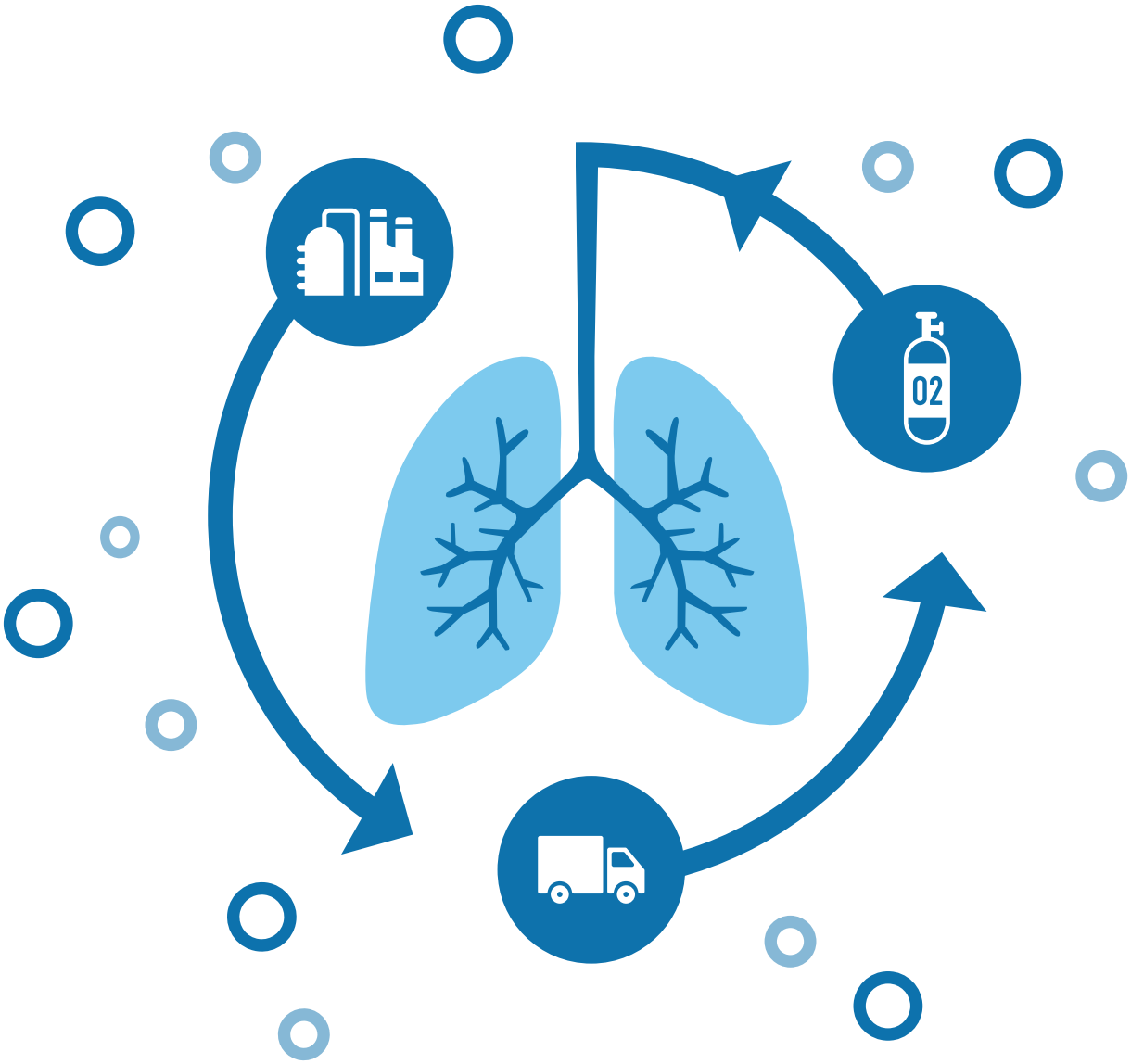
OXYGEN HUB

INSTITUTE FOR TRANSFORMATIVE TECHNOLOGIES



CLOSING THE MEDICAL OXYGEN GAP IN SUB-SAHARAN AFRICA

A case for a decentralized hub-spoke network of pressure swing adsorption plants

JANUARY 2021

This report was made possible through generous support from the Skoll Foundation and ELMA Philanthropies. We'd like to acknowledge valuable contributions from Nicholas Sukitsch, Nikki Tyler, and Helen Petach. We are also grateful for technical feedback from the Clinton Health Access Initiative. Any remaining errors are the responsibility of the authors.

Attribution
Please cite this work as follows: “Closing the medical oxygen gap in sub-Saharan Africa: A case for a decentralized hub-spoke network of pressure swing adsorption plants," Institute for Transformative Technologies (ITT) and Oxygen Hub, January 2021.

For more information: info@transformativetechnologies.org
www.transformativetechnologies.org | www.oxygenhub.org

SUMMARY

Sub-Saharan Africa (SSA) has historically suffered from an acute shortage of medical oxygen. Most countries in SSA have less than 10% of the volume needed to treat high-burden conditions like pneumonia, chronic obstructive pulmonary disease (COPD), and neonatal respiratory syndrome. COVID-19 has both exacerbated and highlighted this oxygen supply gap.

Historically, the most common method of supply in SSA has been in the form of cylinders filled with oxygen gas from cryogenic distillation plants that produce liquid oxygen[1] (LOX). Most of these factories were built decades back to serve industrial applications—particularly extractives. To date, they continue to focus heavily on those applications and have served only a fraction of the existing need for medical applications.

More recently, smaller pressure swing adsorption (PSA)[2] plants have emerged as an alternative to cryogenic plants. However, these systems have often not been adequately maintained, and a sizable portion of them are not currently operational. Unsurprisingly, the existing medical oxygen capacity in SSA has been insufficient to meet the surge needed for COVID-19.

COVID has increased awareness about the importance of oxygen and has generated strong interest from governments, funders, and other influential stakeholders to significantly and sustainably increase access, including to rural areas.

It has also sparked a vibrant debate about optimal mechanisms to increase oxygen supply in SSA—especially about the relative merits and disadvantages of PSA vs. LOX as potential solutions at a large scale.

A key finding of our analysis is that—contrary to conventional belief—*the per-unit cost of oxygen[3] in SSA is similar across the various methods of production*. This is because the cost of producing oxygen is only a small portion of the total cost of delivering oxygen to patients, and post-production operations (e.g., cylinder filling, distribution) are virtually the same. Furthermore, many of the LOX facilities in SSA are relatively small, and hence do not benefit from the economies of scale typical of LOX factories around the world.

A second observation is that many SSA countries currently rely on a nontrivial amount of imported oxygen, suggesting that domestic LOX production capacity enjoys high levels of utilization.

Third, the majority of people in SSA live in rural areas, and most patients have access only to primary clinics even for conditions that need oxygen treatment.

Finally, adding new LOX production capacity in SSA explicitly for medical use will likely be cost prohibitive.

> **The per-unit cost of oxygen in SSA is similar across the various methods of production.**

[1] Cryogenic air separation plants also produce a number of other industrial gases.
[2] More recently, a variation of the PSA process known as vacuum swing adsorption (VSA) has also emerged as a high-potential option. For the purposes of this discussion, we use "PSA" to refer to both PSA and VSA.
[3] Per-cylinder cost for oxygen suppliers. Note that market price to buyers of oxygen may not reflect the cost.

For individual (or a small number of) tertiary hospitals especially in urban/peri-urban areas, the optimal choice is onsite LOX tanks, vaporized on demand and delivered to patients via piped systems (the norm in high-income countries). These hospitals can serve as "anchor users" and be used as hubs for distributing oxygen cylinders to local primary/secondary clinics.

Such a solution may be appropriate for rural tertiary hospitals as well, but only if the transportation infrastructure allows easy and regular access for large LOX trucks. Otherwise, onsite PSA systems may be more appropriate.

However, to reach a meaningfully large population, including in rural areas, an extensive decentralized oxygen infrastructure will be needed. The two choices for such a decentralized infrastructure are networks of (a) PSA plants that produce oxygen and fill cylinders and (b) LOX bulk storage sites with cylinder filling stations, regularly replenished via trucks from a central production facility.

Since the per-unit costs of PSA and LOX are similar, the choice between PSA and LOX in developing a large decentralized infrastructure should be based on the tradeoff between:

- for LOX: (i) reliable availability of large volumes of LOX, often via imports; and (ii) reliability of the logistics of regular LOX deliveries via insulated cryotank trucks across a decentralized system.

- for PSA: the ability to reliably operate and manage the plants.

There is likely enough surplus LOX capacity across the global production system to meaningfully increase the supply of medical oxygen to SSA. However, LOX is a capital-intensive commodity, and a basic economic tendency of capital-intensive production industries is to maximize the utilization of available capacity. As such, it is unlikely there is enough surplus LOX to solve the problem at the needed scale—unless new capacity is developed.

At the same time, the operational complexity of PSA plants with cylinder filling stations is only incrementally more than that of LOX bulk storage sites with the same type of filling stations. We believe this incremental operational complexity offsets the logistical complexity of managing a large number of regular deliveries by LOX tanks. Importantly, PSA plants will ensure much greater local control over a critical lifesaving commodity.

On the margin, therefore, we believe that a decentralized network consisting largely of PSA plants—incorporating LOX stations based on how much supply can be guaranteed—offers the most promising option for a sustainable, self-reliant, large-scale solution to SSA's medical oxygen deficit.

1. MEDICAL OXYGEN PRODUCTION AND DELIVERY: A BRIEF PRIMER

Dry atmospheric air contains, by volume, 78.09% nitrogen, 20.95% oxygen, 0.93% argon, 0.04% carbon dioxide, and small amounts of other gases. Air also contains a variable amount of water vapor, on average around 1% at sea level. Medical grade oxygen requires concentration/purity of at least 82%.[4]

Increasing the concentration of oxygen from 21% in the air to above 82% requires a process for separating it from the various other constituent gases. The two most widely used methods for doing this are cryogenic distillation and pressure swing adsorption.[5]

Cryogenic air separation (also known as *cryogenic distillation*) works by cooling air to about –112°C until it is liquified, at which point the oxygen can be separated from the other components by fractional distillation, because of the different boiling points of the gases (Exhibit 1). The air is purified prior to cooling to remove water vapor. Cryogenic separation produces ultra-pure (>99.5%) liquid oxygen (LOX) needed for specific industrial processes in extractives, metallurgy, etc.

These facilities are highly capital intensive, costing tens of millions of [US] dollars. Existing facilities vary significantly in capacity, producing 5 million to 500 million m^3 of oxygen (the equivalent of 750,000 to 75 million cylinders) per year.

A LOX factory can last for decades and is typically amortized over a period of 30 years. The first cryogenic air separation plant for oxygen production was developed by Carl von Linde in Germany in the first decade of the 1900s.

The technology has now scaled up globally and there are thousands of cryogenic oxygen plants around the world. There are a small number of companies that own/operate LOX factories, of which BOC/Linde and Air Liquide are the most well known. Both operate plants across SSA.

