can be found in table 5.1.

5.1 Is it time to review the LOX systems?

Both the literature study and the interviews revealed that the common system of using LOX in tanks together with a pipeline system is a widely established, appreciated and unquestioned system. Little research is to be found regarding the costs of central LOX systems, and there are articles that simply refer to it as of ”economical advantage” without further explanation (Paul et al., 2020). The Polish publication previously mentioned did however state that LOX was not necessarily the most cost-effective choice (Balys et al., 2021).

For home oxygen therapy there has on the contrary been declared that LOX is a very expensive system. The comparison carried out by Andersson et al. already in 1998 revealed the high costs of LOX for oxygen therapy in the patient's home, which seems to still be relevant since this interview study revealed that LOX is not even a choice at some clinics due to the high cost. However, as presented in table 4.2, oxygen in large quantities appear as notably cheaper. An approximation of 8,000 litres delivered every week, with a hospital that has two LOX tanks results in an annual cost of almost 1 million SEK, according to table 4.2:

$$8,000 litres \cdot 52 weeks \cdot 2 SEK + 2 tanks \cdot 12 months \cdot 4,000 SEK = 928,000$$

. A comprehensive comparison of the costs for different systems, if utilized in Sweden, could be a subject for future research. The interviews did also reveal a comprehensive maintenance arrangement surrounding the LOX and the

Table 5.1: Comparison of the different oxygen supply systems.

System	LOX	PSA plant	Cylinders	Oxygen concentrators
One time costs	Significant.	Significant.	Low/no cost.	Moderate.
Operational costs	Purchase of LOX, maintenance, tank rent.	Electricity, maintenance.	Purchase of oxygen, cylinder rent.	Electricity, maintenance.
Energy consumption	During production, nothing at facility.	Continuos.	During production, nothing at facility.	Continuos.
Transportation required.	Yes.	No.	Yes.	No.
Exhaustible supply	Yes.	No.	Yes.	No.
Transferability to low resource setting	Low.	High.	Moderate.	High.

pipelines, and that this was so costly that risk management was carried out in order to find how these costs could be decreased.

Regarding the function of the central oxygen supply systems the interviews witnessed about a positive attitude towards the current system, however this was often with regards to the fact that a free flow of oxygen was easily available. This indicates that the source of oxygen may not be of huge importance for the health care professionals, which was also stated by one respondent. Furthermore it is presumably reliability and user friendliness that are the essential characteristics of an oxygen source. The findings did however also reveal that experts in the area had not had any reason to question the current system. This may indicate that the system is a good option, or that there have never been any presented alternatives to consider.

Considering the environmental impact of the arrangement for Stockholm's hospitals, just looking at the transportation costs raises the question if there could be better alternatives. Including only the seven main hospitals of Stockholm having approximately one truck delivery of oxygen per week from the current supplier 80 km away means:

$$7\, hospitals \cdot (80 \cdot 2)\, km \cdot 52\, weeks \approx 58000\, km$$

There are i.e. heavy tank trucks driving 58 000 km per year to deliver LOX, only for this small area. Even if the findings did not indicate that oxygen concentrators would be a viable choice for hospitals at the moment, this is an indication that there might be valuable to work towards something else. If oxygen concentrator or larger PSA or VSPA systems were developed in the right direction so oxygen could be produced on-site, that might be an option that could reduce the environmental impact this transportation of LOX implies. Furthermore the mentioned considerations regarding transportation of dangerous goods is another reason to decrease the freight. Worth mentioning is however that the energy consumption for LOX production as oxygen concentrators appear to be similar.

Even if this rather brief investigation does not thoroughly investigate the mentioned issues, this does indicate that there are reasons to further explore the area. The lack of previous research signals that few evaluations of central LOX systems have been carried out. This type of oxygen supply system might entail such financial and constructional investments that once established few would question it. The interview findings also reveal that alternatives were not a common knowledge in the group of interviewed people, and that this system has been used for what many people would consider as ’forever’. If this represents the view of a larger portion of the population, it might explain why LOX tanks are used without questioning. To conclude this issue this study argues that it might be positive for the future to examine the possibility of different alternatives to LOX tanks, however not necessarily individual oxygen concentrators. The findings implies that there are many positive aspects of using pipelines, hence an area for future research may be to investigate larger PSA or VSPA systems for on-site production. With that type of arrangement transportation and purchase of oxygen would be removed, and the healthcare professionals would still have access to oxygen ”in the wall’. This approach is also used in low resource settings to increase the availability of oxygen (UNICEF, 2022*a*). If hospitals in Sweden and similar countries would use this that would also most probably spur the development of the technology, which in the long run could positively affect the performance.

