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Pressure swing adsorption plants

Common issues and solutions to prevent future disrepair

November 2023

PATH

Acknowledgments

This report is based on research through a Unitaid-funded grant to the Clinton Health Access Initiative. The findings and conclusions contained within are those of the authors and do not necessarily reflect the positions or policies of Unitaid.

The report was developed by PATH as part of the *Catalytic interventions to increase sustainable access to medical oxygen (MOXY)* project.

This report was written by Alice Guo and Alec Wollen from PATH, with support from Lisa Smith, Alex Rothkopf, and Carrie Hemminger, also from PATH. The authors would like to thank the organizations Build Health International, Partners in Health, and Assist International for their insightful contributions.

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Abbreviations

BHI	Build Health International
LMIC	low- and middle- income countries
PIH	Partners in Health
PSA	pressure swing adsorption
VSA	vacuum swing adsorption

Key takeaways

Pressure swing adsorption (PSA) plants—as the primary source of bulk medical oxygen for many health facilities—play a vital role in many countries' medical oxygen supply systems. However, plant operations are complex, with issues such as maintaining oxygen purity, frequent breakdowns, and lengthy repairs.

Common issues that arise along the PSA plant life cycle include:

- **Installation and training:** Poor installation practices were observed in many of the facilities, including electrical wiring issues, missing personnel safety equipment, inappropriate materials, and inappropriate installation methods. Few of the facilities had on-site personnel with technical training and expertise related to plant maintenance and repair. Training, maintenance, and acquisition of spare parts are also often omitted from plant tenders.
- **Operations and maintenance:** 60 percent of PSA plants were overdue for maintenance at the time of assessment. Almost all of the facilities had no spare parts on-site, no full set of tools for maintenance, and none of the facilities noted having a maintenance log. Budget allocations toward the plant's maintenance needs are often sporadic.
- **Environmental factors:** High heat and humidity (exacerbated by inadequate insulation or ventilation) can accelerate wear of mechanical components and chemical degradation, leading to premature failure of PSA plants. Dust can accelerate the wear of moving components, cause overheating, and restrict airflow.
- **Lack of ownership:** Health facility managers and plant operators are often not involved in purchasing decisions yet are expected to allocate limited resources toward sustaining plants. Financing staff often lack full understanding of PSA plant needs and costs to effectively plan and budget for their operations.
- **Lack of a skilled workforce:** Many countries face low numbers of trained biomedical engineers and technicians due to insufficient local capacity for relevant training programs, as well as challenges retaining skilled workers long term.

There are several solutions across the entire plant life cycle that can help alleviate some of the common issues:

- For **planning and decision-making**: increase involvement of biomedical engineers / facility managers in equipment purchasing decisions; develop ownership transition plans for donated plants beyond the initial warranty/coverage period; improve understanding of the total cost of ownership for oxygen generation plants and proactively allocating budget toward preventive and corrective maintenance; and stipulate operations and maintenance training for facility staff in plant procurements.
- For **installation and training**: perform an independent inspection after initial installation of a PSA plant by a third party not involved in procurement (quality check); and ensure provision of graphic-rich operating and maintenance manuals and spare parts list in the local language.
- For **operations and maintenance**: upskill on-site technicians by training them on how to assess plants and obtain support; explore alternative ownership models and service-contracting mechanisms that more appropriately fit facility contexts; and embed preventative maintenance checks into routine facility tasks.
- For **other factors**: improve countries' biomedical engineering capacity through educational, training, and retention programs; explore mitigation strategies for low-quality power with grid operators and/or facility managers; and design robust procurement specifications that effectively consider manufacturing quality.

Introduction

"Hypoxemia" is low levels of oxygen in the blood. It affects millions of people annually who suffer from a range of common conditions, such as pneumonia, newborn complications, obstetric emergencies, noncommunicable diseases, and respiratory care infections like COVID-19.[1] Medical oxygen therapy is essential for treating hypoxemia. Despite its critical role in treating many common conditions, nearly half of hospitals across low- and-middle-income countries (LMICs) have inconsistent or no oxygen supply.[1]

Medical oxygen is produced by different types of systems, such as air separation units, pressure or vacuum swing adsorption (PSA or VSA) plants, or concentrators. Depending on the generation method, different storage and distribution options are available, such as gas piping systems, gas cylinders, or liquid storage tanks. Oxygen delivery interfaces and accessories facilitate and regulate oxygen therapy for patients across the health system.[i] Error! Reference source not found. detail the different ways oxygen can be produced, stored, and delivered to patients.[2]

PSA/VSA plants, as the primary source of bulk medical oxygen for many health facilities, play a vital role in a country's medical oxygen ecosystem. LMICs have invested hundreds of millions of dollars in PSA/VSA plants over the past two years to strengthen oxygen supply and delivery. However, practice has shown that the operation of these plants is complex, with issues such as difficulty producing the right level of oxygen purity, frequent breakdowns, and repairs that take months, or even years, to complete. To sustain access to lifesaving oxygen beyond the COVID-19 emergency response, it is imperative to ensure these plants continue to function over time. Understanding the common difficulties they face and the potential causes will be critical for developing more effective strategies to operate and maintain them.

PSA/VSA plants are complex medical devices that require regular maintenance by specially trained staff to ensure sustained operations. The two plant types operate in a similar way but use slightly different methods to produce medical grade oxygen. This report focuses on PSA plants specifically as it summarizes the results from an analysis that PATH—in collaboration with Build Health International (BHI), Partners in Health, and Assist International—conducted on PSA plant failures and opportunities for improved management. It highlights common issues and causes of failure across the PSA plant life cycle—from planning and decision-making to installation, training, and operations/maintenance—and recommends ways to redress them so that decision-makers, health facility managers, suppliers, and plant operators can improve plant management.