Pressure swing adsorption (PSA) and the closely related *vacuum swing adsorption* (VSA) use an adsorbent material (typically zeolite) that adsorbs oxygen and nitrogen at different rates as the pressure changes. As pressure increases, relatively more nitrogen than oxygen adsorbs onto the zeolite, thus producing an oxygen-rich gas stream from the adsorption bed (Exhibit 2).

When the zeolite surface is saturated with nitrogen, the pressure is reduced and the nitrogen is desorbed and released from the zeolite and is purged to the atmosphere. PSA and VSA processes produce 90–95% purity oxygen, also well above what is needed for medical treatment. PSA/VSA oxygen is used primarily for medical purposes.

A typical PSA facility costs $150,000–250,000 for a plant that produces 150,000–500,000 m^3 of oxygen per year (20,000–75,000 cylinders per year), with a service life of about ten years. VSA plants are typically larger by an order of magnitude, with a longer service life. PSA systems for oxygen production were first used in the 1970s, and the first VSA oxygen systems were commercialized in the 1990s.

[4] Source: "WHO-UNICEF Technical Specifications and Guidance for Oxygen Therapy Devices," World Health Organization, 2019.
[5] Other methods—such as membrane gas separation and oxygen generation from chemical feedstock—exist, but are not widely used.

Cryogenic liquid oxygen plant

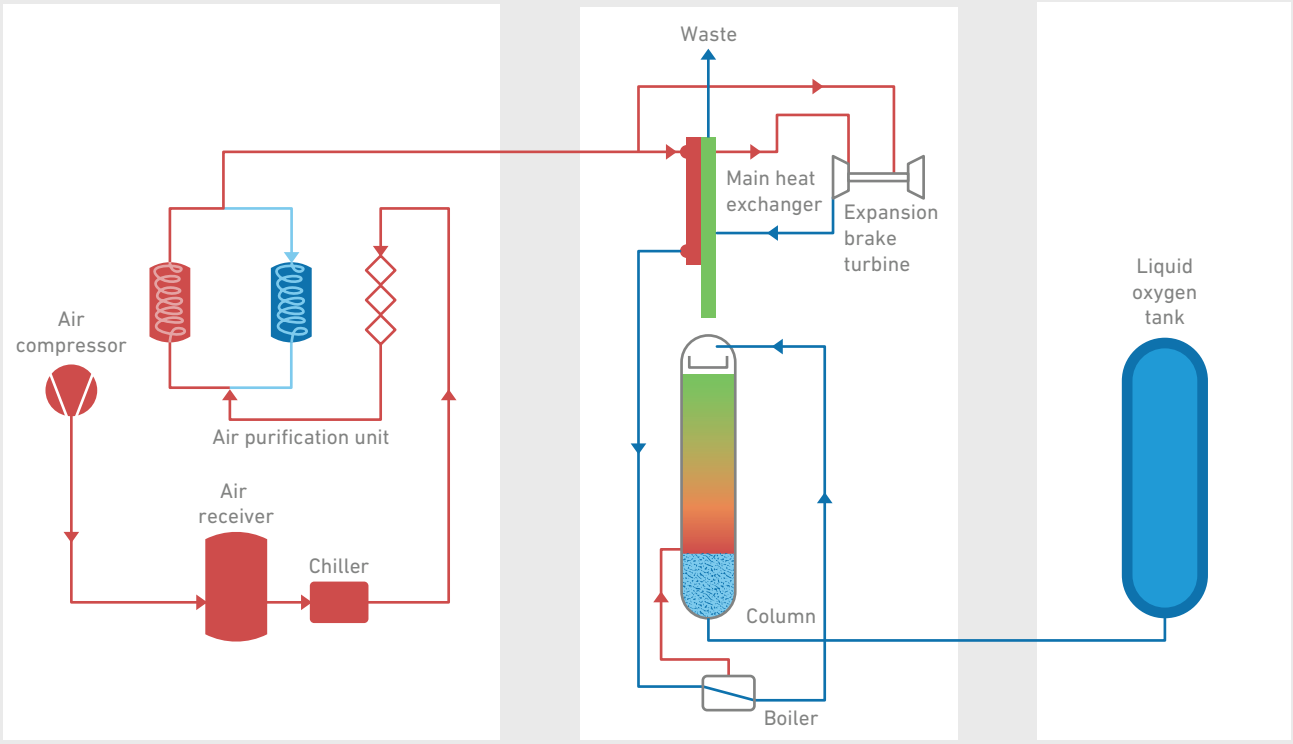


Exhibit 1: Cryogenic air separation begins by compressing and purifying ambient air, followed by liquification and fractional distillation to separate oxygen from other components. The resulting liquid oxygen (LOX) is >99.5% pure, well above what is needed for medical treatment. The photograph shows a typical LOX plant.

Pressure swing adsorption oxygen plant

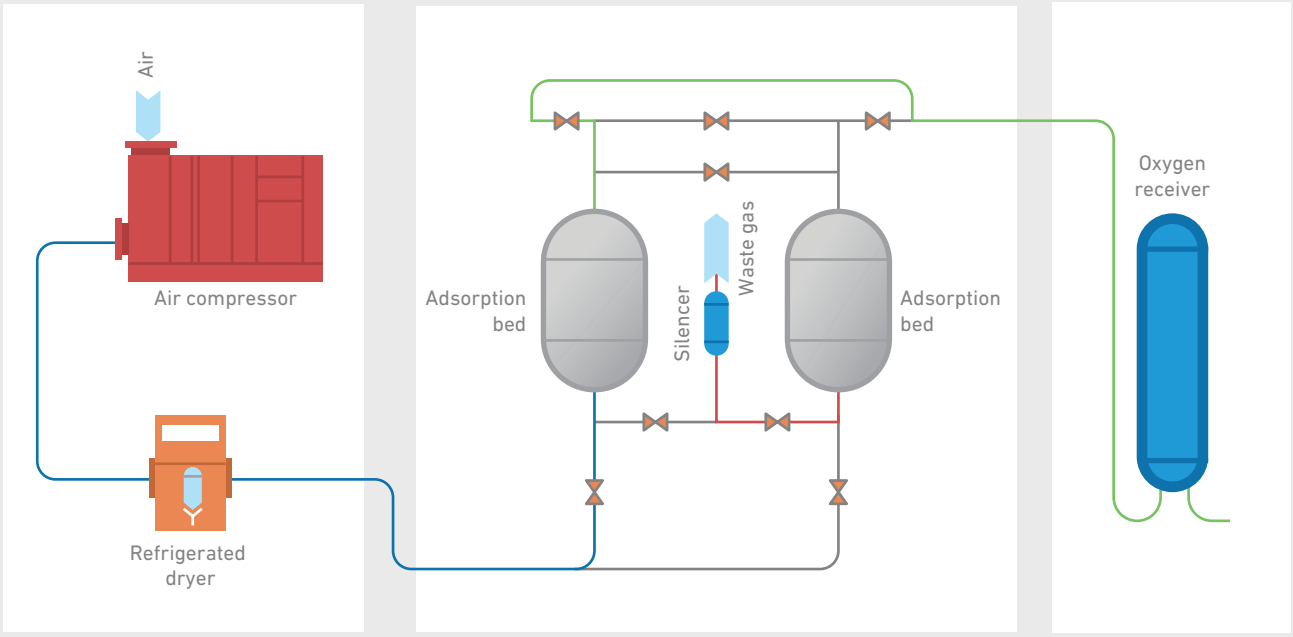


Exhibit 2: PSA systems typically have two adsorption beds, which alternate between adsorbing nitrogen from air while allowing oxygen to flow through, and venting the accumulated nitrogen into the atmosphere. VSA uses the same general principle but operates at lower (vacuum) pressures. The photograph shows a typical PSA facility filling cylinders. (Courtesy: Hewatele, Kenya)

Medical oxygen is typically provided to patients through one of three methods, depending on patient condition and the type of healthcare facility. The three modes of supply are:

- **Cylinders:** Refillable cylinders that are filled with high pressure oxygen and transported to treatment sites are the easiest to use in smaller or poorly equipped facilities and in homes. However, they need to be regularly cleaned, inspected, and refilled for each use. Also, distribution to treatment sites can be logistically challenging. Cylinders are by far the most widely deployed delivery mechanism for medical oxygen in SSA and can be filled with vaporized LOX or oxygen from PSA/VSA plants. While they come in different sizes, a standard "J" cylinder contains 6.8 m^3 of oxygen, the unit size used in our analysis.

- **Piped Systems:** Piped systems in tertiary hospitals connect to large LOX storage tanks or on-site PSA plants, delivering oxygen to the bedside. Piped systems are the simplest mechanism for hospitals with large numbers of beds. However, installing them requires capital investment. As a result, very few hospitals in SSA have oxygen piping infrastructure.

- **Oxygen Concentrators:** Small oxygen concentrators are intended for one (or a small number of) patients at a time. Concentrators are based on the PSA process at a very small scale. They separate oxygen from ambient air and therefore can ensure a reliable, ongoing—albeit small—source of oxygen. They can also be used in a variety of settings ranging from tertiary hospitals to primary clinics and homes. However, they require reliable electrical power and need regular maintenance, without which they can stop functioning within one year.

Oxygen can be delivered into the patient's lungs via several types of breathing interfaces based on patient condition and sophistication of the clinical facility. The simplest and most common is a nasal cannula—which delivers a limited oxygen flow close to the patient's nostrils—and facemasks. For severe conditions, including advanced COVID-19, oxygen can be delivered to the lungs via endotracheal tubes.

2. THE CONTEXT FOR MEDICAL OXYGEN IN SUB-SAHARAN AFRICA

Oxygen is critical for treating a number of life-threatening conditions such as pneumonia, asthma, chronic obstructive pulmonary disease (COPD), neonatal respiratory syndrome, and pulmonary hypertension.

In SSA, these conditions collectively account for an estimated 1.75 million deaths[6] each year (Exhibit 3). Surgery and emergency use of oxygen, not included in Exhibit 3, are also large drivers of demand. Table 1 shows the estimated amount of oxygen needed to treat a typical patient suffering from these and other conditions.