5.2 Cylinders may be used just cause there is nothing better out there

The literature research and the interviews revealed that cylinders with compressed oxygen is a reliable system for countries with functioning infrastructure, however it is not perfect. The interviewees seemed pleased with the fact that the cylinders facilitated mobility, yet this was presented in comparison to the oxygen wall outlets. The exhaustible nature of the cylinders seemed as a present complication both in the hospital, the ambulance, and especially in the home health care. The findings declare that when provided with oxygen concentrators as an option to cylinders, these were happily accepted, e.g. since the Swedish choice seem to be oxygen concentrator for as many home oxygen therapy patients as possible. The similar sequence of events can be seen in rural areas with scarce resources, when oxygen concentrator is a preferred choice for many hospitals that otherwise would rely on oxygen cylinders (World Health Organization, 2023). Additionally the findings briefly describe that nursing homes and other Swedish health facilities already benefit form the use of oxygen cylinders, indicating that this environment might also be a subject for future research regarding oxygen concentrator development.

The findings did not indicate that oxygen cylinders was a problem for the ambulance. Yet it did imply some questionable aspects of the cylinder management, and it brought forward that oxygen was considered as rather costly. Considering the findings regarding the cost for oxygen cylinders for home health care and research carried out for low resource settings there are implications that oxygen concentrators may be a future option for ambulances (World Health Organization, 2015). The peak flow rate in one ambulance of 15 LPM presented by one respondent is another implies that an oxygen concentrator could be an excellent choice for the ambulance, if built for it and if it reached this flow rate. Additionally if a concentrator could be less heavy than oxygen cylinders it would be another positive aspect for the ambulance. This topic does also lack extensive previous research. There are systems available for this purpose e.g. in USA, further demonstrating that it is absolutely possible (On Site Gas Systems, n.d.). If some type of PSA system could be manufactured to fit the needs of a Swedish ambulance, *and* if it could decrease cost and weight there is a lot to win. It could also decrease the stress for health care professionals of oxygen cylinders emptying while they are taking care of a patient. Eliminating the management of oxygen cylinders would also increase the safety for all ambulance personnel, and remove the task of checking the oxygen supply. This could be an outstanding opportunity for any manufacturer, if they could develop a device that lives up to the needed standard. Further this type of oxygen concentrator would also most probably be possible to use in any setting, especially since the environment that the ambulance operates in is more challenging. Hence this is also an opportunity to increase the availability of durable oxygen concentrators, which is absolutely necessary for low resource settings.

5.3 Benefits of improving the oxygen concentrators

As for the findings regarding the low resource setting this respondent confirmed that oxygen concentrators are a life saving device that suits the rural areas well, in accordance to the literature study. However they also expressed that a more robust version would be beneficial, describing features that has also been brought up in research carried out by UNICEF (World Health Organization, 2022*a*) (UNICEF, 2021). The oxygen concentrators meant for Swedish environments could however also be improved with some of these features to increase patient comfort, according to the findings. UNICEF describes that the oxygen concentrators they aimed to design would include features like resistance to dust, heat, and humidity, increased energy efficiency, and a more robust design. They also mention that they aim to explore alternatives to deal with power outages. The findings reveal that home health care patients in Sweden can only use their stationary oxygen concentrators indoors, meaning that patients have to rely on their portable system e.g. when spending a day in their garden. If their oxygen concentrators would be more robust and be dust, heat, and humidity resistant that could improve their quality of life. Since the findings revealed that portable oxygen concentrators can be used outdoors the technology is evidently available. Increasing the energy efficiency of the device would naturally be beneficial for every user, independent of where in the world, which the findings also state. Similarly a system to deal with power interruptions was mentioned as a desirable future feature, both for use in Sweden and in the low resource setting. Furthermore the findings signals that users of oxygen concentrators all want them to be smaller, more silent, and easier to move and use. Ergonomic improvements self-evidently be positive for anyone managing the device. The study does i.e. indicate that similar development of oxygen concentrators is desirable independent of the context, however it also implies that there seem to be a demand for improvement of the device here in Sweden. The UNICEF project and the wide availability of technology and advanced equipment that is made today signals that all of the mentioned features should be feasible to achieve.

The findings clearly show that the current market for oxygen concentrators in Sweden includes at least a large portion of the home oxygen therapy patients, plus a number of nursing homes. Furthermore the respondents made it clear that the current wish was to use oxygen concentrators for an even larger number of patients, given that the flow rates would increase. I.e. if the suppliers would improve the performance of the device there could be a wider market available.

During the interviews there were indications that oxygen therapy is used more carefully now than historically, due to the risk of oxygen toxicity. For many mediums of delivery the FiO2 does not reach close to 100%, hence one may speculate that the necessary oxygen concentration may not be 100%. A thorough examination of the subject would naturally be necessary, however there might be reason to explore methods of delivering lower concentrations of oxygen if this could decrease costs or energy consumption.

5.4 Methodological considerations

A strength of the study was that the interviews and the analysis was carried out by the same person (i.e. the author), however it can be argued that having only one person present during the interviews can decrease credibility.

All of the selected participants did or had previously worked within the healthcare and should thereby have the patients benefits as a common goal, especially since the Swedish health care system is mostly non-profit. The participant could however still be biased due to their current roles or collaborations with companies or people with different interests. Since this research implies to look for possible changes that might affect the participants work situation it is also important to consider that they could have personal interests regarding the subject.