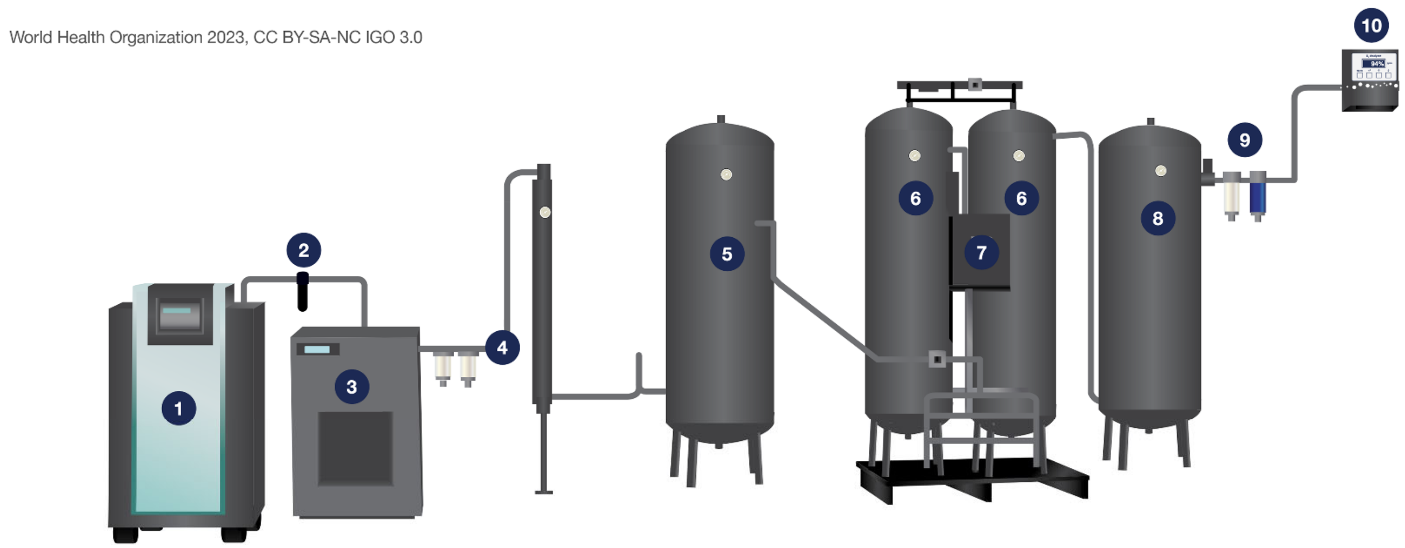
Overview of PSA plant technology

PSA plants comprise five main components, each coming in 5 to 15 different models and sizes, all of which have several parts that require regular maintenance and replacement (**Figure 1**). PSA plants can be installed as a single unit or, for

[i]Such as nasal cannula, nasal catheters, bubble humidifiers, oxygen masks, supply tubing, pressure-reducing valve or regulator, input connections, cylinder valves, and Thorpe tube flowmeters.

additional oxygen production capacity or redundancy,[ii] as multiple ones, commonly called "duplex" or "triplex" (as applicable). The life span of PSA plants is, at a minimum, ten years,[3] but with regular maintenance and good operating practices, they can last up to 20 years or more.[4]

Figure 1. Component overview of pressure swing adsorption (PSA) plants.



1 Air compressor
2 Water trap
3 Refrigeration or adsorption dryer
4 Filtration assembly:
- pre-filter (> 5 micron),
- coalescing filter (0.1 micron)
- coal filter or coal tower, alternatively activated carbon filter

5 Compressed air tank
6 PSA – O_2 generator
7 Control panel
8 Product/buffer tank
9 Bacteria/sterile filter
10 Oxygen analyser

PSA technology concentrates oxygen from ambient air by preferentially removing the nitrogen. Ambient air is first compressed, filtered, and then dried using an air compressor, filters, and dryers, respectively. Control valves direct the clean pressurized air into one of two pressure adsorption vessels that house zeolite, a porous mineral containing aluminum and silicon compounds. Under pressure the zeolite preferentially adsorbs nitrogen while allowing oxygen to pass for delivery. Once the zeolite is saturated and the oxygen is collected, the control valves release the pressure and, with it, the remaining nitrogen-rich air before repeating the process with the other adsorption vessel. The oxygen can be distributed from the storage tank to patients using a medical gas pipeline system, can be fed to a booster compressor to fill high-pressure cylinders, or both configurations can be utilized at the same site.[iii]

[ii] Redundancy refers to having multiple generation plants that can operate independently to improve overall oxygen production reliability. It allows for continuous oxygen generation even if one plant is turned off, either deliberately during maintenance activities or due to malfunction.

[iii] Additional details about PSA plants can be found in the oxygen generation and storage: pressure/vacuum swing adsorption plant brief: https://www.path.org/resources/oxygen-generation-and-storage/

Methodology, scope, and data sources

PATH and partners used a mixed-methods approach to analyze 43 facility reports from eight countries in Africa and Latin America that had assessed 50 PSA plants (five facilities had more than one plant).[iv] Available information included plant configuration, functional status, maintenance practices, and related infrastructure. The analysis identified and distilled common issues and their causes. These results were further complemented by four semi-structured interviews with ten stakeholders involved in plant operations and maintenance.[v]

Additionally, a PSA and compressor manufacturer landscape analysis was conducted using data from the assessment reports and a repair tracker data source from BHI (**Figure 3**). A separate database, co-developed by 13 organizations actively involved in assessing and restoring PSA plant function across 21 LMIC, was used to calculate PSA plant statuses (**Figure 4**). **Table 1** summarizes all data sources used in this report (where they originated, how they are used, and what their limitations are).

Table 1. Data sources for analysis.