Annual deaths across sub-Saharan Africa from various respiratory-related conditions

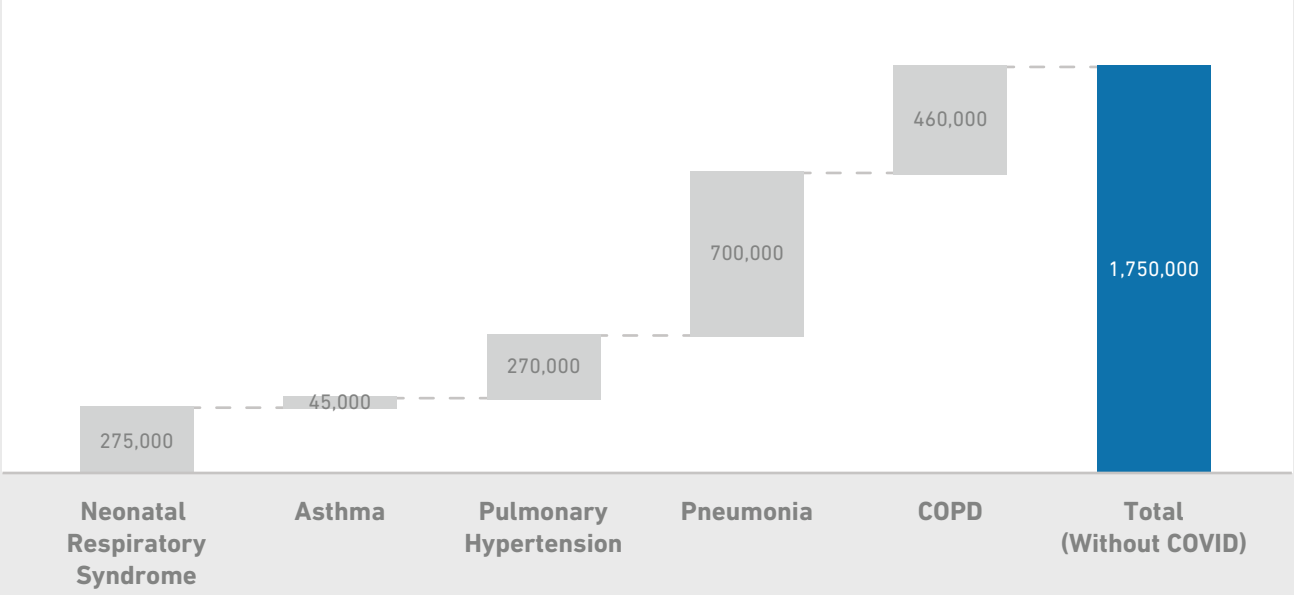


Exhibit 3: Oxygen is critical for treating a number of life-threatening conditions that collectively account for 1.75 million deaths in SSA annually. Beyond these conditions, surgery, emergency use, etc. drive additional demand. Note that oxygen may not, by itself, prevent fatality without complementary interventions.

[6] Sources: (1) B. Dadonaite, OurWorldInData.org, 2018. (2) R. Ahmed et al., "The epidemiology of noncommunicable respiratory disease in SSA, the Middle East, and North Africa," Forum of International Respiratory Societies, 2017. (3) Forum of International Respiratory Societies, "The Global Impact of Respiratory Disease," European Respiratory Society, 2017. (4) J.B. Griffin et al., "Evaluating WHO-Recommended Interventions for Preterm Birth: A Mathematical Model of the Potential Reduction of Preterm Mortality in Sub-Saharan Africa," World Health Organization, 2019.

Condition	Avg treatment time	Total O_2 required	Cylinders per patient[7]
COPD (adult)	7 days	40, 320 liters	5.9
Pulmonary oedema	5 days	21, 600 liters	3.2
Pneumonia (adult; severe)	2 days	11, 520 liters	1.7
Pulmonary hypertension	2 days	11, 520 liters	1.7
Pneumonia (infant; severe)	2 days	5, 760 liters	0.8
Asthma (adult)	1 day	7,200 liters	1.1
Neonatal respiratory syndrome	1 day	720 liters	0.1

Table 1: Amount of oxygen needed for various high-mortality conditions.

[7] Assuming standard 6.8 m^3 cylinders.

The incidence of each of these conditions varies by country, depending on demographics, underlying risk factors, and access to preventative measures.

In order to treat these conditions, wealthier countries have access to abundant medical oxygen affordable to the majority of their patients. On the other hand, lower-income countries suffer severe shortages and often have to ration oxygen to patients who either need it the most, or—more often—who can afford it.

As Exhibit 4 shows, average per capita consumption of medical oxygen in the US and EU is more than ten times that of SSA (1.35 m^3 vs. less than 0.1 m^3 per year)[8].

Oxygen is also one of the most effective treatments for COVID-19. As the global medical community has wrestled with the learning curve of dealing with COVID, the exact amount of oxygen needed per patient has been unclear, but the aggregate need appears to be stretching the supply of even wealthy countries like the US.[9] In SSA, it has exposed the dire urgency of the gap.[10]

Average per capita medical oxygen consumption (cubic meters per year)

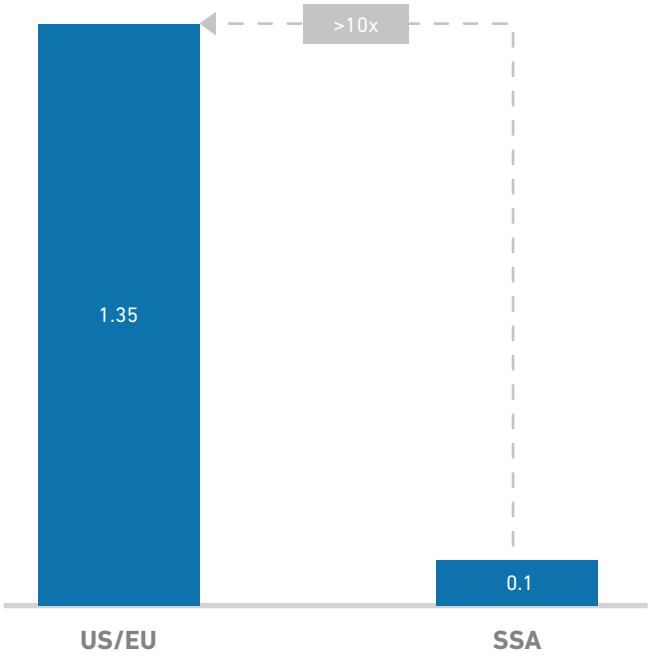


Exhibit 4: Even before COVID-19, SSA has had an acute shortage of oxygen. COVID has exacerbated the situation.

[8] Sources: (1) Gómez-Chaparro et al., "Analytical Determination of Medical Gases Consumption and Their Impact on Hospital Sustainability," Sustainability, August 2018. (2) J. Raquet, "Covid-19 versus oxygen supply—the status on supply and demand," Gasworld, April 2020. (3) Ministry of Health, Uganda. (4) Ministry of Health, Ethiopia. (5) Expert interviews.
[9] Source: R.-G. Lin et al., "Oxygen supply shortages bedevil hospitals already overwhelmed by COVID-19 patients," LA Times, December 2020.
[10] Source: E. Onyeji, "How the scramble to save Femi Odekunle's life yielded over 170 oxygen cylinders," Premium Times, January 2021.

As COVID has brought this gap into focus, it has prompted a debate about the optimal means of achieving significant increases in the supply of medical oxygen—specifically about the relative merits and challenges of LOX and PSA with respect to cost and operational/logistical considerations.

This article attempts such an analysis, using cost drivers from Kenya as an illustrative example. Note that we use Kenya as the example because it is among the more mature markets in SSA, and because of our experience there. We recognize that not all of the analysis can be extrapolated to the rest of SSA.

In Kenya, about 70% of current medical oxygen supply is from about 70 PSA plants across the country. Recent surveys suggest that about half of them are not functional. The majority of PSA plants in Kenya are public, operated by the government. The other 30% is LOX, most of which is produced by the country's single cryogenic air separation plant (Exhibit 5). A small amount of LOX is imported.[11]

Total supply of medical oxygen in Kenya

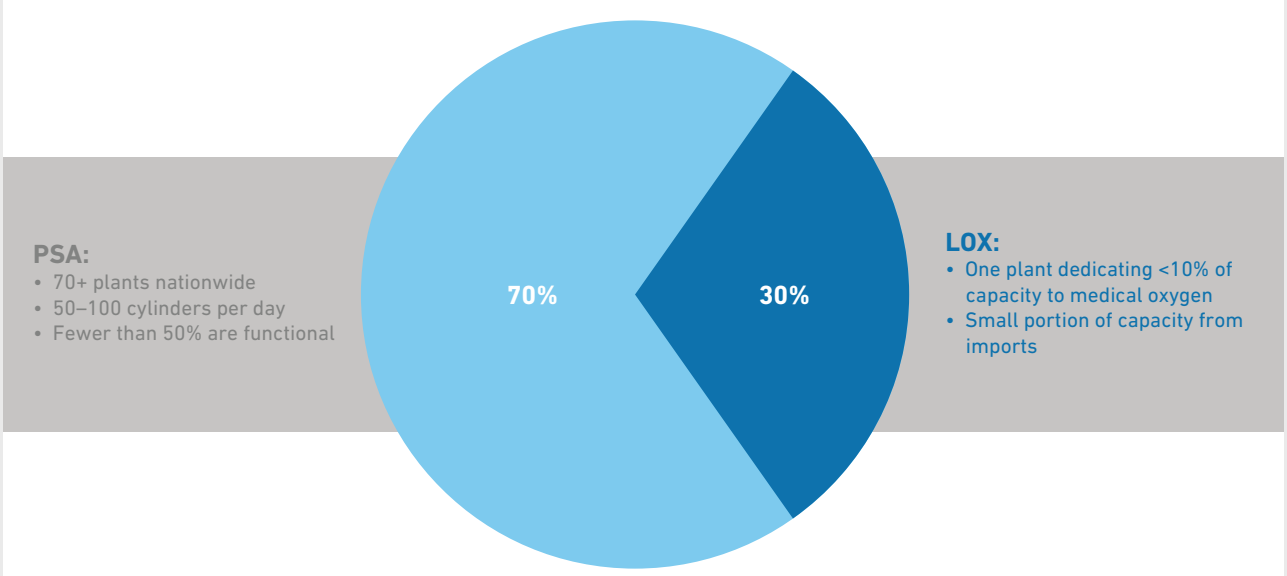


Exhibit 5: Most of Kenya's medical oxygen comes from 70+ PSA plants, about half of which are not functional. Most of the remaining 30% is supplied by the nation's lone LOX plant.

[11] Sources: (1) PATH, "Oxygen as a Utility: An Innovative Model for Increasing Access to Oxygen in Low- and Middle-Income Countries," 2019. (2) PATH, "COVID Oxygen Needs Tracker," 2020. (3) BOC Kenya, "Annual Report", 2018 and 2019.

3. COST ANALYSIS: LIQUID OXYGEN

Across SSA there are over 50 cryogenic air separation plants producing LOX. Most of the capacity of these plants is dedicated to industrial applications such as mining, petroleum, metallurgy, and chemical industries.

Given their capital cost, it is unlikely LOX plants will be constructed in SSA for medical needs alone. LOX plants are typically large, as the process has significant economies of scale beyond a certain size (Exhibit 6). Plants with a production capacity greater than 300,000 m³ per day are capable of producing global lowest-cost oxygen.

However, many liquid oxygen plants in SSA are at the smaller end of the scale, with relatively high per-unit capital cost.[12] For example, the BOC and Air Liquide factories in Kenya and Nigeria—and Tanzania's factory operated by TOL—all produce less than 50,000 m³ per day.