Transferability is a component of the trustworthiness of a qualitative study. Since the participants of this study were key people and experts representing different parts of the oxygen therapy healthcare, the findings should most probably reflect people in similar positions. The results from this study should also be relevant for similar settings, for instance the nearby countries or areas with similar healthcare systems and financial resources.

6 Future potentials

This study has revealed that there are reasons to further research the possibility to develop oxygen concentrators or larger PSA systems for on-site oxygen production. To finalize this project a design thinking process has taken place, in order to construct possible ideas that might have future potential. As presented in the methodology chapter the following was carried out according to the design thinking process that utilizes the steps *empathize, define, ideate, prototype, test* (Hasso Plattner Institute of Design at Stanford, n.d.). The presented ideas are then evaluated by using the framework that includes *desirability, feasibility, and viability* (IDEO U, n.d.).

6.1 Empathize

The demand for oxygen concentrators in low resource settings is large, according to the literature study. The interview findings indicated that there is currently a stable demand in Sweden of the current availability of oxygen concentrators within:

(I) Home health care for patients that require flow rates up to 9 LPM (this number may vary between regions of Sweden), and for some special cases where multiple oxygen concentrators are used together.

(II) Nursing homes that lack gas pipeline systems.

However, this study presents that there could be an increased demand within the mentioned areas if oxygen concentrators could increase their performance, especially regarding the flow rate. The patients that require a higher flow than what is available today are currently depending on alternative systems. Further, as previously mentioned, health care professionals presented that a free flow of oxygen available ”from the wall” is appreciated. The findings regarding the oxygen system in the ambulance did indicate that compressed oxygen cylinders are their current option, which is working well, however it is fairly expensive. Additionally the handling of oxygen cylinders include risks.

6.2 Define

The major issue regarding oxygen is the widespread shortage, which is the foundation of this project. Furthermore the study has shown indication regarding a possibility for a broadened use and development of oxygen concentrators or other on-site PSA or VPSA systems, which, as mentioned, should contribute to an increased availability of oxygen therapy. However, there are a number of problems and needs:

- The oxygen flow rate output needs to be increased in order to capture a larger patient group in the home health care.
- The oxygen concentrators would preferably operate more silently.
- There should be a backup system within the oxygen concentrator in case of power interruptions.
- The oxygen concentrators should consume as little energy as possible.
- Ergonomic improvements should make flow rate adjustments easier and facilitate transportations (for stationary oxygen concentrators).
- LOX and compressed oxygen cylinders are expensive for the home health care.
- LOX and compressed oxygen cylinders require deliveries from a supplier, which is relevant for all facilities and home health care patients.
- Ambulances need an oxygen system that is lightweight, reliable, and easy to use with a flow rate up to 15 LPM.

6.3 Ideate

There are a number of different products available that utilize PSA and VPSA technology to generate medical and non-medical concentrated oxygen. Oxygen concentrator is just the name that is commonly used for the bedside model or the portable model. Larger versions are often referred to as oxygen generators.

6.3.1 Evaluate the inside technology

In order to decrease the noise level of the operating oxygen concentrators there needs to be an evaluation of the inside technology. This development could include an evaluation of the compressor system, since there are many different types of compressors on the market. The scarce availability of oxygen concentrators on the Swedish market indicates that there may not have been any incentives to decrease the noise. A future development of oxygen concentrators should thereby investigate this matter. Furthermore the compressor may also affect the performance, i.e. the flow rate, of the concentrators. Ideally a comprehensive examination regarding the entire inside of the different oxygen concentrators should be carried out, to see how flow rates could increase, how noise levels could decrease, and overall how the device could be more durable.

According to the specifications of the durable oxygen concentrator that UNICEF has written about developing, two key features they discuss are the possibility to work in warm and dusty environments (UNICEF, 2021). During the compression state of the oxygen concentration the air becomes warmer, making the device prone to overheating in high temperatures (World Health Organization, 2015). High temperatures is not something that only occurs in low resource settings, i.e. there is no reason to not improve this feature for oxygen concentrators made for Sweden.

Regarding dusty environments this is naturally less occurring in a country like Sweden where the oxygen concentrator is mostly used indoors. However, if oxygen concentrator manufacturers would keep in mind that the device should be able to use in other environments, this could be easily carried out. According to the target product profile of a resilient oxygen concentrator made by UNICEF dust-resilience mainly includes using more or better filters (UNICEF, 2022*b*). It should not be challenging for a manufacturer to make the filters exchangeable according to the environment that the oxygen concentrators are meant to operate in.

To further evaluate the inside technology of oxygen concentrators there are manufacturers that argue that VPSA systems have many advantages over PSA systems. VPSA is said to, among other things, consume less energy, need less maintenance, and handle humid environments better (Caitlin Kamminga at OSI Oxygen Solutions, 2021). However, there are other studies that suggest that PSA is still preferred due to e.g. weight reasons (Ackley, 2019). There might be reasons to use PSA systems for one type of oxygen concentrator and VPSA for another, depending on how the device will be used.

Considering the availability of so called oxygen generators that produce large quantities of oxygen there really is a question why there are no stationary oxygen concentrators that provide higher flow rates on the Swedish market.