Data source	Owner	Where data are used in analysis	Sample size	Limitations
Main sources				
Assessment reports	Developed by BHI, Partners in Health, Assist International, Mediquip Global, and Foxolution	Common issues, brand proliferation	43 reports on unique health facilities that collectively have 50 PSA plants in total	Each reporting organization had different facility selection criteria, reporting formats, and levels of technical detail. Technical details of facilities with multiple PSA plant installations were sometimes combined or missing (e.g., a report for a facility with three PSA plants that only indicated two installation dates). Assessment reports provided only a snapshot and limited insight into events leading up to the failure or the outcomes of any attempted repairs (i.e., whether a repair solved the problem).
Semi-structured interviews	Collected by PATH	Potential causes of failure	Four interviews, which included ten individuals in total	Only four interviews were performed, with limited follow-up, and the sample included primarily maintenance providers. Additional potential causes of failure may be identified through interviews with other types of stakeholders in additional geographies.

[iv] The reports were developed by BHI, Partners in Health, Assist International, Mediquip Global, and Foxolution.

[v] Stakeholder types ranged from international nongovernmental organizations to ministries of health and private suppliers.

Data source	Owner	Where data are used in analysis	Sample size	Limitations
Complementary sources				
PSA/VSA plant database	Coordinated by PATH and collected from 13 different organizations	Plant status breakdown	670 known oxygen generation plants installed in 31 countries	Database was more likely to include nonfunctioning or sub optimally functioning plants due to the aims of the coordination effort.
BHI repair tracker	Taken from internal BHI document	Brand proliferation	55 PSA plants (including 21 assessment report duplicates)	The tracker only includes plants that are actively supported by BHI.

Abbreviations: BHI, Build Health International; PSA, pressure swing adsorption; VSA vacuum swing adsorption.

Infrastructure issues such as electric grid quality and reliability were noted when relevant to PSA plant disrepair, but determining their causes and recommending next steps for these issues would require engaging a broader set of stakeholders and therefore fall outside the scope of this report.

PSA plant analysis

Details about the installation dates, configurations, booster compressors, and sizing of the PSA plants included in the analysis can be found in **Figure 2**.

Figure 2. Description of a pressure swing adsorption (PSA) plant sample.

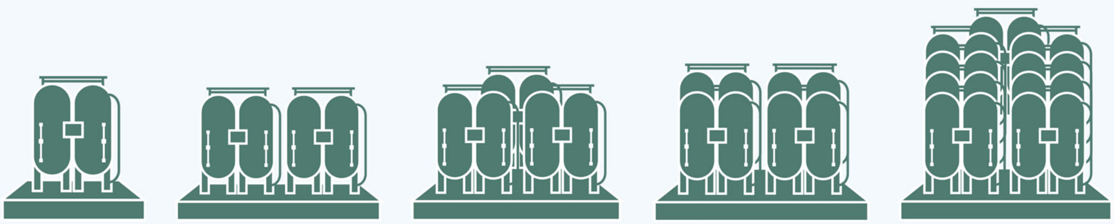
PSA plant sample

PATH conducted a PSA plant analysis using data from **43 health facility** assessment reports which included **50 PSA plants in total**—**seven installed prior to 2013, 20 installed between 2013 and 2020, and 23 installed after 2020**. Details about the plant configurations, booster compressor availability, and whether plant size met demand are highlighted below.

PSA plant configurations

PSA plants have different configurations that depend on user needs and manufacturer offerings. A common differentiation point is the number of PSA units in the system, which can vary from single to multiple units.

38 of the surveyed facilities had one PSA plant with unit configuration ranging from single to nineplex:



27 single PSA units

8 duplex PSA units

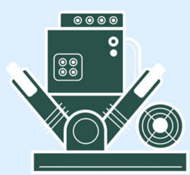
1 triplex PSA unit

1 quadriplex PSA unit

1 nineplex PSA unit

The **remaining 5 facilities** had multiple PSA plants installed at different times.

Booster compressor availability



30 facilities had at least one booster compressor **(20 functional and 10 nonfunctional)**

12 facilities had no booster compressors

1 facility had an unknown amount of booster compressors

Plant size meeting demand

Of the 43 assessments reviewed, **26 facilities** highlighted oxygen demand:

11 facilities reported plants as correctly sized to meet current demand

11 facilities reported plants as undersized for current demand

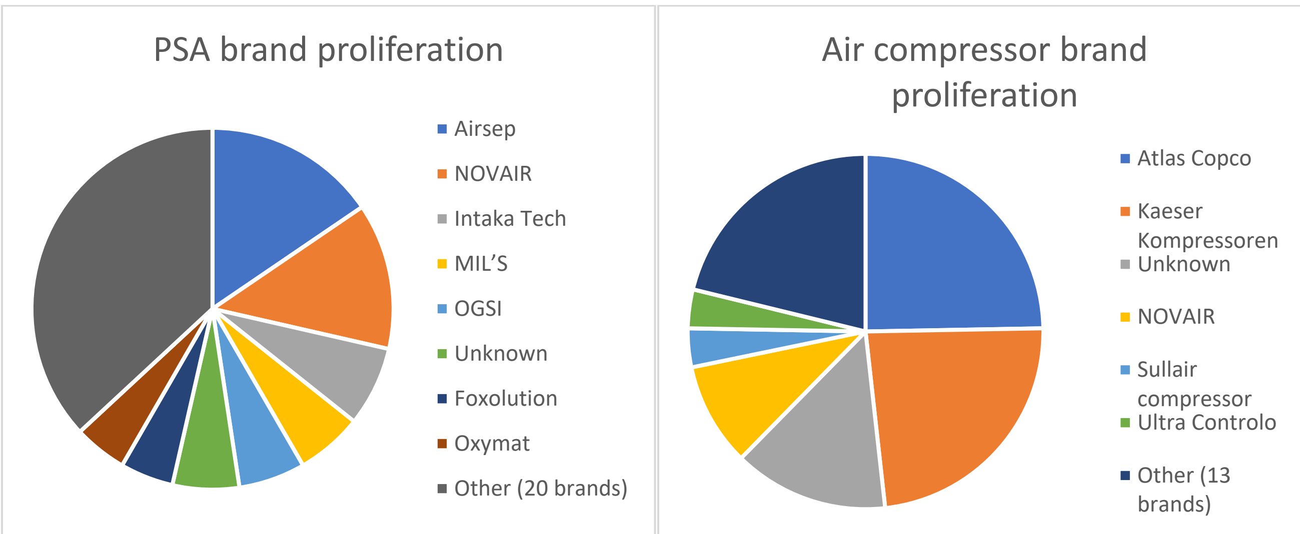
3 facilities reported plants as oversized for current demand