Note that while these factories are less efficient than the optimal size, they are not necessarily bad business investments. Presumably, these companies made the optimal investment choice based on projected market demand. The limited local production capacity means that industrial customers often import LOX when demand exceeds local supply. Indeed, as Exhibit 7 shows, many countries with local LOX facilities still rely on imports.[13]

Liquid oxygen: Capital investment vs. capacity

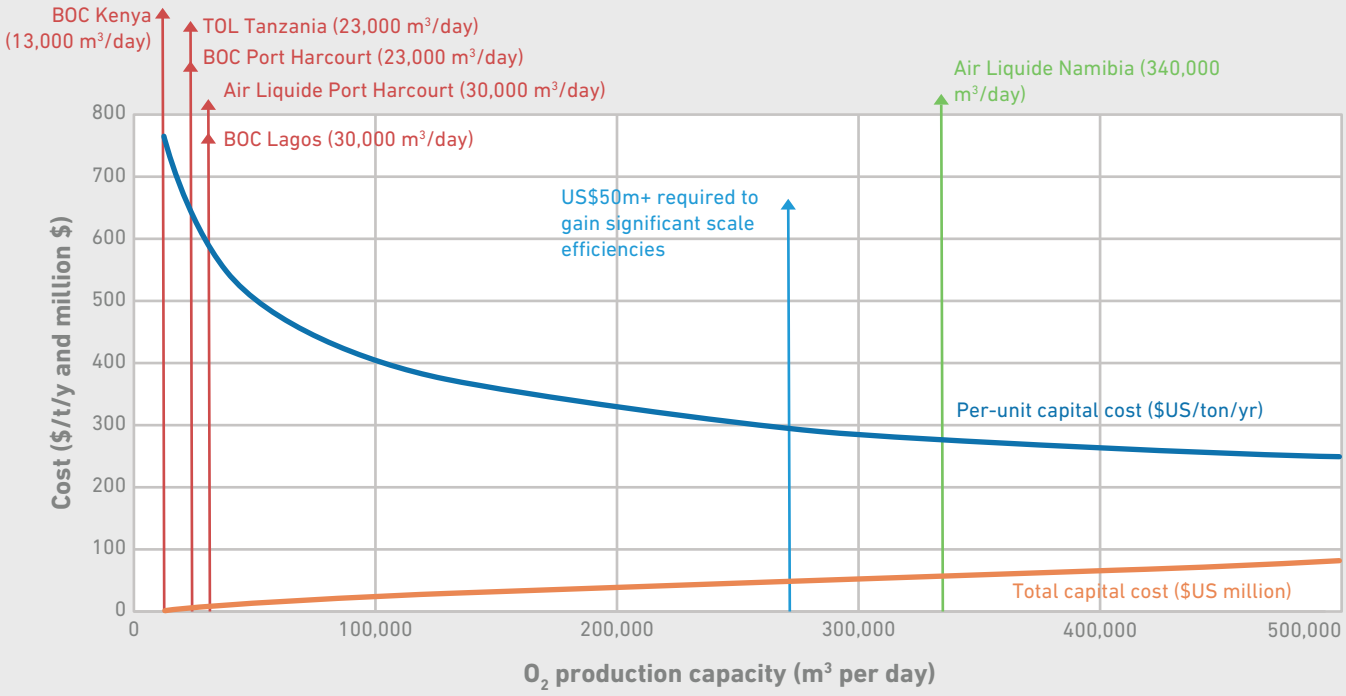


Exhibit 6: Liquid oxygen plants enjoy significant economies of scale, but many in SSA are small, with relatively high per-unit capital cost.

[12] Sources: (1) Ebrahimi et al., 2015. "Energetic, exergetic and economic assessment of oxygen production from two columns cryogenic air separation unit" Energy 90(2):1298-1316. (2) Industry websites.
[13] Source: World Bank, 2020.

Oxygen imports

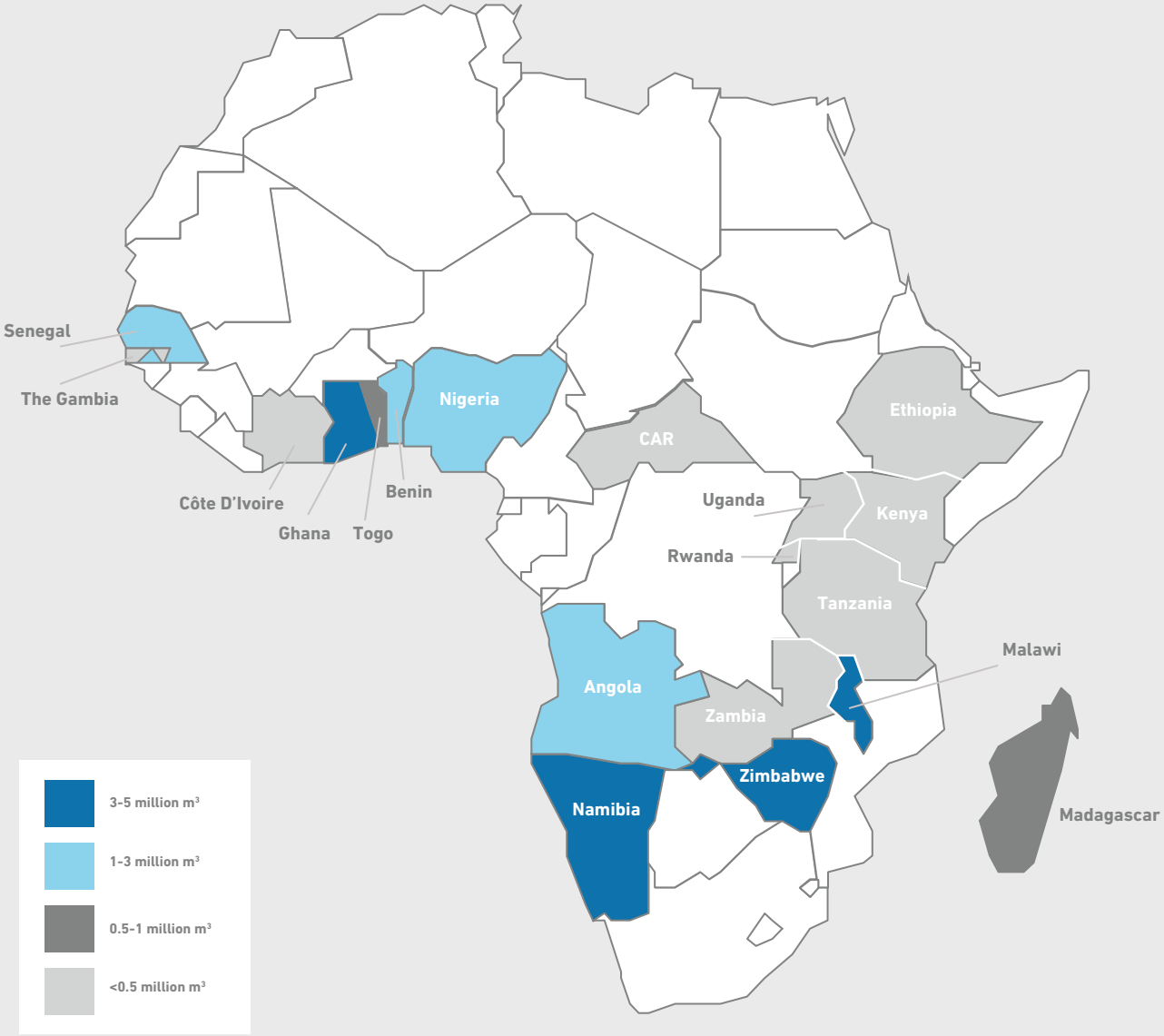


Exhibit 7: Several countries in SSA import oxygen to satisfy their needs for medical and industrial oxygen. Note this figure excludes data for South Africa.

As such, it can be assumed that existing surplus LOX capacity in many countries will be insufficient to reliably meet the entire local medical need.

For example, in 2019, the main LOX plant in Kenya dedicated about 83% of its liquid oxygen capacity for industrial applications and 9% for medical needs; 8% of capacity went unused. If this 8% were fully diverted to medical needs, it would boost overall national oxygen supply by 25% (Exhibit 8).[14] While not trivial, it is a far cry from the 10x increase required to meet the full national medical need.

Because industries that produce capital-intensive commodities tend to maximize their capacity utilization, it is reasonable to believe that there is insufficient surplus capacity across relevant LOX production facilities to meet the scale of need in SSA.

While it is entirely possible that new LOX facilities can be constructed, they will likely be for industrial customers rather than exclusively for medical demand.

Medical oxygen in Kenya (cubic meters per year)

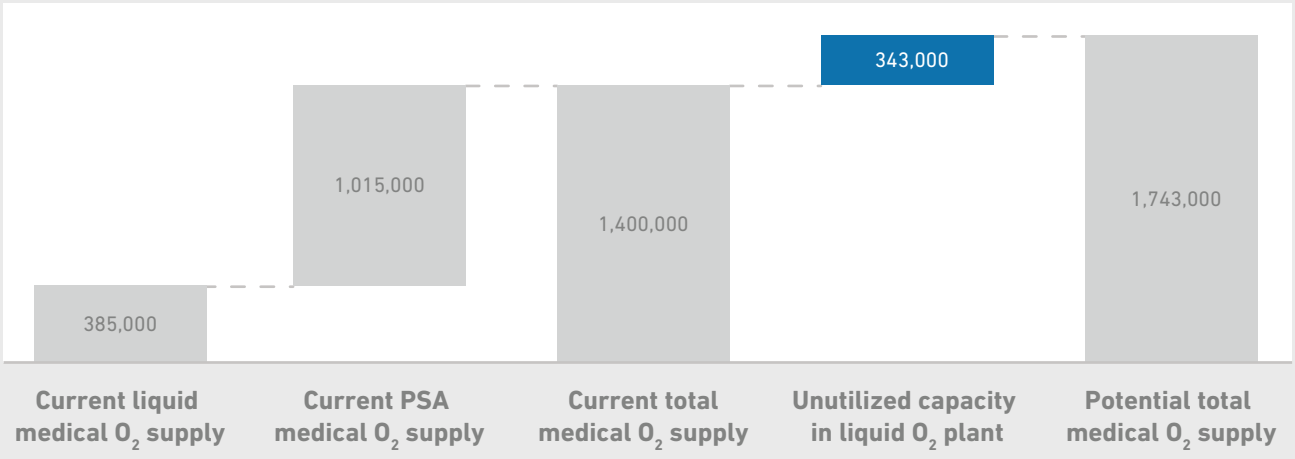


Exhibit 8: Liquid oxygen supplies a minority of Kenya's current medical oxygen, and full utilization of existing cryogenic capacity would augment national supply by only 25%.

[14] Analysis based on (1) PATH, "Assessment and recommendations to increase access to oxygen and pulse oximetry in Kenya," March 2018. (2) BOC Kenya, "Annual Report", 2018 and 2019.

To understand and compare the unit cost of oxygen from different types of plants and distribution pathways, we have developed a bottom-up cost model. The unit of volume in our analysis is 6.8 cubic meters of oxygen (i.e., a standard "J" cylinder).

As mentioned earlier, our analysis is based on cost estimates in Kenya (for electricity, labor, land, etc.), and will therefore need to be adjusted for other countries.

Exhibit 9 shows that the projected per-unit cost of LOX immediately after it is produced, prior to being stored or otherwise deployed, is $2.10.[15] Note that our cost modeling is based on small-scale LOX plants located in SSA, with relatively high per-unit capital cost.

The cost of LOX produced at larger facilities will be lower (by up to 15–20%), but that oxygen will likely need to be transported across greater distances, potentially negating the cost advantages of scale.