Desirability, feasibility, and viability

- *Desirability* - Oxygen concentrators are already a demanded product, and according to the interview findings there are patients that are waiting for improvement. As long as an improved product would not imply heavily increased costs the desire would at least remain the same.

- *Feasibility* - Different types of evaluations would require varying financial and technological resources. For some situations at may be necessary to work with skilled technicians and health care professionals, which may result in higher costs. Disregarding financial aspects the evaluations are otherwise feasible, since all technology is already available.

- *Viability* - This idea is one step for other products, and not an independent product. However, it appears as viable to let already existing devices undergo this type of evaluation since all the proposals are meant to result in a more durable or improved product. If the processes would not result in any unforeseeable raised expenses, the idea appears as viable.

6.3.2 High-flow oxygen concentrators

According to the interview findings there are a number of home health care patients in Sweden that require higher flow rates than the oxygen concentrators today can deliver. There is thereby reason to develop an oxygen concentrator with higher flow rates, to increase the life quality for these patients and the costs for the prescribing hospitals (i.e. government costs). With the technology that is used today there is evidently possible to develop a device that delivers higher flow rates, however this may result in rather large equipment with high noise levels. Nevertheless this option would most probably still be preferable to cylinders and LOX. If this device would be produced there are reasons to believe that it would be further developed, which additionally may result in a better product, and thereby increased life quality for the patients, in the future.

To carry out this type of project one need to explore the number of patients it could benefit, and what flow rates would be necessary. This device would also benefit many facilities that today are depending on cylinders, both in Sweden and other countries. Since there already is a demand in the Swedish home health care there is definitely reason to believe that this idea is feasible to carry through.

Desirability, feasibility, and viability

- *Desirability* - The idea originates from the pronounced lack or this product in the interview findings, and can thereby be judged as desired.
- *Feasibility* - All the technology is available for this product, since this is rather just a new model of something that already exists.
- *Viability* - The already present demand indicates that this type of device should be able to enter the market seamlessly. The oxygen concentrators that are already used are not very different from this idea, and the current businesses around those imply that this should also be possible.

6.3.3 An ambulance system

Like previously mentioned there are oxygen concentrators, or PSA systems, available for ambulances (On Site Gas Systems, n.d.). To speculate regarding a suitable PSA system for ambulances one idea is to manufacture an entirely new system. The device could be made to fit the ambulance specifically regarding size and flow rate output, to be placed in the space where there today are oxygen cylinders. Further there should preferably be possible to access oxygen in a similar manner as the health care professionals are today, or surveys should be utilized in order to find what would fit the ambulance personnel. The intake of surrounding air could be from either the inside or the outside of the ambulance, depending on what shows to be the cleanest or of best temperature.

Since the device would not need to be moved or easily accessed by the personnel there are also reasons to evaluate if it could be place e.g. on the roof of the ambulance, since this would make the space within the ambulance larger. If the device would be placed out of reach a control panel or a remote control should be used to manage the device.

Since weight is an important matter for the ambulance it is crucial to explore how the device could be manufactured to weigh as little as possible. Furthermore it would be beneficial if the device presented both flow rate and oxygen concentration, to make it easy for the user to determine functionality.

Since ambulance care also involves taking care of patients outside of the ambulance car there are also reason to evaluate if a portable oxygen device could be an option. However these are currently providing flow rates that are too low, hence this might not be an option for the foreseeable future.

Possible revenue and savings

According to table 4.3 the annual cost for oxygen in one ambulance is approximately 16, 800 SEK:

$$7,000 * \frac{12}{5} = 16,800 SEK$$

A 9 LPM oxygen concentrator that is a popular choice for the home health care in Stockholm costs about 18, 000 SEK, and one device from the same manufacturer with an output of 5 LPM costs about 7,000 SEK (Oxycare Gmbh, 2023). The price of the oxygen concentrator i.e. seems to increase with the flow rate. To approximate the price of a 15 LPM oxygen generating system could cost 30,000 SEK. Since the current market is driven by profit, it is implied that the prices referred to here generates profit for the supplier and distributor.

In Stockholm there are about 90 ambulances that carry out acute care. If a supplier provided these ambulances with an oxygen system this would mean a revenue of

$$30,000 * 90 = 2,700,000 SEK$$

Additionally there would be an annual income from maintenance, given that this is performed by the manufacturer. If the maintenance cost is approximated to

Table 6.1: Approximation of costs for ambulance oxygen consumption with cylinders and if on-site oxygen generation had been utilized, for one ambulance.

Product	**Cost (SEK)**	**Frequency of cost**
Oxygen cylinders (inc. transportation)	16,800	Annually
Oxygen concentrator Maintenance	30,000 1,500	One time purchase Annually
Product	**Cost (SEK) for 5 years**	**Total**
Oxygen cylinders (inc. transportation)	84,000	84,000
Oxygen concentrator Maintenance	30,000 7,500	42,500

5% of the costumer price, this would mean a revenue of:

$$2,700,000 * 0.05 = 135,000 SEK$$

Further calculations can be found in table 6.1, that indicates that this product could reduce oxygen costs for the ambulance by half. Additionally it shows that the product could have a significantly higher price and still be a cheaper option than oxygen cylinders.

