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Optimizing Medical Oxygen Production Asset Lifecycle Performance: A Multidimensional Assessment of PSA Plant Readiness, Reliability and Sustainability

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Abstract: Pressure swing adsorption (PSA) oxygen plants have become important health-system assets, particularly where hospitals seek to strengthen local access to medical oxygen and reduce dependence on external supply chains. Yet installed production capacity does not necessarily translate into a reliable oxygen service. PSA performance also depends on electricity, supporting infrastructure, maintenance, technical competence, quality assurance, safety, distribution, and the institutional capacity to sustain these functions over time. This study examined the lifecycle performance of nine hospital-based PSA oxygen installations, including six existing plants that had undergone rehabilitation and three newly deployed installations. Data were obtained through document review, structured interviews, direct inspection, and technical measurements. Assessment domains included needs–capacity alignment, site and equipment readiness, electrical supply, oxygen production and quality control, infrastructure, maintenance, spare parts, workforce capacity, safety, distribution, operational records, and sustainability arrangements. Rehabilitation restored several previously unavailable components and recovered substantial technical capability. Most installations were technically capable of meeting their intended production requirements, although vulnerabilities remained outside the PSA generator itself, including electrical instability, infrastructure and ventilation deficiencies, incomplete safety arrangements, maintenance-contract risks, gaps in operational records, and weak longer-term sustainability mechanisms. Cross-site analysis suggested a useful distinction between installed capacity, operational capacity, service-delivery capacity, and sustainable performance. These states are not proposed as a maturity model or new framework, but as analytical boundaries for understanding where asset value may be preserved or lost between installation and clinical service. Optimizing PSA assets therefore requires attention not only to whether equipment functions, but to whether safe, quality-assured oxygen can be produced, delivered, and sustained under actual operating conditions.

Keywords: *Medical Oxygen; Pressure Swing Adsorption; PSA Oxygen Plant; Asset Lifecycle Management; Healthcare Technology Management; Asset Performance; Maintenance; Reliability; Sustainability; ISO 55000.*

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I. INTRODUCTION

Medical oxygen is an essential therapeutic resource used across emergency care, surgery, anaesthesia, intensive care, neonatal and paediatric services, and the management of severe hypoxaemic conditions [1–3]. Persistent gaps in oxygen availability became particularly visible during the COVID-19 pandemic, when many health systems experienced sharp increases in demand while relying on supply arrangements that were not always able to respond reliably [4–6,8].

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Hospital-based pressure swing adsorption (PSA) production has increasingly been used to strengthen local oxygen supply. PSA systems separate oxygen from ambient air and can reduce dependence on externally supplied cylinders or liquid oxygen where electricity, infrastructure, maintenance, and technical capability are adequate [1,2]. Their usefulness, however, depends on more than the nominal capacity of the generator.

- *The presence of a PSA plant does not, by itself, guarantee oxygen availability to patients.*

Unlike many stand-alone medical devices, a PSA installation functions as part of a broader technical system. The generator depends on compressors, air-treatment equipment, receivers, boosters, control systems, and monitoring devices. These components depend in turn on electricity, ventilation, suitable technical spaces, and appropriate environmental conditions. Once oxygen has been produced, pipelines, manifolds, cylinders, filling systems, storage areas, and transport arrangements determine whether it reaches the services for which the installation was intended [1–3].

Maintenance, spare parts, trained personnel, quality assurance, and operating procedures add further dependencies. Evidence from hospital oxygen programmes has repeatedly shown that equipment procurement alone does not guarantee reliable oxygen access when infrastructure, maintenance, workforce capability, distribution, and organizational arrangements remain weak [9–16].

This creates an important problem for equipment-performance assessment. A PSA plant may be commissioned and technically functional while still being unable to provide the intended oxygen service continuously. Conversely, deterioration of individual components does not necessarily mean that the entire installation has reached the end of its useful life if rehabilitation can restore dependable operation [14–16].

- *The issue is therefore partly one of how performance is defined.*

If a PSA plant is considered mainly as a piece of equipment, assessment tends to focus on whether the generator operates, whether the oxygen concentration falls within specification, and whether nominal output can be achieved. If the same installation is considered as a healthcare physical asset system, the question becomes broader: can the installation continue to provide the required quantity and quality of oxygen, at the required level of availability, under the technical, organizational, and financial conditions in which it actually operates?