Liquid oxygen production cost, per 6.8 m^3

Exhibit 9: Production cost of liquid oxygen in Kenya is about $2.10 for 6.8 m^3 (the volume in one "J" cylinder, but excluding the cost of cylinder filling). Note that amortized CapEx is modeled for small-scale LOX plants located in SSA, with relatively high per-unit capital cost.

[15] Key assumptions include: (1) Amortized CapEx cost includes machinery, civil works, and land lease associated with a relatively small (17 tons/day capacity) cryogenic plant. Service life is assumed to be 30 years, with 85% utilization of 24x7x365 capacity. (2) Maintenance costs estimated at 2% of capital cost per year, including labor and components. (3) Electricity, at a rate of 200kWh per ton of oxygen (corresponding to 2,950 kWh per day), and a price of $0.20 per kWh including backup power. (4) Labor, based on 20 workers per plant, each earning $24,000 per year.

Producing oxygen in a factory is only the beginning. Getting the oxygen to clinics and patients can be a logistically complex and expensive process. Broadly, there are three main pathways for the distribution of liquid oxygen (Exhibit 10), as well as hybrids such as hospital-attached systems with on-site cylinder filling stations.

i. *Centralized cylinder filling & distribution:* The most common pathway in SSA is a centralized system where cylinders are filled at the cryogenic plant, followed by truck distribution of the cylinders to clinics and hospitals. This method is the most expensive of the three per unit of delivered oxygen, and becomes more expensive as the delivery distance grows.

ii. *Large liquid tanks direct to hospital:* In another pathway, liquid oxygen is taken directly to hospitals, where it is stored in large tanks and vaporized on demand and distributed to patients via pipes. This pathway has the lowest cost but requires the hospitals to have installed appropriate piping.

iii. *Hub-spoke network of storage/filling stations:* A third pathway is a hub-spoke network: liquid oxygen is delivered to storage/filling stations, where it is vaporized and compressed into cylinders and sent by truck to local clinics and hospitals. This is relatively cost-effective but requires a decentralized infrastructure and associated operational complexity.

Distribution pathways for cryogenic liquid oxygen

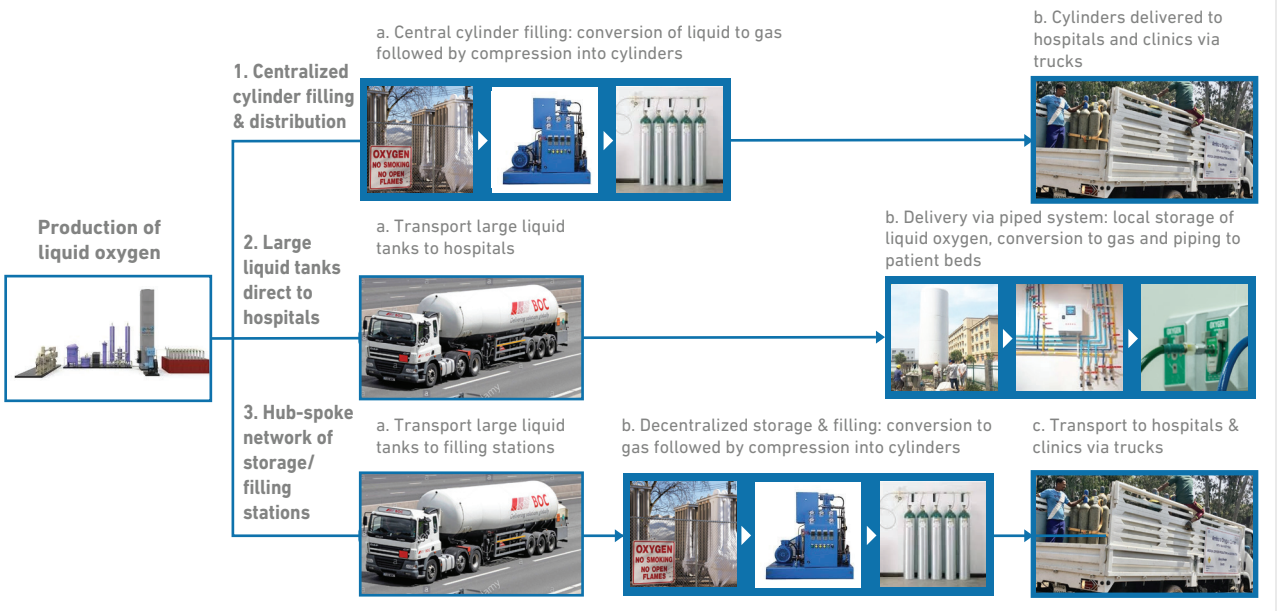


Exhibit 10: There are three main pathways for distributing liquid oxygen to patients in hospitals and clinics. Hybrids of these models are also possible.

The first model of deployment (centralized cylinder filling and distribution) includes the incremental cost of cylinder filling (cylinders, and a booster for compressing gaseous oxygen into the cylinders), labor required for sales and distribution, delivery trucks, fuel, a management team, and miscellaneous other costs of doing business.[16]

As Exhibit 11 shows, the total cost of delivery (TCOD) of an oxygen-filled cylinder is $15.40, more than 7x the cost of production.

Cost of each filled 6.8 m^3 oxygen cylinder at point-of-use in clinics or hospitals

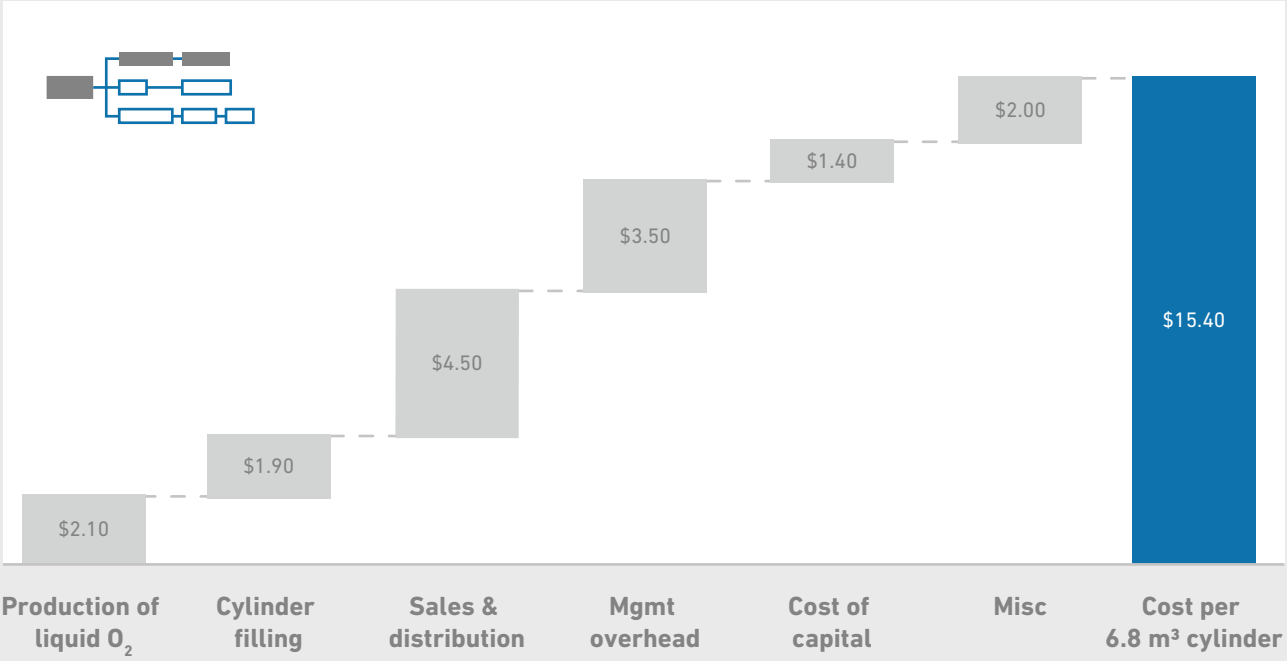


Exhibit 11: Projected total cost of delivery (TCOD) is about $15.40 for each 6.8 m^3 cylinder of oxygen produced at a LOX cryogenic plant and delivered to health facilities at a delivery distance of 100 km. This is a substantial increase from its production cost of about $2 at the cryogenic plant. The specific cost of power, labor, and so on are estimated for Kenya.

[16] Key assumptions: (1) The booster compressor uses 2.4 kWh of electricity per cylinder, and has a service life of ten years. (2) Cylinders cost $160 each and have a service life of ten years. (This is a conservative estimate as cylinders can last for decades if inspected regularly for safety.) (3) The operational labor of one worker is included. (4) Sales and distribution efforts include a diesel truck distributing 100 tanks per run, over a round-trip distance of 100 km with a fuel cost of $1 per liter. (5) Cost of delivery, marketing and sales personnel included. (6) Management overhead is based on oxygen allocation of overhead in the existing Kenyan cryogenic gas business as stated in the annual report. (7) Cost of capital is 10%. (8) Miscellaneous costs include losses, regulatory expenses, and so on.

Cost of each filled oxygen cylinder (6.8 m³) at point-of-use

Exhibit 12: Cylinder delivery distance is an important factor in the cost of medical oxygen at point-of-use. Our main analysis considers a round-trip delivery distance of 100 km by diesel truck. Beyond a certain distance, the oxygen becomes cost prohibitive. As such, this centralized model is unsuitable for broad, nationwide coverage.

In the second distribution pathway (large liquid tanks direct to hospital), liquid oxygen is taken directly to hospitals, where it is stored in large tanks, vaporized on demand, and distributed to patients via hospital piping.[17]

In contrast to transport of oxygen gas compressed into cylinders (the focus of Exhibit 12), transport of liquid oxygen is cost-effective over longer distances, due to the much-higher density of liquid oxygen compared to gaseous oxygen. As Exhibit 13 shows, this pathway has the lowest cost of the three options. However, the pathway faces two important constraints:

- A very small portion (10%) of the population in SSA currently has access to tertiary hospitals. Further, barely 10% of hospitals have piping systems installed. Therefore, existing piped oxygen systems are accessible to only 1% of patients (Exhibit 14).[18] While it is cost-effective in the long run to have piped systems, most hospitals cannot (or choose not to) make the capital investment.
- LOX cryotanks are well insulated, but the temperature gradient between the tank's contents and warmer ambient air (particularly in tropical countries) drives heat flow that warms the LOX. To maintain heat and pressure balances, some of the liquid oxygen "boils off" and is vented from the cryotanks. We estimate this venting causes a loss of about 15% per filling cycle for a cryotank refilled every three weeks.

[17] Key assumptions: (1) Transport cost of $400 per round trip for cryotank containing 17,000 m³ of oxygen. (2) Cost of hospital piping is $70,000 per facility amortized over 20 years.
[18] Analysis based on: "Survey says 90 percent of hospitals countrywide lack piped oxygen," Sunday Nation, July 2020.