Other benefits

An oxygen concentrator with a flow rate of 15 LPM would be possible to use for hospitals in low resource settings. If a development of this product would lead to an enhancement of performance and decrease the weight this would additionally be positive for users everywhere. Furthermore an oxygen concentrator that operates within an ambulance has to be durable due to the changing environment, which again gives the durability aspect importance in a Swedish context.

Desirability, feasibility, and viability

- *Desirability* - If this product would decrease cost there would definitely be a demand for it, as long as the performance is good enough. In the Swedish market the device is also unique and there are thereby no competitors except the current cylinder suppliers.

- *Feasibility* - Since the technology is available in other countries it is feasible to create a similar device for a Swedish context.

- *Viability* - According to the financial approximations the product should be possible to produce with profit. To introduce a new device there would however be necessary to carry out comprehensive research or evaluations in order to produce a viable product. This would naturally need funding.

6.3.4 On-site bulk production

Further in the future there may be reason to utilize on-site production of oxygen for all medical environments. For the ambulance stations there are definitely reason to explore if it would be preferable to become self-sufficient, i.e. if the station would include a large oxygen concentration system that could be utilized to fill up cylinders. This technology is however already developed by a number of manufacturers (Atlas Copco, 2023).

For larger hospitals there could be an idea to also become self-sufficient of oxygen. As mentioned there are already large PSA and VPSA systems that carry out this technology, even if it is not widely used in Sweden. To speculate, these larger devices could be placed outside of the hospital to keep the noise level down, and then provide oxygen to the patient via the same pipeline system that is currently utilized for LOX. If multiple plants would be used, there would also be backup available in case of malfunction.

Desirability, feasibility, and viability

- *Desirability* - There is currently no demand for a product like this, which could be since there may be little knowledge about it. This study presents, as mentioned, that the current central oxygen supply systems are functioning very well, hence there is little reason to question it. If on-site PSA/VPSA plants are cheaper and/or more environmentally sustainable, the demand would however undoubtedly follow. This is a subject for further research.

- *Feasibility* - These products are already available on the market, hence the idea is feasible.

- *Viability* - This type of product would imply long term contracts and ongoing revenue due to possible maintenance agreements. Financially there is thereby good reason to determine it as viable. However it is still necessary to reconstruct facilities and rearrange some operations. If these obstacles are overcome, the idea would most probably be a viable solution, since it already is in other locations.

6.3.5 Portable oxygen concentrators for transportation

Currently Swedish hospitals utilize oxygen cylinders when transporting patients inside and between facilities. If an evaluation of the flow rates that are used would be carried out this could be an additional opportunity for oxygen concentrators. For a patient bed it could be possible to hang an oxygen concentrator to be taken with the patient. An exploration of how patient transportation is carried out would be necessary to evaluate what solution would be suitable. To speculate: an oxygen concentrator that is light enough to not bother the health care professionals could be placed on the bed instead of the cylinder, which would reduce the risk of oxygen exhaustion, and remove the danger of handling cylinders. This does include development of the current technology in order to obtain a device that is small enough, hence this is a subject for the future.

Desirability, feasibility, and viability

- *Desirability* - Similar to on-site bulk production there is currently a functioning system where this device would operate. Again there would have to be proof of advantages when comparing portable oxygen concentrators to cylinders in order for the demand to emerge. If the product would be developed to have clear superiority to cylinders in terms of user-friendliness, costs, and environmental impact the desire would most probably arise.

- *Feasibility* - The current portable oxygen concentrators do not fulfil the requirements that this type of device would need. The product would have to be small and light with high performance, i.e. an improved version of what is available today. The necessary technology is thereby not currently available, however this may be a product for the future.

- *Viability* - If a device would be constructed to fit the requirements, without becoming too expensive, there are should be no obstacles for a business to produce it. Except for the fact that a minor rearrangement of the day-to-day work for healthcare professionals would be necessary, this idea should be viable.

7 Conclusion

To conclude, this project implies that there are reasons to further develop oxygen concentrators, e.g. to make them suit a larger number of patients within the home health care. Additionally Swedish ambulances could possibly benefit by using oxygen concentrators in the future, if development of a suitable model would be in place. This could reduce some workload, increase safety, and it might decrease costs. There seem to be an opportunity for an increased market if the performance of oxygen concentrators would be improved, specially when there is an opportunity to replace cylinders. The advancements are not very different from the progress that low resource settings would benefit from. There are thereby reasons to believe that such development would benefit health care in low resource settings as well, since they depend on the same global market as Sweden does.