This wider perspective is consistent with lifecycle-oriented asset management. ISO 55000:2024 places value realization, organizational objectives, lifecycle management, and the relationship between performance and risk at the centre of asset management [17]. ISO 55001:2024 further emphasizes lifecycle planning and operations, decision-making, risk and opportunity management, information, knowledge, and sustained value from assets [18]. In healthcare, the value of an oxygen-production asset is therefore not represented by the physical installation alone. It lies in the clinical service that the installation is able to sustain.

The present study examines PSA oxygen production from this lifecycle perspective. It does not seek to introduce a separate asset-management framework for oxygen infrastructure. Instead, it uses observations from newly deployed and rehabilitated installations to examine how technical functionality is translated into operational capability, oxygen-service delivery, and longer-term performance.

The objectives were to: (1) examine hospital PSA installations from a lifecycle asset-performance perspective; (2) identify technical, infrastructural, organizational, and sustainability factors influencing performance; (3) distinguish equipment functionality from effective oxygen-service delivery; and (4) derive practical implications for lifecycle optimization of medical oxygen production assets.

II. CONCEPTUAL BACKGROUND

- *PSA Plants as Healthcare Physical Asset Systems*

A PSA installation occupies an intermediate position between medical equipment and hospital infrastructure. Although the oxygen generator forms the technological core of the installation, the resulting service depends on a combination of physical assets, utilities, technical processes, and human capabilities.

At production level, the system generally includes air compression, air treatment, adsorption, oxygen storage, pressure control, monitoring, and, depending on configuration, cylinder-filling equipment. Downstream elements may include medical gas pipelines, manifolds, cylinders, pressure regulators, flowmeters, and transport arrangements [1–3].

The surrounding infrastructure is equally important. Electrical supply must be adequate and sufficiently reliable. Ventilation and environmental conditions must remain compatible with equipment operation. Production and cylinder-handling areas require appropriate access and safety arrangements, while backup systems must be capable of supporting service continuity when the normal supply is interrupted [1,2,19].

The practical boundary of the PSA asset therefore extends beyond the generator.

From the hospital's perspective, the relevant output is not simply a volume of oxygen measured at the plant outlet. What matters is whether oxygen of appropriate quality, quantity, pressure, and continuity is available where clinical care is delivered.

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For this reason, the PSA installation is considered here as a **healthcare physical asset system**, rather than as an isolated item of equipment.

- *Functionality Is Necessary but Does Not Fully Describe Performance*

Functionality remains fundamental. A non-functional oxygen generator cannot fulfil its intended purpose.

The limitation arises when functionality becomes the main or only measure of performance.

A generator may produce oxygen within specification while recurrent electrical interruptions substantially reduce its availability. Another plant may have adequate production capacity but insufficient filling or downstream distribution capability. A third installation may be operating satisfactorily at the time of assessment while its future performance remains uncertain because maintenance funding, spare parts, or specialist technical support have not been secured.

These situations represent different performance conditions even though the core production equipment may be described as functional.

Experience from oxygen programmes in low-resource settings supports this broader interpretation. Effective oxygen interventions have generally combined equipment with infrastructure, clinical and technical training, maintenance, monitoring, and institutional support [11,16,20]. More recent studies examining oxygen ecosystems and PSA programmes have similarly emphasized that an oxygen source, by itself, is not sufficient to guarantee reliable access [12,13].

Functionality is therefore an important component of performance, but it is not equivalent to performance.

- *A Lifecycle View of PSA Performance*

The lifecycle considered in this study extends from the identification of oxygen needs through capacity planning, acquisition or rehabilitation, site preparation, installation, commissioning, operation, maintenance, quality assurance, distribution, performance monitoring, and longer-term renewal or sustainability.

These stages are connected.

Sizing influences the ability of the system to respond to future demand. Site preparation affects equipment reliability. Procurement choices influence spare-parts availability and maintainability. Training affects operation and first-line maintenance. Maintenance influences availability and remaining useful life. Performance information supports later decisions about repair, rehabilitation, expansion, or replacement [21–24].

Lifecycle performance is therefore not simply the sum of individual technical activities. It reflects how effectively these activities remain connected around the service expected from the asset.