1 facility reported plant as undersized for COVID-level demand

PSA plant brands and functionality analysis

There are dozens of PSA plant brands, as well as component part brands. The combined data set of the Assessment Reports and BHI repair tracker comprising 84 PSA plants (excluding duplicates) identified 29 PSA plant brands, whose companies are headquartered in 12 different countries, and 20 brands of air compressors, whose companies are headquartered in 9 different countries (**Figure 3**).[vi] The global footprint of manufacturers results in a complex supply system, where suppliers have limited contact with customers and lack a local presence in the countries they supply—particularly component part suppliers, whose customer base is spread across dozens of PSA plant brands. This leaves suppliers struggling to meet the often uncoordinated and sporadic demand.

Figure 3. Pressure swing adsorption (PSA) plant and air compressor brand distribution of assessed plants.



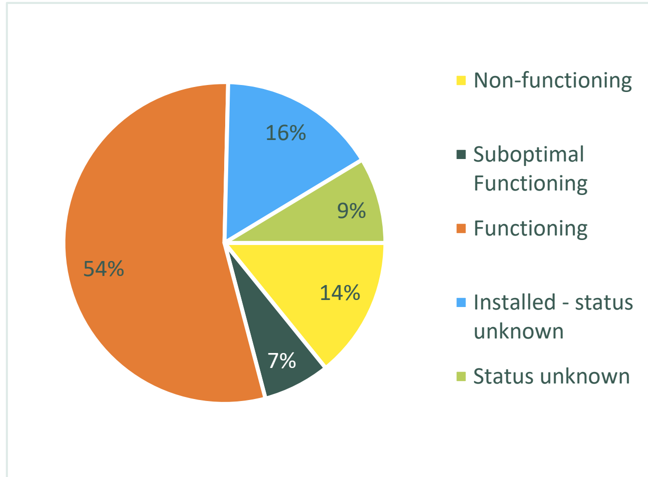
Note: Data may not be comprehensive or proportional to the global market (see "Methodology, Scope, and Data Sources" section for more details).

PSA plants are an attractive supply option for health facilities with a consistent baseline demand for oxygen, a desire to own and manage their oxygen source, and access to reliable electricity. As such, PSA plants are predominantly used in secondary and tertiary health facilities across LMIC, where baseline demand is steady and dependency on external oxygen supply (e.g., liquid oxygen or gas oxygen cylinders/tanks) is costly. Further, if appropriately configured, neighboring facilities may benefit from oxygen supplied by health facilities with PSA plants through the distribution of cylinders.

[vi] Combined dataset comprised of de-duplicated assessment reports and BHI repair tracker – refer to Table 2 for details.

A critical aspect of PSA plant operations is regular preventative, as well as appropriate corrective, maintenance. Without it, plants fall into disrepair. Information from the PSA/VSA plant database suggests that only half of all PSA plants are functioning, while one in five plants are either nonfunctioning or suboptimally functioning (**Figure 4**).[vii]

Figure 4. Pressure swing adsorption (PSA) plant status (N=670).



Source: PATH oxygen generation plant tracker.

Framework for understanding PSA plant failures

A PSA plant's sustained functionality is dependent on several factors across the product life cycle, from planning to installation to maintenance. Contributing factors include the surrounding infrastructure, availability of skilled human resources, and equipment quality. **Figure 5** presents a life cycle framework, with common issues that arise, the potential reasons for their occurrence, and possible actions to prevent future disrepair.

Figure 5. Pressure swing adsorption (PSA) plant life cycle and factors that impact functionality.

Planning and decision-making*	Installation	Operations and maintenance	Other factors
• Stakeholder involvement • Budgeting • Procurement practices	• Installation contracting • Installation practices • Training	• Maintenance practices • Maintenance capacity • Spare parts availability • Service contracting	• Environment (heat/air conditioning, humidity, dust) • Infrastructure (power grid) • Equipment quality* • Skilled human resources*

**Discussed in the "Potential Causes of Failure" section.*

Common issues across the PSA plant life cycle

Numerous issues were identified throughout the 43 assessment reports. These issues are further exacerbated by environmental and infrastructural factors, such as high heat, humidity, dust, and the reliability of the electricity supply. The following sections characterize in greater detail the common issues that arise across the PSA plant life cycle.

[vii] The remaining ones have unknown statuses.

Installation and training

Installation contract issues

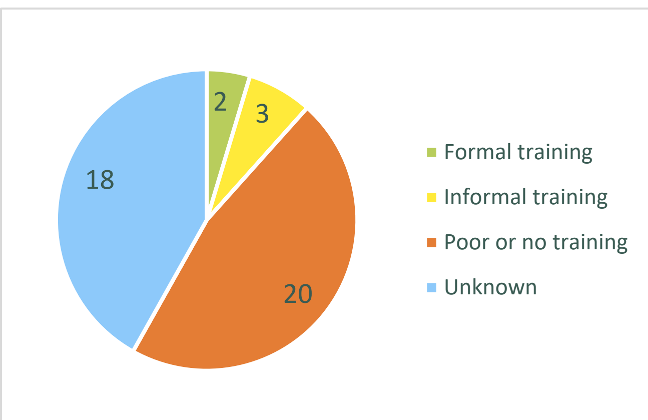
Several facilities had performance issues with PSA plant installers: Four facilities had been in the process of installing PSA plants for over five years without completion. Another facility experienced a premature failure of a booster compressor that was speculated to be caused by improper installation. Yet another facility noted issues in PSA plant operations due to the presence of a manual changeover valve that should have been an automatic unit. Specifically, the facility's biomedical engineering technicians were concerned that patient safety could be compromised if an operator forgets to switch over the oxygen source, so the entire system was not being used.