The findings did not indicate that bedside oxygen concentrators seemed like a viable choice for Swedish hospitals. Nevertheless there are reasons to consider PSA or VPSA oxygen generation systems for on-site production of oxygen for hospitals. The shortage of available oxygen supply technology in resource scarce areas naturally spurs the research to find alternatives in order to provide patients with life-saving treatment. There are indications that Sweden has never experienced this type of problem, and hence never had to explore options to the current system that is used within the hospitals. This study reveals that comparisons of the available systems are scarce, and little argue that LOX necessarily would be preferable over PSA or VPSA systems. Evaluation of what arrangement is the most cost efficient and environmentally sustainable needs to take place, to ensure that right choices are made in the future. Currently there are reasons to believe that many countries are unintentionally and without good reason gatekeeping other parts of the world from oxygen therapy by using a system that can never be transferred to a low resource setting.

References

1177, Region Stockholm (2023*a*), 'Covid-19', https://www.1177.se/Stockholm/sjukdomar--besvar/lungor-och-luftvagar/inflammation-och-infektion-ilungor-och-luftror/om-covid-19--coronavirus/covid-19-coronavirus/. Accessed 2023-06-18.

1177, Region Stockholm (2023*b*), 'Kol', https://www.1177.se/Stockholm/sjukdomar--besvar/lungor-och-luftvagar/andningssvarigheter-och-andningsuppehall/kol--kroniskt-obstruktiv-lungsjukdom/. Accessed 2023-06-18.

1177, Region Stockholm (2023*c*), 'Lunginflammation', https://www.1177.se/Stockholm/sjukdomar--besvar/lungor-och-luftvagar/inflammation-och-infektion-ilungor-och-luftror/lunginflammation/. Accessed 2023-06-19.

Ackley, M. W. (2019), 'Medical oxygen concentrators: a review of progress in air separation technology', *Adsorption* **25**, 1437–1474.

Advisory Board (2021), 'The latest pandemic shortage: Oxygen', https://www.advisory.com/daily-briefing/2021/09/01/oxygen-shortage#:%18:text%C2%BCCovid%2D19%20surges%20lead%20to,struggling%20with%20low%20oxygen%20supplie.

Alvehus, J. (2013), *Skriva uppsats med kvalitativ metod: en handbok*, Liber.

Andersson, A., Ström, K., Brodin, H., Alton, M., Boman, G., Jakobsson, P., Lindberg, A., Uddenfeldt, M., Walter, H. and Levin, L. (1998), 'Domiciliary liquid oxygen versus concentrator treatment in chronic hypoxaemia: a cost-utility analysis', *European Respiratory Journal* **12**, 1284–1289.

Atlas Copco (2023), 'Ogp+ 3-30 psa oxygen generator', https://www.atlascopco.com/en-tw/compressors/products/oxygen-generators/ogp-plus-3-30-psa. Accessed: 2023-08-14.

Balys, M., Brodawka, E., Korzeniewska, A., Szczurowski, J. and Zarebska, K. (2021), 'Lca and economic study on the local oxygen supply in central europe during the covid-19 pandemic', *Science of The Total Environment* **786**, 147401.

Blodgett, A. N. (1890), ‘The continuous inhalation of oxygen in cases of pneumonia otherwise fatal, and in other diseases’, *Boston Medical and Surgical Journal* **123**, 481 – 485.

Caitlin Kamminga at OSI Oxygen Solutions (2021), ‘9 reasons to consider vpsa over psa process technology’, `https://osioxygen.com/blog/vpsa-over-psa-technology/`. Accessed: 2023-08-14.

Dobson, M. B. (1991), ‘Oxygen concentrators offer cost savings for developing countries’, *Anaesthesia* **46**, 217–219.

Dobson, M. B. (2001), ‘Oxygen concentrators and cylinders’, *The International Journal of Tuberculosis and Lung Disease* **5**, 520–523.

Duke, T., Pulsan, F., Panauwe, D., Hwaihwanje, I., Sa’avu, M., Kaupa, M., Karubi, J., Neal, E., Graham, H., Izadnegahdar, R. and Donath, S. (2021), ‘Solar-powered oxygen, quality improvement and child pneumonia deaths: a large-scale effectiveness study’, *Archives of Disease in Childhood* **106**, 224–230.

Eaton (2023), ‘Oxygen concentrators’, `https://www.eaton.com/us/en-us/catalog/life-support-systems/oxygen-concentrators.html`. Accessed: 2023-08-02.

Grainge, C. (2004), ‘Breath of life: the evolution of oxygen therapy’, *Journal of the Royal Society of Medicine* **97**, 489–493.

Graneheim, U. and Lundman, B. (2002), ‘Qualitative content analysis in nursing research: concepts, procedures and measures to achieve trustworthiness’, *Nurse Education Today* **24**, 105–112.

Hasso Plattner Institute of Design at Stanford (n.d.), ‘An introduction to design thinking process guide’, `https://web.stanford.edu/~mshanks/MichaelShanks/files/509554.pdf`. Accessed: 2023-08-14.

Hill, S., Njie, O., Sanneh, M., Jallow, M., Peel, D., Njie, M., Weber, M., Hill, P. and RA Adegbola, S. H. (2009), ‘Oxygen for treatment of severe pneumonia in the gambia, west africa: a situational analysis’, *The International Journal of Tuberculosis and Lung Disease* **13**, 587–93.