III. MATERIALS AND METHODS

- *Study Design*

A multi-site observational technical assessment was undertaken across nine hospital-based PSA oxygen installations.

Six were existing installations that had undergone rehabilitation following previous deterioration or technical failure. Three were newly deployed plants undergoing installation, commissioning, or transition toward routine operation.

The study used information collected during a structured technical and operational assessment rather than an experimental intervention.

To preserve confidentiality, the country, hospitals, geographical locations, manufacturers, suppliers, financing arrangements, equipment models, serial numbers, and identities of individual respondents are not reported. Sites are identified only by anonymized letters where differentiation is required.

- *Data Collection*

Information was collected from four complementary sources.

First, available technical and administrative documentation was reviewed. This included equipment characteristics, previous technical assessments, rehabilitation documentation, maintenance information, specifications, and available operational records.

Second, structured interviews were conducted with personnel involved in hospital administration, engineering, maintenance, PSA operation, and oxygen distribution.

Third, each installation and its supporting infrastructure were physically inspected. Particular attention was given to production equipment, electricity, ventilation, building condition, cylinder-filling and storage areas, manifolds, distribution arrangements, and safety provisions.

Fourth, portable instruments were used where appropriate to verify selected technical parameters, including oxygen concentration and relevant electrical or environmental conditions.

The use of several information sources allowed documentary evidence to be compared with actual site conditions. For rehabilitated installations, previously documented equipment condition could be compared with reported maintenance activities and with the condition observed during the assessment.

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➢ *Assessment Domains*

The assessment covered:

- correspondence between identified oxygen needs and production capacity;
- site suitability and installation conditions;
- condition and functionality of PSA components;
- electrical supply and backup arrangements;
- ventilation and environmental conditions;
- oxygen production capability;
- oxygen quality assurance;
- preventive and corrective maintenance;
- spare-parts arrangements;
- maintenance and warranty provisions;
- technical workforce capacity;
- pipeline and cylinder distribution;
- filling, storage, handling, and transport;
- safety and fire protection;
- operational records and periodic checks; and
- longer-term sustainability arrangements.

These domains were examined together because weaknesses outside the generator could substantially alter the effective performance of the oxygen service.

➢ *Data Analysis*

Data analysis was conducted in two stages.

First, evidence from technical documentation, interviews, direct observations, and field measurements was triangulated for each installation. For rehabilitated plants, documented pre-intervention conditions were compared with reported maintenance and rehabilitation activities and with the technical condition observed during the assessment. For newly deployed installations, the analysis focused mainly on readiness for routine operation, including equipment condition, supporting infrastructure, utilities, quality assurance, maintenance arrangements, distribution capability, and technical support.

Rather than treating individual observations as isolated deficiencies, the second stage examined how they could affect the ability of each installation to fulfil its intended oxygen-service function. Observed issues were considered in relation to six interdependent domains: **technical capability, enabling infrastructure and utilities, maintenance and supportability, quality and safety, distribution capability, and organizational sustainability**. Particular attention was given to dependencies capable of limiting overall performance even when the PSA generator itself remained functional.

Cross-site comparison was then used to identify recurrent differences between nominal technical capability and capacity effectively available for service delivery. This comparison showed that binary functional/non-functional classification did not adequately represent the conditions observed. Some installations had technically functional production equipment but remained exposed to limitations involving electricity, distribution, maintenance continuity, safety, or supporting infrastructure. Conversely, rehabilitation restored several previously unavailable components without necessarily resolving all system-level constraints.

Four progressively broader performance states were consequently used to organize the findings: **installed capacity**, referring to production capability physically installed or restored; **operational capacity**, referring to the portion of that capability that could be reliably operated under actual site conditions; **service-delivery capacity**, referring to the extent to which produced oxygen could reach intended users; and **sustainable performance**, referring to the conditions required to preserve that service over time.

These states were used as analytical distinctions rather than predefined scoring categories. No numerical weighting or composite performance score was applied. The analysis remained descriptive and comparative, with the purpose of identifying where technical capacity was preserved, constrained, or potentially lost between installation and sustained oxygen service.

IV. RESULTS

➢ *Rehabilitation Restored Significant Technical Capability*

The rehabilitated installations showed substantial recovery of previously unavailable equipment.