Poor installation practices

A number of poor installation practices were observed in many of the reports, including electrical wiring issues, missing personnel safety equipment (e.g., fire extinguishers, adequate lighting, warning signage, fire alarms, cylinder storage racks), inappropriate materials (e.g., industrial hydraulic hose instead of medical oxygen–rated tubing, incorrect compressor oil, improperly sized components), and inappropriate installation methods (e.g., inadequate ventilation, equipment that was not bolted to the floor, generator exhaust that was near intake). It is not clear from the reports why these deficiencies occurred, but potential reasons include cost savings, lack of knowledge, or parts availability.

Reporting on the prevalence of these issues quantitatively is not possible given the nature of facility visits, which are conducted by multiple organizations and individuals without an explicit list of inspection criteria. In addition, the variety and severity of electrical issues make it hard to compare one with another. For example, some facilities noted faulty grounding systems, while others noted exposed power wires, missing circuit breakers, or arcing connections. About half (21 of 43) noted specific issues with the distribution wiring or electrical equipment related to the PSA plants, while 13 others noted issues with power infrastructure (outages, lack of/inappropriately sized/non-functioning backup generators, or poor grid/power quality). Only 4 facilities noted no issues with the electrical system, and the final 5 are unknown.

Figure 6. Facility staff on-site technical capacity (level of training) for pressure swing adsorption plant repair (N=43).



Training

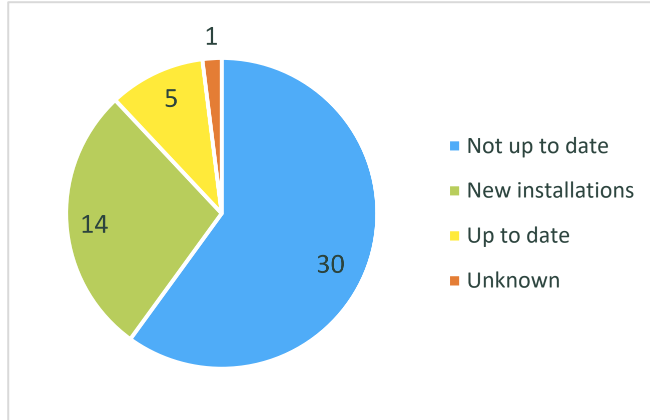
Few of the 43 facilities had on-site personnel with technical training related to PSA plant maintenance and repair (**Figure 6**): 2 had a formally trained technician, 3 had a technician with informal training (including self-taught), 20 had poor or no training, and the status of the remaining 18 is unknown or unreported. In the event of a failure, most facilities would be reliant on outside technical services for diagnostics and repair.

Operations and maintenance

Maintenance practices

A majority of PSA plants (30 of 50 plants in the 43 facilities) were overdue for maintenance at the time of the facility assessment (**Figure 7**). Only 5 plants older than one year were up-to-date on maintenance. Of these, 1 had broken down shortly after the previous service visit, and 1 had lapsed on payment of the service contract, jeopardizing future visits. A further 14 were new installations, and 1 was of unknown maintenance status.

Figure 7. Current maintenance status of pressure swing adsorption plants (N=50).



* "Up-to-date" is defined as maintenance having been performed within the past year, or more frequently if required by the manufacturer.

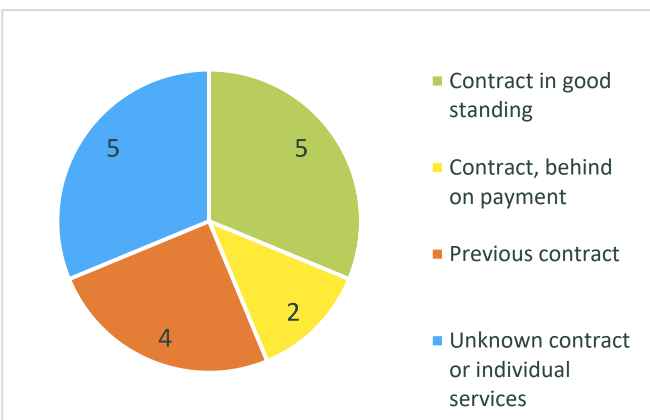
Facility maintenance capacity

Only 1 facility noted having any spare parts on-site, while 21 facilities were confirmed as not having any. The remaining 21 are unknown. Similarly, the facility with on-site spare parts was the only one with a full set of tools for maintenance (including an oxygen analyzer), while a further 3 had basic hand tools available, and 15 did not have any tools. The remaining 24 are unknown. None of the facilities noted having a maintenance log (including 27 unknowns).

Maintenance contract issues

Several issues with installation and/or maintenance service providers were noted in the analyzed reports. About a third of facilities (16 of 43) outsource maintenance to a service provider (**Figure 8**). Of these, 5 had an active maintenance contract in good standing, 2 were behind on payments so that maintenance activities may stop in the future (depending on resolution of contract terms), 4 had made it to the end of their contract period without renewing and thus were no longer actively maintaining the PSA plant, and the final 5 either had unspecified contract details or scheduled maintenance visits individually. For the other 27 facilities, 10 did not have any maintenance service providers, and the remaining 17 had unknown status regarding maintenance providers.

Figure 8. Breakdown of facilities that outsourced maintenance to a service provider at least once (N=16).



An active service contract or scheduled maintenance did not guarantee uptime for PSA plants. There were two specific instances of PSA plants under an active service contract at the time of reporting that were still in a nonfunctional state. Another facility had a PSA plant fail shortly after a service visit from the installer.