Cost of 6.8 m³ of oxygen via piped system (i.e., without cylinders)

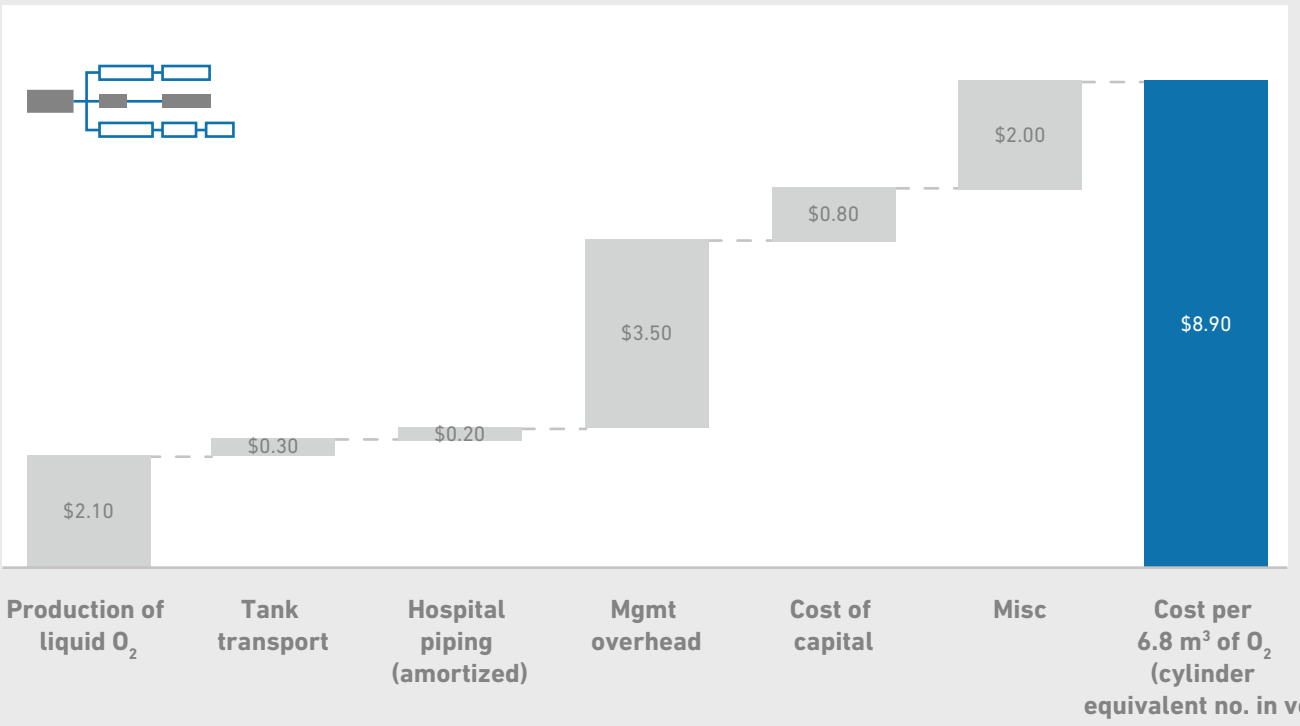


Exhibit 13: Transporting liquid oxygen in cryotanks to hospitals, followed by onsite vaporization and delivery to patients via hospital piping, yields a projected TCOD of about $9. This exhibit is based on units of 6.8 m³ of oxygen—a volume equivalent to a standard cylinder—though no cylinders are used in this distribution mechanism.

Patients with access to piped systems

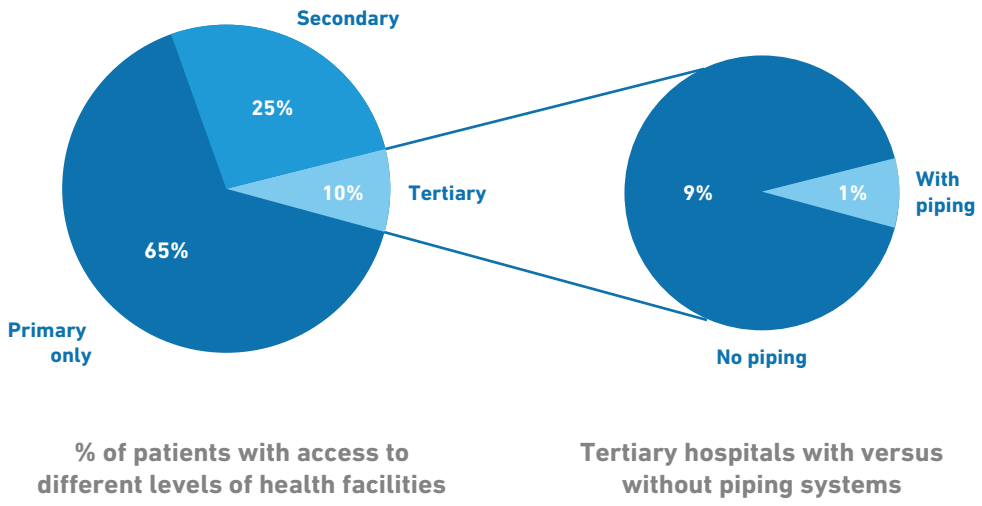


Exhibit 14: Only 1% of Kenya's population has access to hospitals with piped oxygen systems.

In the third distribution pathway (hub-spoke network of storage/filling stations), liquid oxygen is delivered from the central cryogenic plant to decentralized storage/filling stations. At these stations, the oxygen is vaporized and compressed into cylinders. The cylinders are then delivered to local clinics and hospitals over a shorter distribution distance than in the centralized pathway shown in Exhibit 11.

This option is cost-effective, and a hub-spoke network of decentralized filling stations can deliver oxygen nationwide at about $15 per delivered cylinder (Exhibit 15).[19] Such a decentralized filling infrastructure does not currently exist anywhere in SSA at any scale, but it can be developed with a moderate investment.

Cost of each filled 6.8 m^3 oxygen cylinder at point-of-use in clinics or hospitals

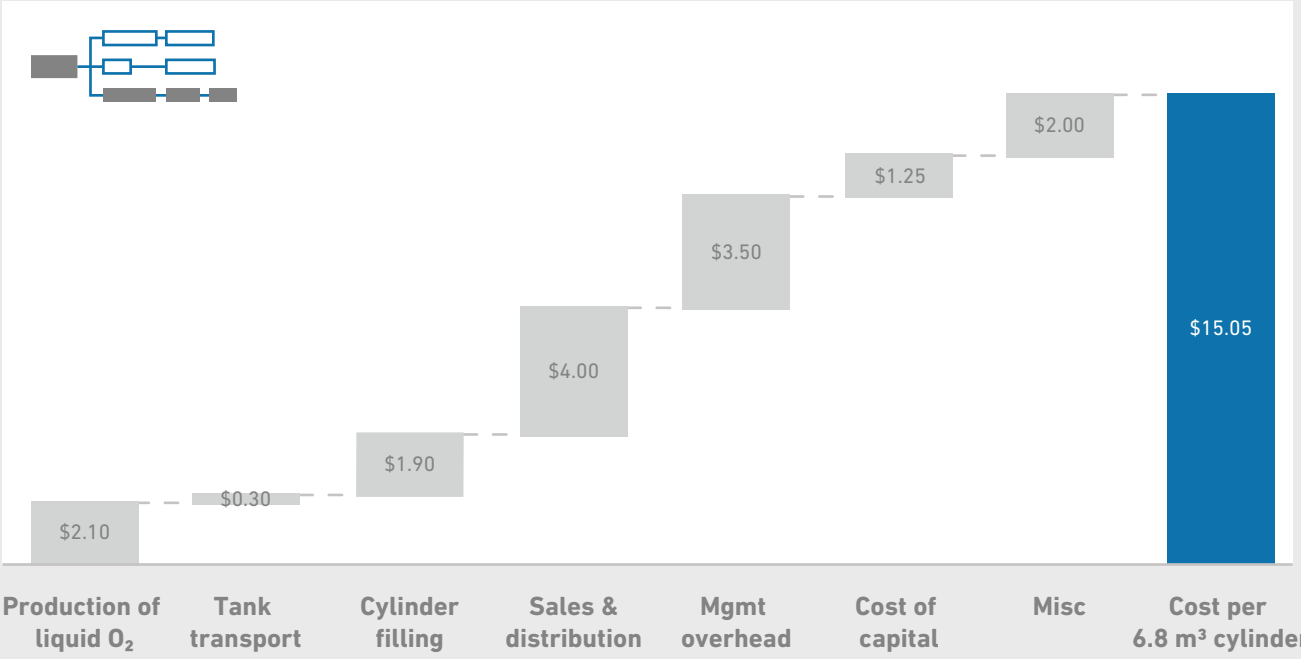


Exhibit 15: A hub-and-spoke model with delivery of liquid oxygen to distributed storage filling stations, followed by cylinder filling and final truck delivery to point-of-use, yields a projected TCOD of about $15.

[19] Key assumptions: (1) Transport costs are $400 per round trip for a cryotank containing 17,000 m^3 of oxygen. (2) Stations are refilled every three weeks. (3) Each filling station costs $100,000 and has a service life of ten years.

4. COST ANALYSIS: PSA AND VSA OXYGEN

Pressure swing adsorption plants are significantly smaller in scale than LOX plants. PSA plants at the larger end of the scale produce some 12,000 m^3 per day. (By contrast, large LOX plants can easily produce 5,000,000 m^3 per day.) On the one hand, the smaller size of PSA plants means that local oxygen production infrastructures can be developed incrementally without the need for massive initial capital expenditure (CapEx) (Exhibit 16).

On the other hand, due to the intrinsic nature of the PSA adsorption process, individual plants do not scale beyond a certain limit. As a result, PSA plants do not enjoy the economies of scale that LOX plants have. That said, since many of SSA's LOX plants are relatively small (see Exhibit 6), their economies of scale are not necessarily more favorable than that of PSA.