Components previously reported as non-functional or degraded—including air-treatment equipment, compressors, oxygen-generation units, pressure-boosting systems, and backup manifolds—had, in several cases, returned to service following corrective work, preventive maintenance, and replacement of parts.

These observations show that loss of function at component level did not necessarily indicate that the complete installation had exhausted its useful life.

Targeted rehabilitation recovered productive capability already embedded in the installed asset base.

Restored component functionality, however, did not eliminate every constraint affecting the wider oxygen system.

➢ *Installed Capacity Was Generally Appropriate, but Nominal Capacity Was Not Always Equivalent to Usable Capacity*

Most installations had production capacities broadly consistent with the needs for which they had been installed or rehabilitated. Available measurements and quality-control information also indicated that oxygen concentration generally remained within the expected range for PSA-generated medical oxygen.

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One installation nevertheless remained unable to meet the full intended service requirement despite rehabilitation of its principal production equipment because an additional pressure-boosting component was still required.

More generally, theoretical generator output did not always correspond to the amount of oxygen that could actually be made available to users.

Effective capacity also depended on electrical availability, compressor and booster performance, downtime, filling capacity, and downstream distribution arrangements.

The observations therefore distinguished **installed production capacity** from **practically usable oxygen-service capacity**.

➢ *Electricity Was a Major Operational Dependency*

Electrical infrastructure appeared repeatedly as an important condition for PSA performance.

Several facilities had both primary and backup power sources, yet voltage fluctuations, supply interruptions, limitations in backup arrangements, fuel-storage constraints, or transfer-system issues could affect production continuity.

These problems did not necessarily originate within the PSA generator.

A plant could remain technically functional while oxygen production stopped because another physical asset—the electrical system—was unstable or unavailable.

This distinction matters for performance monitoring. Recording every interruption simply as PSA downtime risks obscuring the true cause and may lead to inappropriate corrective action.

Experiences elsewhere have similarly shown that continuity of oxygen service can be compromised by infrastructure and power constraints even when oxygen-producing equipment is available [13,19].

➢ *Infrastructure Conditions Influenced Equipment Performance*

Basic site and installation conditions were generally acceptable, although infrastructure deficiencies remained at several sites.

Observed issues included inadequate or partly non-functional ventilation, incomplete building-maintenance arrangements, and physical or environmental conditions requiring corrective measures.

These observations illustrate the difficulty of managing PSA equipment independently from the infrastructure housing it.

A compressor may receive preventive maintenance on schedule while operating in a technical room with inadequate ventilation. Maintenance compliance can therefore appear satisfactory while the wider reliability risk remains significant.

➢ *Safety Was Unevenly Integrated into Asset Performance*

Several productions, cylinder-filling, or manifold areas did not have all expected fire-protection provisions at the time of inspection. Other observations concerned access control, physical separation, cylinder movement, and safe circulation between technical and clinical areas.

These conditions did not necessarily prevent oxygen production during the assessment.

They nevertheless matter when performance is viewed from an asset-management perspective.

An installation that delivers the required output while exposing personnel, patients, or infrastructure to avoidable risk cannot reasonably be regarded as fully performing.

Safety is therefore part of the value expected from the asset rather than an external consideration applied only after technical functionality has been established.

➢ *Maintenance Recovered Value but Continuity Was Not Always Secured*

The rehabilitated plants provided a practical illustration of what maintenance can achieve.

Previously unavailable components returned to operation following corrective intervention, preventive maintenance, and replacement of parts. Maintenance therefore recovered productive capability from assets in which considerable capital had already been invested.

From a lifecycle perspective, this represents preservation of asset value rather than merely completion of maintenance activities.

Maintenance continuity, however, remained a potential vulnerability.

Some maintenance arrangements were approaching expiry. In others, the scope, intervention frequency, responsibilities, or contractual conditions required greater clarity.

This becomes particularly important during the transition from externally supported installation or rehabilitation to routine institutional management.

A plant may leave the commissioning or rehabilitation period in good technical condition and subsequently deteriorate if maintenance funding, specialist support, and spare-parts supply are not secured.

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Previous studies of oxygen equipment have similarly shown that relatively modest maintenance interventions can extend asset life, but only where technical support, spare parts, and maintenance capability remain available [14–16].