Other factors

Environment

Several environmental factors contribute to premature failure of PSA plants in LMIC. High heat contributes to accelerated wear of mechanical components and can also accelerate chemical degradation, such as oxidation of rubber, electrical insulation, and lubricating oils. High environmental heat levels can be further exacerbated by plant installation and facility details, such as inadequate insulation or poor ventilation. Air conditioning is an option for reducing ambient air temperature, but it is an additional capital cost and large consumer of energy. Eight reports specifically recommended additional ventilation, insulation, or air conditioning due to high ambient temperatures in the plant room. For example, one facility's indoor temperature reached higher than 40°C, even with air conditioning, highlighting the need for additional insulation.

High humidity is also commonly found in LMIC climates and can accelerate the degradation of zeolite sieve beds. However, no specific issues in the reports noted humidity as a contributing factor.

Finally, dust can contribute to component failure. It is abrasive and will accelerate wear of moving components. It can build up on surfaces and clog filters, reducing cooling efficiency and causing overheating. It can block the air stream filters, leading to flow restrictions and low output. Inadequate dust control was specifically cited by two facilities, and one compressor was noted as needing to be cleaned out.

Infrastructure

The presence and functionality of a backup generator are important elements of contingency planning with respect to the electrical grid. Outages are common in many settings, and absence of power will prevent the generation of oxygen without a backup energy source. Most facilities (32 of 43) had access to a backup generator for their PSA plants. Of these, 20 were confirmed or assumed to be functional, 9 were of unknown status, and 3 were reported as nonfunctional. Of those 20 with functioning generators, 2 were overdue for service and thus at an increased risk of breakdown. A small number of facilities (5 of 43) had a backup generator at the facility that was not connected to the PSA plant, due to either insufficient capacity or insufficient wiring to support a connection. Of the remaining 6 facilities, 5 were confirmed to have no backup generator, and 1 was of unknown status (not reported). In addition to functionality, provision of fuel was specifically cited as an issue by one facility, but this criterion was not evaluated in most facility reports.

> *EXAMPLE: LONG DISTANCES FROM TECHNICAL SERVICES*
>
> *One facility noted the nearest major city that was able to fill cylinders or provide maintenance services was 900 km away. Given the nonfunctional state of their PSA plant, they were forced to transport and fill 50 cylinders per week to maintain an oxygen supply at the facility. Repair visits and spare parts procurement also needed to be coordinated from this location, significantly adding to procurement and travel costs for the technician.*

Result of common issues

A combination of the above factors leads PSA plants to fall into disrepair. Of the 50 PSA plants reviewed as part of the 45 facilities assessed, common issues for plants in disrepair were:

- Clogged filters and drains, resulting in reduced flow and/or overheating.
- Contamination of sieve beds, resulting in low purity output.
- Compressor failure, resulting in error codes and/or overheating.
- Booster failure, resulting in slow fill times and/or overheating.
- Leaky valves, resulting in low purity output, fire, and/or noise.

One of the unfortunate realities of deferred or absent maintenance practices is that subsequent disrepair events are more serious and expensive to fix. For example, lack of oil-separating (coalescing) filter changes (a relatively simple and inexpensive task) can lead to downstream oil contamination of the sieve beds, requiring full disassembly, cleaning, and zeolite replacement (many hours of labor and several ***thousand*** dollars in US currency). Another example is inadequate or improper oil changes that can lead to more serious air compressor damage.

Depending on the value and age of a plant, performing advanced repairs such as these may be less economical than purchasing a replacement. This is especially true for plants with low initial cost and poor-quality assurance and customer support: they are at higher risk of breaking down, and manufacturers can be harder to contact for service and spare parts. In these cases, repair may not be worth the time, cost, or effort, given that something else may break down in relatively short order.

Potential causes of failure across the PSA plant life cycle

This analysis revealed that there are several challenges that impact every stage of the PSA plant life cycle, from installation to maintenance. To prevent common issues from occurring in the first place, it is imperative to understand why they exist. This next section illustrates some of the potential causes of failure across the life cycle. These insights are developed from semi-structured interviews with key informants directly involved in PSA plant operations, maintenance, and decision making.

Planning and decision-making

How a PSA plant is purchased and what decisions go into it (e.g., how much budget should be allocated, where the plant should be placed, who is responsible for operating and maintaining the plant, etc.) significantly impacts a plant's functionality. A potential reason why decisions do not adequately address facilities' PSA plant needs is a lack of ownership by those who ultimately bear the responsibility of operating and maintaining the plants. Health facility managers, plant operators, and/or subnational authorities are often not involved in purchasing decisions yet are expected to allocate scarce resources toward sustaining the plants. This hampers their ability to allocate resources based on their own determination, as well as their sense of responsibility for, and willingness to safeguard, the plants.

> *"[There is] …only one plant that's [a] self-motivated purchase… The rest are donations or ordered [by central authorities] … [They have] a two-year service contract, and then you're on your own." – Interview respondent*

This lack of ownership was further exacerbated during the COVID-19 pandemic, when many plants and related services were donated. These donations can inadvertently create a dependency on external support for continued resources to restore or replace plants when they are nonfunctioning or suboptimally functioning. Facilities are disincentivized to dedicate their limited resources toward maintaining the plant if someone else will restore or replace the plant for free. Plant donations may be part of an exchange of goods/services, which further disincentivizes additional resource allocation on a recurring basis to sustain plants, as all parties have already gotten what they wanted at the time of the exchange.

> *"[There is a] … dependency model where there's expectation that donors / external partners will provide aid for free, so [facilities will] run [the] equipment to the ground and depend on someone to come in and fix it or buy a new one." – Interview respondent*

Beyond the lack of ownership, there are also gaps in the ability to appropriately procure, plan, and budget for PSA plant operating needs. Procurement staff are often unaware of the ongoing maintenance and operating needs associated with PSA plants. Even if there is awareness, current global estimates lack the precision needed to effectively support procurement staff in incorporating accurate costs. As a result, training, maintenance, and spare part provisions are often omitted from or insufficiently included in plant tenders. When spare part purchase orders come in, procurement staff are often unaware of which suppliers to order from and who to contact.