IDEO U (n.d.), 'How to prototype a new business', https://www.ideou.com/blogs/inspiration/how-to-prototype-a-new-business. Accessed: 2023-08-22.

Internetmedicin (2023), 'Kronisk obstruktiv lungsjukdom (kol)', https://www.internetmedicin.se/behandlingsoversikter/lungmedicin/kol-kroniskt-obstruktiv-lungsjukdom/. Accessed 2023-06-18.

Ismail, J. and Bansal, A. (2022), 'Medical oxygen: A lifesaving drug during the covid-19 pandemic—source and distribution', *National Library of Medicine* **89**, 607–615.

Jacobsen, D. I. (2002), *Vad, hur och varför? - Om metodval i företagsekonomi och andra samhällsvetenskapliga ämnen*, Lund: Studentlitteratur.

Jha, M. and Gaur, N. (2022), 'Life cycle of medical oxygen from production to consumption', *Journal of Family Medicine and Primary Care* **11**, 1231–1236.

Karolinska Institutet (2021), 'Syrgasbehandling (oxygenbehandling)', https://utbildning.ki.se/media/81725/download. Accessed 2023-06-21.

Linde CryoPlants Ltd (2023), 'Oxygen plants - lox', https://www.linde-engineering.com/en/images/old_LCL%20LOX%20Brochure_tcm19-97611_tcm19-563338.pdf. Accessed 2023-06-22.

Linde Healthcare (2013), 'Säkerhetsdatablad', https://www.linde-healthcare.se/sv/images/SE_SDS_Conoxia_GOX_tcm584-126668.pdf. Accessed 2023-06-22.

Linde Healthcare (2014), 'Linde integrated valve', https://www.akademiska.se/contentassets/0b6e4e3320494d348d066b0e478686ff/liv_instructions_swe.pdf. Accessed 2023-06-22.

Linde Healthcare (2022), 'Flasksortiment', https://www.linde-healthcare.se/sv/images/SE_HC-Cylinder_brochure_2022-11_tcm584-391515.pdf. Accessed 2023-06-21.

Linde Healthcare (2023), 'Centralgasutrustning', https://www.linde-healthcare.se/sv/equipment_accessories/central_gas_equipment/index.html. Accessed 2023-06-22.

MSB (2023*a*), 'Syre (oxygen), komprimerad', https://rib.msb.se/fa/Substance/Index?id=376. Accessed: 2023-08-05.

MSB (2023*b*), 'Syre (oxygen), kyld, flytande', https://rib.msb.se/fa/Substance/Index?id=376. Accessed: 2023-08-05.

National Heart, Lung, and Blood Institute (2022), 'What is copd?', https://www.nhlbi.nih.gov/health/copd. Accessed 2023-06-18.

National Heart, Lung, and Blood Institute (2023), 'What is pneumonia?', https://www.nhlbi.nih.gov/health/pneumonia. Accessed 2023-06-17.

On Site Gas Systems, I. (n.d.), 'Medical grade oxygen generators (pogs) for ambulance services & ems', https://www.onsitegas.com/medical-grade-oxygen-ambulance-ems/. Accessed: 2023-08-02.

Oxford Medical Education (2023), 'Oxygen - delivery services', https://oxfordmedicaleducation.com/prescribing/oxygen-delivery/. Accessed 2023-06-15.

Oxycare Gmbh (2023), 'Stationary oxygen concentrators', https://www.oxycare.eu/en/oxygen/stationary-oxygen-concentrators/. Accessed: 2023-08-14.

Patil, A. (2021), 'As the coronavirus rages in california, l.a. medics are told to ration oxygen', *The New York Times* .

Paul, C., Paul, J. and Babu, A. (2020), 'Hospital oxygen supply: A survey of disaster preparedness of indian hospitals', *Indian Journal of Respiratory Care* **9**, 216–20.

Priestley, J. (1775), *Experiments and Observations on Different Kinds of Air*, Thomas Pearson, Birmingham.

Rennstam, J. and Wästerfors, D. (2015), *Från stoff till studie- Om analysarbete i kvalitativ forskning*, Studentlitteratur AB.

Sabatier, P. A. (1986), 'Top-down and bottom-up approaches to implementation research: acritical analysis and suggested synthesis', *Journal of public policy* **6**, 21–48.

Segovia, B., Velasco, D., Oriol, A. J. and Lobato, S. D. (2018), 'Combination therapy in patients with acute respiratory failure: High-flow nasal cannula and non-invasive mechanical ventilation', *Arch Bronconeumol.* pp. 166–7.

Sharma, S., Danckers, M., Sanghavi, D. K. and Chakraborty, R. K. (2023), 'High-flow nasal cannula', *StatPearls* .

Sveriges Riksdag (2006), 'Lag (2006:263) om transport av farligt gods', `https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/lag-2006263-om-transport-av-farligt-gods_sfs-2006-263/`. Accessed: 2023-08-05.

Swar, B. (1987), 'Oxygen concentrators', *Canadian Journal of Anaesthesia* pp. 538–539.