- *Technical Personnel Were Available, but Competence Requires Continuity*

Personnel responsible for routine operation or maintenance were identified at most sites and generally had relevant technical backgrounds.

Maintenance tools and portable oxygen-analysis equipment were also available in several facilities.

Initial supplier training, however, cannot be considered equivalent to lifecycle competence.

Equipment condition changes with age, staff turnover occurs, and troubleshooting becomes more demanding as components deteriorate. The relevant question is therefore whether the organization can retain sufficient capability for routine inspection, preventive maintenance, quality testing, fault diagnosis, safety, documentation, and timely escalation when specialist support is required.

This interpretation is consistent with ISO 55012, which emphasizes people involvement and competence as part of sustained asset-management performance [28].

- *Quality Assurance Extended Beyond Oxygen Concentration*

Several facilities had oxygen analyzers, trained personnel, testing procedures, and quality records.

Differences remained in the consistency with which tests were scheduled, recorded, and communicated.

This distinction matters.

A concentration measurement indicates the condition of oxygen at a particular point in time. For that result to support clinical assurance, it must also be recorded, communicated, interpreted, and acted upon when necessary.

Quality assurance therefore involves a chain of:

testing → recording → communication → corrective response.

It should consequently be regarded as an organizational process surrounding the production asset rather than as an isolated technical measurement.

- *Distribution Defined the Effective Boundary of the Asset*

Oxygen reached clinical services through direct pipelines, cylinders, or combinations of the two.

The assessment therefore extended beyond production equipment to include manifolds, filling systems, cylinders, storage areas, regulators, flowmeters, transport equipment, and circulation arrangements.

At some installations, production infrastructure was available while parts of the downstream cylinder system remained incomplete or were not yet fully operational.

This creates a fundamental distinction between technical production and clinical availability.

From an engineering perspective, a PSA installation might be considered to end at the plant outlet.

From a health-service perspective, the useful system extends much closer to the patient.

Oxygen that has been successfully produced but cannot reliably reach its intended user represents only partially realized asset value. This interpretation is consistent with studies showing that oxygen availability should be assessed across the complete delivery pathway rather than simply by the presence of an oxygen source [9–13,30].

- *Actual Performance Data Were Less Consistently Available Than Design Data*

Theoretical production capacity could generally be determined from equipment specifications.

Actual production over time was less consistently documented.

At some facilities, monthly production information remained unavailable or required updating, particularly where plants had only recently entered service.

This creates a practical management problem: an organization may know what an installation **was designed to produce** without knowing with equal confidence what it **actually delivers**.

Similar challenges have been reported in health-facility oxygen assessments, where equipment availability and nominal capacity do not always provide sufficient evidence of actual service performance [9,10].

Routine recording of a limited set of indicators—operating hours, oxygen output, concentration, downtime, failure events, maintenance interventions, cylinder-filling activity, and interruptions in oxygen availability—would allow performance to be followed longitudinally rather than only during periodic assessments.

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WHO guidance on equipment management and computerized maintenance systems also emphasizes the value of inventories, maintenance histories, scheduled activities, failure information, and performance indicators for evidence-based management [21–24].

➢ *Sustainability Remained Broader Than Technical Readiness*

The broadest gap concerned the mechanisms needed to preserve performance over time.

Individual sites demonstrated varying combinations of technical personnel, maintenance support, quality control, and operational organization.

What was less consistently evident was an integrated approach linking maintenance financing, spare-parts supply, workforce development, quality assurance, performance information, electricity, and future renewal.

Sustainability therefore cannot reasonably be treated as an issue that begins only when an asset becomes old.

Many of its determinants are established much earlier, during planning, procurement, contracting, installation, and commissioning.