> *"[They] … don't know what parts to specifically ask for. Even if they know parts, they don't know which distributor to order from." – Interview respondent*

Budgeting and finance staff often have limited knowledge of the total cost of ownership of a PSA plant. This results in limited forecasting of maintenance needs and efforts to secure maintenance budgets in advance.

> *"No one knows the behavior of [the] plant[s] ... [the] preventative maintenance/corrective maintenance needs, so [no one] … budget[s] in advance. Once [the] PSA plant breaks, [then the finance person] starts budgeting." – Interview respondent*

Installation and training

Many of the poor installation practices and contract issues highlighted above can be attributed to lack of the training and technical expertise needed to appropriately operate and complete basic preventative maintenance activities. Training, provision of maintenance, and acquisition of spare parts are often omitted from plant tenders, resulting in an insufficient number of on-site technicians who are equipped to effectively operate plants, perform basic maintenance, and order parts at the time of installation.

> *"[We] … didn't find any technicians that were trained on operating machines because [they] weren't obliged during procurement." – Interview respondent*

All the above puts plants at risk of inappropriate operation and delayed maintenance. In response, technicians have at times resorted to teaching themselves the basic skills needed to operate the plant.

> *"For the most part, local staff [are] informally trained, and they make it up as they go… Some people refer to online documentation or are self-taught." – Interview respondent*

Some PSA plant suppliers further exacerbate this skill gap by restricting the extent to which training and information (such as service manuals and spare part lists in the applicable local languages) are provided to plant operators due to concerns that incorrect servicing by plant operators would be blamed on them. They may also be concerned that bolstering plant operators' capabilities would detract from future business opportunities to service the plant.

> *"Spare part lists or maintenance manuals are not provided by supplier[s], sometimes on purpose. [This is because] … the less skilled the local technician is, the more business you have in the future for servicing, [and they] don't want local technician[s] to mess up [a] plant during [the] warranty period … [The] responsibility [is on] … the buyer to ask for everything before they pay for the plant." – Interview respondent*

Operations and maintenance

The inconsistent or insufficient maintenance practices highlighted in the "Common Issues" section can be ascribed to insufficient technical capabilities for assessing and maintaining plants, as well as inadequate budget allocation toward operations and maintenance activities.

There is limited technical capacity in public facilities to assess plants and limited visibility of PSA plant supply chains. This often leads to not knowing what is broken in the plant and which parts need to be repaired and/or replaced. Even if the right parts are identified, facilities can struggle to identify the right suppliers and to place orders using the correct technical language. On the other hand, suppliers are inundated with one-off orders, which often require follow-up conversations for clarification. This creates significant transaction costs for suppliers and disincentivizes them from responding to unclear, low-volume orders. Fragmented demand and limited demand visibility also drive suppliers to produce parts to order, which can expose suppliers and customers to production delays.

Challenges faced by public facilities and by suppliers ultimately result in significant delays (three months to a year) in accessing spare parts or hinder access altogether.[5]

> *"[It's a] challenge [to] know where to get spare parts [and] who to reach out to. Only [a] handful of people with specific training know where to reach out ... Local staff don't have the right language to ask for the right parts ..., [and] ... manufacturers are not incentivized to fulfill unclear asks [since they see it] as 'white noise' and put it aside." – Interview respondent*

Even if the spare parts arrive at facilities, maintenance beyond the initial warranty / service coverage period is often provided by informally trained technicians who may know how to perform only some of the maintenance activities required to sustain a plant's function. This can further hinder the ability to restore plant function.

> *"Maintenance [is] done by someone who doesn't fully understand [the] system or [a] contractor that's difficult to deal with." – Interview respondent*

Moreover, sporadic budget allocation toward the plant's maintenance needs further exacerbates challenges in accessing spare parts and sustaining maintenance beyond the initial warranty or service period. Budgets are often allocated and disbursed only after issues arise, which delays the ability to place orders for parts. The lack of adequate, proactive, and long-term financing toward plant maintenance also results in limited and variable maintenance practices beyond the initial warranty or service period. As a result, facilities struggle to access sufficient funds to perform the needed preventative maintenance on a plant.

> *"[Out of] 10 sites, only one site has a contractual agreement with suppliers for five years to have maintenance from supplier ... All other sites were installation only and [the] hospital [has the] responsibility to maintain plants afterwards." – Interview respondent*

Even when maintenance is included in budgets, emergency repairs often take precedence, which further deprioritizes investments in preventative maintenance, despite such maintenance costing much less, in many cases, than bringing the equipment back into service.

> *"[It is] ... difficult to get [a] large budget approved in management. There often is not even a line item ... for medical device maintenance." – Interview respondent*

Other factors

The roots of failure across the plant life cycle also lie in the lack of a skilled workforce. Many countries have few institutions that train biomedical engineers and technicians (the average across LMIC is 0.3 and 0.4 per 10,000 people, respectively[6]), resulting in a limited understanding of either as a promising career pathway, low numbers of trained personnel, and difficulty in finding a skilled workforce, with countries sometimes needing to source from abroad. Retaining skilled workers also proves to be a challenge for many countries as they struggle to provide favorable working conditions (competitive pay, a clear growth and development trajectory, reasonable workload), risking relocation of the few skilled workers that exist.

> *"There are no academic institutions training biomedical engineers in this country... [People] would have to go to other countries [to get this training] ... I haven't met any biomedical engineers that studied abroad and came back to work for the government." – Interview respondent*

Equipment quality may also impact a plant's long-term sustainability. When procurement specifications do not adequately consider equipment quality, plants may be selected based on price only, risking selection of lower-quality products that decrease in function or stop working altogether after a shorter time.