PSA oxygen plant: Capital investment vs capacity

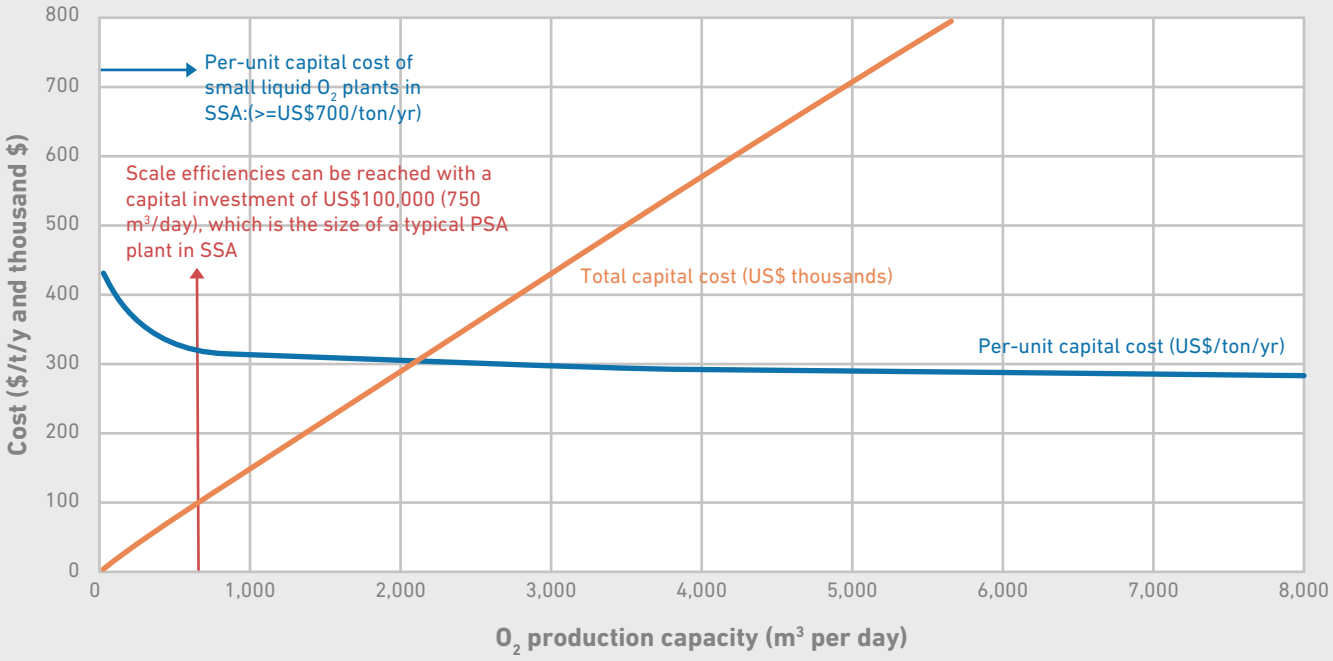


Exhibit 16: The PSA process lends itself to a much smaller scale than cryogenic separation. Therefore, constructing new plants does not require much CapEx. On the other hand, the PSA process does not benefit from the economies of scale that cryogenic separation does. However, the per-unit CapEx for a typical PSA plant in SSA is less than that for smaller LOX plants like the one in Kenya (illustrated by the blue arrow on the y-axis).

PSA technology is relatively immature in the SSA market, and this has led to substantially higher capital costs than necessary. Our research has shown that CapEx can be reduced by more than 50% by optimizing the supply chain. Exhibit 17 compares the CapEx for nominally equivalent PSA plants from two different suppliers. Each plant has an operational capacity of about one ton of oxygen per day.[20] The more expensive plant is manufactured by the market leader, which has a worldwide reputation and numerous installations in SSA.

A competitive plant is available for less than half the price from an India-based manufacturer that has some market presence in SSA, but is not widely known. The cost advantage is largely driven by lower fabrication costs in India. The Indian plant quality appears to be comparable to that of the market leader.

PSA system CapEx from different suppliers

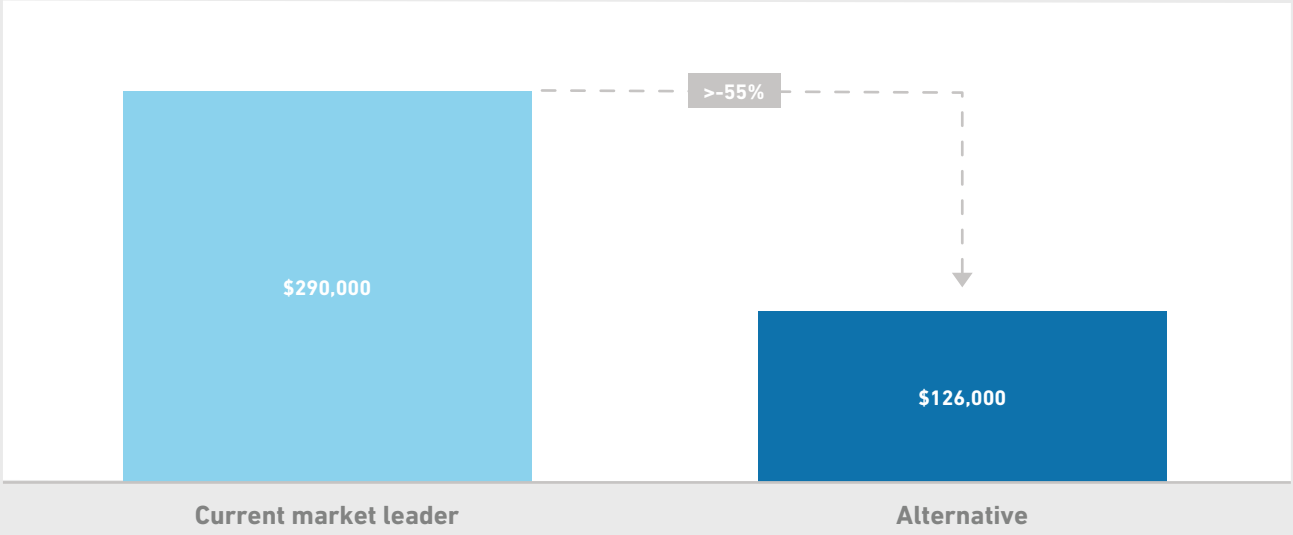


Exhibit 17: There is a wide variation in the capital cost of nominally equivalent PSA plants from different suppliers, suggesting that there is considerable room for reducing cost compared to the status quo in SSA.

[20] Based on quotes from equipment suppliers and interviews with equipment customers.

Vacuum Swing Adsorption (VSA) is a relatively newer configuration of the same adsorption process as PSA, and it is currently cost-competitive at scales intermediate between PSA and LOX. Like PSA, VSA delivers oxygen purity levels of 90–95% by volume. VSA plants are typically larger-scale than PSA plants (producing from 750 to 200,000 m^3 of oxygen per day) and have higher CapEx but lower operating expenditure (OpEx) compared to PSA, driven by lower energy requirements.

As a newer technology, VSA has very limited presence in SSA. On the other hand, its relative nascence is leading to a number of promising innovations. VSA may also have advantages over PSA at high altitude and in high-temperature locations.

Exhibit 18 shows the per-unit cost of 6.8 m^3 of oxygen gas from different production processes, not including compression into cylinders or any other form of packaging or delivery. By far, the biggest differentiator in the production cost of oxygen across the different processes is electricity. On a per-unit basis, the PSA process needs slightly less than double the electricity of the VSA process, and more than four times that of the LOX process.

> **By far, the biggest differentiator in the production cost of oxygen across the different processes is electricity.**

One notable observation is that the per-unit CapEx for PSA and VSA[21] are lower than for small-scale LOX plants. As mentioned earlier, this cost would be considerably lower for larger-scale plants, but since many of the LOX factories in SSA are at the smaller end of the spectrum, we considered it a more appropriate comparison.

We estimate that labor costs are slightly lower for the PSA/VSA systems since they are relatively simple compared to LOX plants, at the scale considered in the analysis. Adding these various costs, PSA oxygen costs 20% more than LOX, but VSA costs essentially the same as LOX on a per-unit basis.

Oxygen production cost, per 6.8 m^3

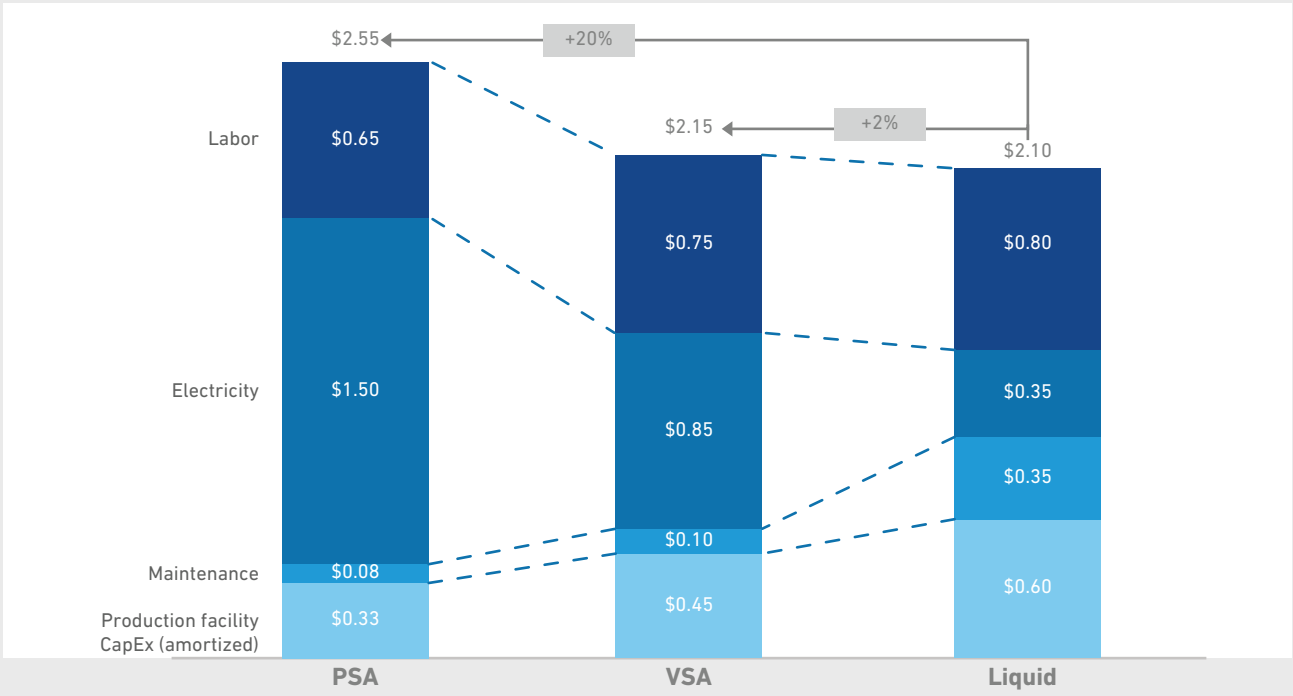


Exhibit 18: On a per-unit basis, the production cost of PSA oxygen is 20% higher than that of LOX and VSA. The largest driver of cost is electricity. Note that this only describes production cost, not the total cost of delivery to patients (which is much higher). Also, per-unit CapEx for PSA and VSA compare favorably to LOX because we use the example of the smaller LOX plants common in SSA.

[21] VSA estimate is based on quotes from one well-known supplier. We will expand this analysis over time but do not expect meaningful changes.