Table 1. Cross-Site Summary of PSA Asset Lifecycle Performance Observations

Site	Asset status	Production / needs alignment	Infrastructure & utilities	Maintenance & technical support	Distribution / service readiness	Main lifecycle issue
A	Newly deployed	Capacity aligned with intended need	Generally adequate; selected safety provisions incomplete	Maintenance support established	Distribution transitioning to routine use	Transition from installation to sustained operation
B	Newly deployed	Capacity aligned with intended need	Supporting infrastructure generally adequate	Longer-term maintenance available; contractual clarity requires attention	Clinical distribution available	Maintenance governance and performance monitoring
C	Newly deployed	Capacity aligned with intended need	Electrical and supporting infrastructure remain operational dependencies	Longer-term technical support available	Distribution established or being operationalized	Consolidation of operational readiness
D	Rehabilitated	Restored capacity broadly aligned with need	Utility and infrastructure dependencies remain	Previously unavailable components restored; continuity requires attention	Oxygen distribution available	Preservation of recovered performance
E	Rehabilitated	Restored production capability; full service requirement not completely covered	Supporting systems influence effective capacity	Major components rehabilitated	Distribution available but effective service capacity constrained	Gap between restored production and required service capacity
F	Rehabilitated	Production capability restored	Electrical reliability remains relevant	Corrective and preventive interventions restored functionality	Distribution available	Utility-related continuity risk
G	Rehabilitated	Capacity broadly consistent with intended service	Infrastructure generally functional with selected safety/environmental issues	Maintenance restored technical capability	Pipeline and/or cylinder distribution available	Safety and infrastructure integration
H	Rehabilitated	Production capability restored	Supporting infrastructure remains part of performance boundary	Maintenance present but continuity or	Distribution capability available	Maintenance sustainability

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				contractual provisions require attention		
I	Rehabilitated	Capacity broadly aligned with need	Infrastructure and utilities influence reliability	Technical capability recovered through rehabilitation	Distribution arrangements available	Long-term preservation of recovered capacity

Note: Sites are intentionally anonymized. The table summarizes dominant lifecycle observations and is not intended as a numerical ranking of site performance. "Aligned" refers to correspondence between assessed production capability and the service requirement identified during the technical assessment.

V. DISCUSSION

➢ *From Installed Capacity to Sustainable Performance*

The principal analytical finding concerns the different meanings that can be contained within the word *capacity*.

A PSA system may have **installed capacity** because equipment has been purchased, installed, or restored.

Only the portion that can operate reliably under actual technical and environmental conditions represents **operational capacity**.

Operational production becomes **service-delivery capacity** when oxygen can reliably reach the clinical services or other users for which the investment was intended.

Maintaining that capability over time requires maintenance, competent personnel, spare parts, quality assurance, energy, financing, information, and organizational responsibility. This broader condition is referred to here as **sustainable performance**.

Thus:

Installed capacity → Operational capacity → Service-delivery capacity → Sustainable performance

These states should not be interpreted as successive maturity levels. Rather, they represent **different performance boundaries through which the same asset system can be observed**.

The distinction matters because progression from one boundary to the next is not automatic.

Installed capacity can be lost before becoming fully operational. Operational production may fail to become effective clinical service. A system delivering oxygen today may remain vulnerable if maintenance, financing, technical support, or performance information are not secured.

This interpretation is consistent with existing evidence. Graham et al. showed that effective oxygen programmes depend on interacting clinical and technical elements rather than equipment alone [11]. Smith et al. similarly described oxygen access as an ecosystem involving production, distribution, maintenance, training, financing, and institutional capacity [12]. Their later qualitative assessment of PSA programmes showed directly that the presence of an oxygen source was not sufficient to guarantee effective service [13].

➢ *The Performance Constraint May Lie Outside the Main Equipment*

One recurring observation across the installations was that overall performance could be constrained by the weakest critical element of the service chain.

- A functioning generator could not compensate indefinitely for unstable electricity.
- Adequate oxygen production could not overcome insufficient distribution.
- Preventive maintenance had limited protective value where spare parts or specialist support were uncertain.
- This type of dependency can be overlooked when healthcare assets are managed one equipment item at a time.

For PSA installations, electricity, ventilation, building conditions, distribution, and safety are particularly important because they may initially be treated as installation requirements and then receive less attention once the generator has been commissioned.

The present findings suggest that these supporting elements should remain within the performance boundary throughout the lifecycle.

➢ *PSA Performance Is Better Understood as a System Property*

Taken together, the observations suggest that PSA performance emerges from interaction among:

equipment + infrastructure + electricity + maintenance + people + quality assurance + distribution + safety + information + governance.

The contribution of each element is not necessarily equal.

At one installation, electrical stability may dominate performance. At another, maintenance continuity, ventilation, distribution capacity, or technical support may become the principal constraint.

This variation supports an adaptive interpretation of lifecycle management.