> *"[The PSA plant is] ... install[ed], [and] within a few months, [the] compressor heats up and doesn't work properly, [and the] O2 purity reduces ... [We] can see corrosion on the machine within a year [and] can understand [that it is] not [up to] quality standard. [Another branded] PSA plant works for longer even if not maintained." – Interview respondent*

Recommendations and next steps

Addressing the causes of plant failure is critical for preventing common issues from arising in the first place. There are several solutions across the entire plant life cycle that can help alleviate some of the common issues (**Figure 9**).

Figure 9. Solutions to common issues across the entire pressure swing adsorption (PSA) plant life cycle.

Planning and decision-making

- Increase involvement of biomedical engineers / facility managers in equipment purchasing decisions.
- Develop ownership transition plans for donated plants beyond the initial warranty/coverage period.
- Improve understanding of the total cost of ownership for oxygen generation plants and proactively allocate budget toward preventative and corrective maintenance accordingly.
- Stipulate operations and maintenance training for facility staff in plant procurements.*

Installation and training

- Perform independent inspection after initial installation of PSA plant by a third party not involved in procurement (quality check).
- Ensure provision of graphic-rich operating and maintenance manuals and spare parts list in the local language.*

Operations and maintenance

- Upskill on-site technicians by training then on how to assess plants and how to obtain support (e.g. when to report to service provider, which suppliers to contact, what technical language to use to place spare part orders, etc.).
- Explore alternative ownership models and service-contracting mechanisms that more appropriately fit facility contexts.
- Embed preventative maintenance checks of plants into routine facility tasks.

Other factors

- Improve countries' biomedical engineering capacity through educational, training, and retention programs.
- Explore mitigation strategies for low-quality power with grid operators and/or facility managers (e.g. voltage stabilizers, backup generators, etc.).
- Design robust procurement specifications that effectively consider manufacturing quality.

** If operations and maintenance by facility staff are relevant in business model.*

Specifically, each stakeholder can ensure sustained plant operations and prevent future disrepair by taking the steps laid out in **Table 3**.

Table 3. Steps for stakeholders to take for sustained plant operations and preventative maintenance.

Stakeholder type	Concrete actions that can be taken
Decision-makers	
Donors	• Quantify the total cost of ownership of purchased plants in each context of use and add costs to existing budget considerations. • Build robust plant ownership transition plan with plant recipients.

Stakeholder type	Concrete actions that can be taken
Public procurement entities	• Involve biomedical engineers / facility managers in plant-purchasing decisions. • Stipulate in tenders the provision of independent quality checks, training, operating and maintenance manuals,* and spare part lists in the applicable local languages. • Explore different service-contracting mechanisms that would be the most appropriate for the facility context and incorporate them into the tenders. • Quantify the total cost of ownership of purchased plants and ensure costs are considered in the total procurement value.
Ministries of health	• Develop procurement guidelines for oxygen generation plants that consider the entire life cycle of a plant from procurement to disposal. Refer to PATH's procurement guide for oxygen delivery devices (if useful). • Develop service standards to be met by maintenance providers. • Evaluate and deploy incentives that reduce response, service, and turnaround times by maintenance service providers (e.g., performance-based contracting). • Design robust procurement specifications that are appropriate to local operations and stipulate their use in procurement. Refer to the WHO technical specifications on pressure swing adsorption plants (if useful). • Quantify the total cost of ownership of purchased plants and ensure adequate budget allocation. • Develop biomedical engineering / technician training programs. • Deploy talent retention schemes that provide biomedical engineers / technicians fair compensation, work-life balance, and clear growth and development trajectories. • Evaluate alternative ownership models and service-contracting mechanisms that allow for greater cost-benefits and more efficient use of oxygen generation plants (e.g., equipment leasing programs, subscription models, etc.). • Consider coordinating or aggregating spare parts purchasing across regions to obtain more favorable purchasing conditions.
Ministries of finance / national treasuries	• Quantify the total cost of ownership of purchased plants and ensure adequate budget allocation, especially for preventative and corrective maintenance. • Ensure timely payment of plant procurement and operational needs.
Suppliers	
Oxygen generation plant suppliers	• Provide alternative ownership models and service-contracting mechanisms that allow for higher cost-benefits of oxygen generation plants across different contexts. • Ensure compliance with procurement and service standards. • Expand geographical presence to adequately service equipment in a timely manner. • Provide sufficient training, as well as operating/maintenance manuals* and spare part lists, in the applicable local languages. • Ensure production capacity that aligns with preventative maintenance needs and develop spare parts stockpile where appropriate.

Stakeholder type	Concrete actions that can be taken
Implementers	
Health facility managers	• Advocate for involvement in plant-purchasing decisions. • Build robust plant ownership transition plan with donors. • Ensure total cost of ownership of plant is incorporated into facility budgets for the entire life span of the plant. • Embed recurring plant assessments into routine facility tasks and develop clear processes to become aware of and respond to issues in a timely manner. • Deploy talent retention schemes that provide biomedical engineers / technicians with fair compensation, good work-life balance, and clear growth and development trajectories. • Request training of plant operators when there is staff turnover.
Oxygen generation plant operators	• Ensure understanding of how to assess plants and when and how to reach out for support. • Embed recurring plant assessments into routine tasks.

** If relevant in business model.*

Concluding remarks

Collectively, the global community is at a critical juncture to ensure the sizeable investments made to strengthen oxygen ecosystems during the COVID-19 pandemic are realized in the years to come. As the bulk of these investments went toward purchasing PSA plants, sustaining plant function will be a crucial element of safeguarding these investments. By understanding the common issues that arise in PSA plants and their potential causes, the global community can better prioritize interventions that more effectively prevent future disrepair.

Implementing the recommendations in this report would not only foster a more sustainable PSA plant ecosystem but also strengthen the medical device ecosystem, as many issues highlighted in this report also plague other medical devices. As such, interventions to address the potential causes of failure highlighted in this report should consider other medical devices to actualize even greater health impact and cost savings.

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For more information

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