The Handbook for Healthcare (2022*a*), 'Att ge oxygen', `https://www.vardhandboken.se/vard-och-behandling/lakemedelsbehandling/oxygenbehandling/att-ge-oxygen/`. Accessed: 2023-06-08.

The Handbook for Healthcare (2022*b*), 'Oxygen via oxygenkoncentrator', `https://www.vardhandboken.se/vard-och-behandling/lakemedelsbehandling/oxygenbehandling/oxygen-via-oxygenkoncentrator/`. Accessed 2023-06-21.

The Handbook for Healthcare (2022*c*), 'Säkerhet vid behandling', `https://www.vardhandboken.se/vard-och-behandling/lakemedelsbehandling/oxygenbehandling/sakerhet-vid-behandling/`. Accessed 2023-06-22.

The Swedish Heart Lung Foundation (2023), 'Kol', `https://www.hjart-lungfonden.se/sjukdomar/lungsjukdomar/kol/`. Accessed 2023-06-18.

UNICEF (2021), 'Unicef to drive development of robust concentrator with support from oxygen colab and uk government', `https:`

//www.unicef.org/supply/stories/unicef-drive-development-robust-concentrator-support-oxygen-colab-and-uk-government. Accessed: 2023-05-25.

UNICEF (2022*a*), 'The oxygen plant-in-a-box: Innovation drives a key response to covid-19', https://www.unicef.org/supply/stories/oxygen-plant-box-innovation-drives-key-response-covid-19. Accessed: 2023-08-02.

UNICEF (2022*b*), 'Target product profile: Resilient oxygen concentrator', https://www.unicef.org/supply/media/12621/file/TPP-for-Oxygen-Concentrator-April-2022.pdf/. Accessed: 2023-08-14.

World Health Organization (2015), 'Technical specifications for oxygen concentrators', https://www.who.int/publications/i/item/9789241509886. Accessed: 2023-05-25.

World Health Organization (2020*a*), 'Oxygen sources and distribution for covid-19 treatment centres', https://apps.who.int/iris/bitstream/handle/10665/331746/WHO-2019-nCoV-Oxygen_sources-2020.1-eng.pdf?sequence=1&isAllowed=y. Accessed: 2023-06-08.

World Health Organization (2020*b*), 'Technical specifications for pressure swing adsorption(psa) oxygen plants', https://www.who.int/publications/i/item/WHO-2019-nCoV-PSA_Specifications-2020.1. Accessed 2023-06-20.

World Health Organization (2022*a*), 'Design for oxygen concentrator usability in under-resourced healthcare settings', https://www.unicef.org/supply/media/13846/file/Design-Guide-Oxygen-Concentrator-Usability-Low-Resource-Settings.pdf. Accessed 2023-06-20.

World Health Organization (2022*b*), 'Pneumonia', https://www.who.int/news-room/fact-sheets/detail/pneumonia. Accessed 2023-06-16.

World Health Organization (2023), 'Foundations of medical oxygen systems', https://www.who.int/publications/i/item/WHO-2019-nCoV-Clinical-Oxygen-2023.1. Accessed: 2023-06-08.

Appendix A Interview questions

A.1 Interview template

This interview is performed in order to collect data to my Master thesis project at The Faculty of Engineering at Lund University. Participation is completely voluntary and the participant can decline any questions without giving an explanation. The participant can also withdraw any response and cancel the interview at any time.

This project examines different types of oxygen use and production. During and after to the COVID-19 pandemic the shortage of oxygen has been widely noticed and many initiatives have arised to use alternative methods for oxygen production. The supply oxygen supply system that Sweden and many other rich countries are utilizing often requires large investments and a relatively stable infrastructure system. Countries with less resources are thereby relying on other alternatives, e.g. oxygen concentrators.

The aim of this interview is to deepen my understanding in [respondents field of expertise].

1. Tell me more about your current employment and your relevant previous experiences.

2. Can you tell me about how [your facility] utilizes oxygen?

3. In what situations are the different systems used? Elaborate.

4. Do you know how the oxygen supply/delivery is carried out?

5. What personnel is relevant for the oxygen systems you are utilizing at [your facility]?

6. What safety measures are used around your oxygen products?
7. What positive aspects can you mention regarding the oxygen system(s) you use?
8. What negative aspects can you mention regarding the oxygen system(s) you use?
9. Anything else you want to mention regarding the oxygen system(s) you work with?

Oxygen concentrators take oxygen from the surrounding air and concentrates it right next to the patient. In Sweden they are used for patients that need oxygen in their home, but in many countries they are also used in the hospitals. I am investigating if Sweden could extend it's use, and how this could affect Sweden and other countries. My idea is that this would drive the development of oxygen concentrators forward.

1. What do you believe could be positive regarding an expanded use of oxygen concentrators? Including costs, safety, and user friendliness.
2. What do you believe could be negative regarding an expanded use of oxygen concentrators? Including costs, safety, and user friendliness.
3. Do you think an expanded use of oxygen concentrators could include any risks?
4. Suppose that oxygen concentrator would be a superior option to the current alternatives - what type of readjustments do you believe would be necessary?