The underlying principles of value, lifecycle thinking, risk, evidence-based decision-making, and continuous improvement can remain stable [17,18]. What changes is the configuration and relative importance of the factors through which those principles are expressed for a particular class of healthcare assets.

➢ *Rehabilitation as a Lifecycle Decision*

The recovery of several previously unavailable components provides another important observation.

Technical failure should not automatically lead to replacement.

Research on oxygen equipment in resource-constrained environments has shown that maintenance capability and targeted repair can substantially extend service life [14–16]. The appropriate intervention, however, depends on condition, supportability, demand, and remaining useful life.

For PSA installations, the choice between repair, rehabilitation, and replacement should therefore consider residual useful life, expected reliability after intervention, spare-parts availability, technical support, energy requirements, clinical demand, safety, lifecycle cost, and the consequences of failure.

- This is more appropriately viewed as an **asset-management decision** than as a simple maintenance decision.
- A well-targeted rehabilitation can preserve asset value.
- Repeated repair of equipment that is obsolete, inefficient, unsafe, or no longer supportable may do the opposite.

➢ *From Maintenance Completion to Performance Preservation*

Healthcare technology management programmes have traditionally used preventive-maintenance completion as an important management indicator [21–23].

For PSA infrastructure, this remains useful but does not provide a complete picture.

A maintenance intervention may be completed on schedule without necessarily demonstrating that availability, output, safety, quality, or service continuity have been preserved.

A stronger performance question is therefore not simply:

Was maintenance performed? but: **Did maintenance preserve the performance required from the asset?**

This shifts the emphasis from **maintenance activity management** toward **asset performance preservation**.

Preventive-maintenance compliance remains part of the picture, but it should be interpreted alongside downtime, failure frequency, oxygen output, quality results, energy interruptions, and service availability. Evidence-based maintenance approaches similarly argue for using failure and performance information to improve maintenance decisions rather than relying solely on scheduled activity completion [26,27].

➢ *Operational Data Are Part of the Asset-Management System*

The difference between known theoretical capacity and incomplete longitudinal production information deserves particular attention.

ISO 55000 and ISO 55001 emphasize information and knowledge as important inputs to lifecycle decision-making [17,18]. ISO 55013 extends this principle specifically to the management of data assets [29]. WHO guidance on medical equipment management likewise recognizes maintenance histories, inventories, schedules, and performance information as essential management resources [21–24].

For PSA installations, even a relatively small dataset could substantially improve decision-making.

Operating hours, actual production, oxygen concentration, failure events, downtime, maintenance interventions, electrical interruptions, filling activity, and oxygen-service interruptions would provide a more realistic picture of performance than nominal design capacity alone.

Such information could subsequently support decisions about maintenance intervals, rehabilitation, capacity expansion, energy resilience, spare-parts planning, and replacement.

➢ *Performance Boundaries and Healthcare Asset Assessment*

A broader implication of the study concerns the boundary at which healthcare asset performance is assessed.

- The same installation may appear to perform differently depending on where the system boundary is drawn.
- At the equipment boundary, the relevant question is whether the generator functions.
- At the operational boundary, the question becomes whether the generator and its supporting technical systems can operate reliably.

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- At the service boundary, attention shifts to whether oxygen reaches the intended users.
- At the lifecycle boundary, the concern becomes whether this service can be preserved over time.

This leads to an important observation:

- ➢ *Healthcare asset performance is partly a question of where the system boundary is drawn.*

A narrow boundary may show a functioning device.

A broader boundary may reveal vulnerabilities involving electricity, infrastructure, quality assurance, distribution, maintenance, information, or governance.

This interpretation helps explain why counts of available or functional oxygen equipment, although useful, may not fully represent access to reliable oxygen service [9,10,13].

- ➢ *Relationship with Lifecycle Management of Diagnostic Assets*

PSA installations share several lifecycle-management principles with diagnostic technologies, but their dependency structures differ.

Diagnostic systems may depend heavily on reagents, consumables, calibration, quality-control materials, software, connectivity, workflow, and operator competence.

The PSA observations place comparatively greater emphasis on the interaction between:

production technology ↔ infrastructure ↔ electricity ↔ environmental conditions ↔ distribution ↔ maintenance ↔ safety ↔ technical workforce.