Distribution pathways for PSA and VSA oxygen

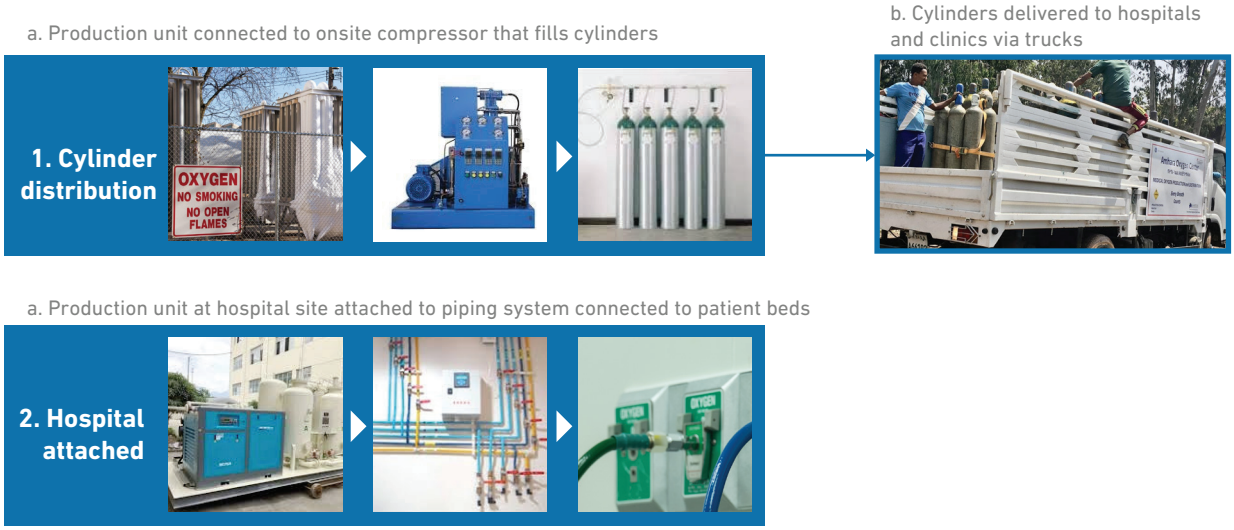


Exhibit 19: There are two main mechanisms for distributing PSA/VSA oxygen to patients in hospitals and clinics.

Analogous to the distribution pathways for LOX shown in Exhibit 10, there are two primary distribution pathways for PSA and VSA systems, each with its own challenges (Exhibit 19). As with LOX, hybrid models for PSA/VSA are possible—e.g., hospital-attached systems with onsite cylinder filling stations.

i. *Centralized cylinder filling & distribution:* Compression of oxygen into cylinders at the point of manufacture, followed by truck distribution of the cylinders to clinics and hospitals. This pathway is the most common but gets more expensive as delivery distances grow.

ii. *Hospital-attached:* A hospital-attached system that distributes oxygen to patients via piping. This has lower cost and simpler logistics, but requires clinical infrastructure. As noted earlier, only a small fraction of healthcare facilities in SSA have oxygen piping.

Exhibit 20 shows the total cost of delivery of one 6.8 m^3 cylinder of oxygen for PSA and VSA, and compares it to the cost of LOX. Conventionally, the unit cost of LOX is often described as being much lower than oxygen from PSA/VSA. However, as post-production costs (cylinder filling, sales and distribution, management overhead, cost of capital, and so on) are added, the total costs of the three processes converge.

Note that we are making the simplifying assumption that all other costs (beyond production) are the same for three processes. This is because:

- the cylinder filling process is exactly the same for all three processes;
  sales and distribution are more a function of (a) how fragmented the customer base is and (b) how much an individual organization chooses to invest in sales/distribution capabilities, rather than of the underlying production process;
- management overhead—while it could be argued that management overhead offers economies of scale for LOX, it is also a significantly more complex operation with many more in-house functions;
- cost of capital—there is no reason to believe this will be a function of the underlying process, although larger companies can negotiate better financing terms;
- miscellaneous—these are various or unforeseen costs associated with the cylinder distribution process (e.g., losses, accessory repairs, etc.) and not dependent on the underlying process.

Cost of each filled 6.8 m^3 oxygen cylinder at point-of-use in clinics or hospitals

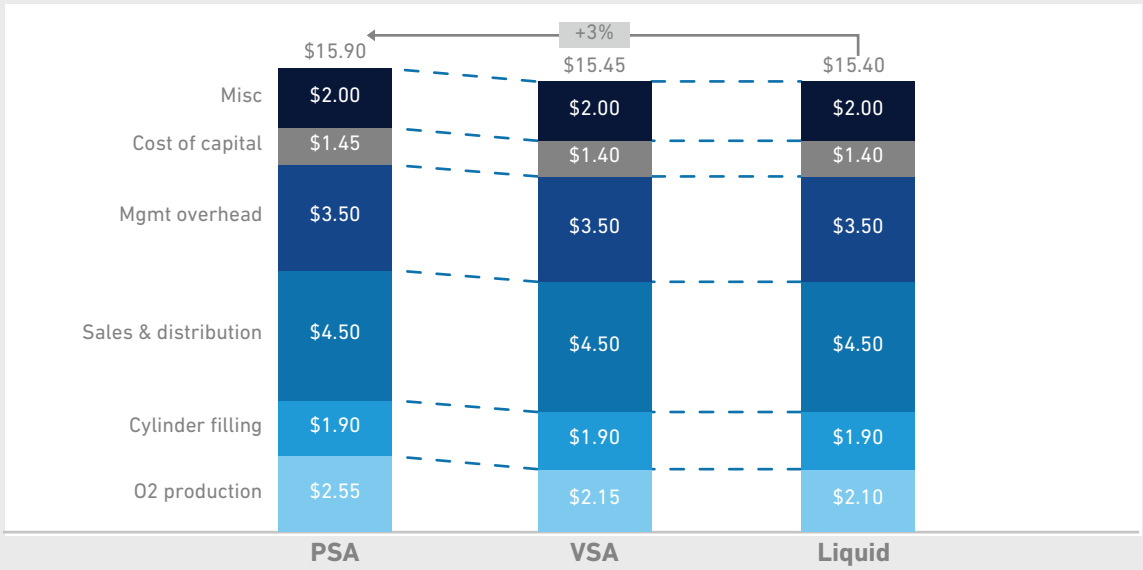


Exhibit 20: The TCOD of a cylinder of oxygen at the point-of-use is virtually the same whether sourced from PSA, VSA, or LOX plants.

Exhibit 21 shows the cost of PSA/VSA for hospital-attached systems, compared to LOX. Again, taking into account the various post-production costs (which, following the earlier argument, will be similar for each of the processes), the unit costs of PSA/VSA and liquid oxygen are very close to each other.

Of course, the problem still remains that there aren't enough accessible health facilities with piping infrastructure.

Cost of 6.8 m^3 of oxygen via piped systems (i.e., without cylinders)

Exhibit 21: The TCOD of distributing oxygen via hospital piping is virtually the same, about $9, whether the oxygen is generated onsite in PSA or VSA plants or vaporized onsite from delivered liquid oxygen.

5. A DECISION-MAKING FRAMEWORK

As the above analysis shows, the unit costs of LOX and PSA/VSA oxygen are close enough to each other that they are within the margin of optimization of all the other costs across the delivery system. There are, however, a number of important differences between the processes. The following summarizes the state of play for LOX:

i. *Industry maturity:* Cryogenic air separation is a mature industry in SSA thanks to the long history of extractive industries in the region. Industry-leading multinational companies have had a presence for decades in many countries across SSA, with sophisticated capabilities and relatively optimized operations.

ii. *Existing capacity:* There is likely not enough local production in most SSA countries to meet the entirety of local demand. However, importing/exporting oxygen is a common practice, with established processes and protocols. The open question is whether there is enough surplus capacity within reasonable shipping distance of the target sites to make importing feasible. Since cryogenic air separation is an extremely capital intensive industry, the economics of LOX production will work only if capacity is maximally utilized. Therefore, it is unlikely that there is enough surplus LOX in the relevant production ecosystem to solve the problem at the needed scale across SSA. However, it is reasonable to believe there is enough surplus to achieve some meaningful impact, especially in targeted locations ripe for investment in medical oxygen (e.g., if a particular national or provincial government makes it a policy priority).

- *Potential for new capacity:* The global LOX industry grew between 2015 and 2019 at a compound annual rate of 6.1%.[22] It is reasonable to believe that such growth will continue, especially driven by economic development in emerging economies. This means new capacity will come online, although it is unlikely such investment will be made exclusively for medical purposes. Independent of LOX supply, an extensive cylinder filling infrastructure—needed to serve rural areas—will take several years.

- *Ease/complexity of operations:* LOX producers have the operational and logistical capabilities to transport large liquid tanks as well as small oxygen cylinders. With cylinders, there are no complex downstream operations involved. Likewise, with hospital-attached systems, there is limited ongoing maintenance required once the storage and piping infrastructure has been installed. However, cylinder filling operations are somewhat involved, requiring air compressors and regular maintenance of other accessories.

[22] Source: "Global Oxygen (Medical & Industrial) Market Report," Global Newswire, 2020.

The state of play for PSA/VSA is:

- *Industry maturity:* The PSA/VSA industry is far less mature in SSA, compared to LOX. There are no local manufacturers, and the supply chain for maintenance and repair is also limited. However, there is a vibrant supply chain in India and other countries with low system-manufacturing costs.

  The skills required for manufacturing PSA/VSA systems are not substantially different from those required for many other mechanical engineering industries experiencing rapid growth in emerging economies. As such, we believe it is feasible—indeed, important—to develop local maintenance and repair capabilities in SSA.

  In the medium term, there is every reason to believe manufacturing capabilities can also be developed in regional hubs with rapidly emerging engineering industries.

- *Existing capacity:* Current capacity is negligible compared to what is needed, and many of the existing plants are not functional—potentially beyond feasible repair. A minor additional supply of medical oxygen may be achieved in some regions by repairing and maintaining some existing equipment.

- *Potential for new capacity:* New PSA plants can be installed as pre-assembled (skid-mounted) systems, available from many sources. However, considering the time required to assemble, ship, and install the systems, any massive ramp-up will take several years. Cylinder filling stations are typically co-located with the PSA plants.

- *Ease/complexity of operations:* Most of the nonfunctional PSA plants in SSA are donor funded, with limited investment in ensuring long-term operational viability. While some effort is involved in maintenance/repair of these plants, we believe these plants could be viable with well-managed operations.

  Importantly, the level of effort to maintain PSA/VSA plants is only marginally incremental to what is needed to maintain cylinder filling stations.

For individual (or a small number of) tertiary hospitals especially in urban/peri-urban areas, the optimal choice is onsite LOX tanks, vaporized on demand and delivered to patients via piped systems. These hospitals can serve as "anchor users" and serve as hubs for distributing oxygen cylinders to local primary/secondary clinics. Such a solution may be appropriate for rural tertiary hospitals as well, but only if the transportation infrastructure allows easy/regular access for large LOX trucks. Otherwise, onsite PSA systems may be more appropriate.

However, to reach a meaningfully large population, including in rural areas, an extensive decentralized oxygen infrastructure will be needed, with networks of PSA plants or LOX bulk storage sites replenished regularly via trucks from a central LOX production facility. Both types of facilities will also need cylinder filling stations.

Based on the above assessment, we conclude that the benefits of local control and predictable supply offered by PSA plants offset the incremental operational complexity involved—particularly considering the logistical complexity of ensuring large numbers of regular deliveries by LOX tanks.

A PSA-led infrastructure can also strategically incorporate LOX sites in appropriate locations based on supply levels. On the margin, therefore, we believe that a decentralized network consisting largely of PSA plants offers the most promising option for a sustainable, self-reliant, large-scale solution to SSA's medical oxygen deficit.

"To reach a meaningfully large population, including in rural areas, an extensive decentralized oxygen infrastructure will be needed, with networks of PSA plants or LOX bulk storage sites replenished regularly via trucks from a central LOX production facility."


OXYGEN
HUB


INSTITUTE FOR
TRANSFORMATIVE
TECHNOLOGIES