The difference suggests that healthcare assets do not necessarily require a separate comprehensive framework for every technology.

A common lifecycle logic can be maintained while the operational determinants of performance are adapted to the characteristics of the asset class concerned.

For PSA systems, the performance boundary therefore extends beyond production equipment toward a wider **production-and-distribution asset system**.

- ➢ *Scientific Contribution*

The contribution of this study lies less in proposing another model for medical oxygen management than in reconsidering the boundary at which healthcare asset performance is assessed.

The observations show that the same PSA installation may appear differently depending on whether performance is examined at equipment, operational, service-delivery, or lifecycle level.

A generator may be technically functional while the production system remains operationally constrained. An operational plant may provide less service than expected because of downstream limitations. An installation delivering oxygen today may remain vulnerable if maintenance, information, financing, or technical support are not secured over time.

The distinction between **installed capacity, operational capacity, service-delivery capacity, and sustainable performance** therefore provides a way of locating where value is preserved or lost across the asset lifecycle without reducing performance to a single functionality indicator.

This perspective does not replace established asset-management principles. Rather, it provides an asset-specific interpretation of how those principles become visible in a complex healthcare production system.

VI. IMPLICATIONS FOR LIFECYCLE OPTIMIZATION AND PERFORMANCE MEASUREMENT

The findings suggest that PSA investments should be followed from the original health-system requirement through to sustained oxygen availability.

A practical performance logic can be expressed as:

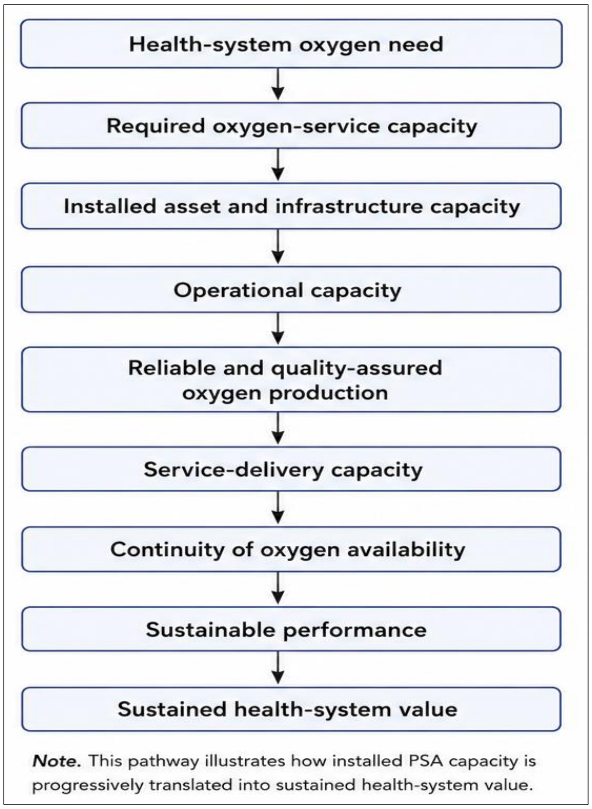

Fig 1 : PSA Asset Lifecycle Performance Pathway (simplied)

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This sequence is not intended as a new framework. Its purpose is to make visible where value may be lost between investment and service delivery.

For example, an installation may have adequate installed capacity but fail to convert all of it into operational capacity because of unreliable electricity. Another may achieve stable production while downstream distribution limits service-delivery capacity. A third may provide the expected service today but have weak maintenance arrangements that threaten future performance.

Looking at these transitions can help managers select appropriate interventions rather than treating every performance problem as an equipment failure.

Performance monitoring should similarly combine several dimensions.

- For asset condition and reliability, relevant indicators include operating hours, availability, failure frequency, preventive-maintenance compliance, repair time, and critical spare-parts availability.
- For production and quality, indicators may include actual versus expected production, oxygen concentration, pressure, production interruptions, and non-conforming quality results.
- For service delivery, relevant measures include pipeline availability, cylinder-filling capability, oxygen-service interruptions, and the extent to which intended demand is covered.
- For lifecycle sustainability, monitoring may include maintenance financing, continuity of technical support, workforce competence, electrical reliability, quality-assurance capability, spare-parts security, operational-data completeness, and renewal planning.

At this stage, combining these dimensions into a single numerical score may obscure more than it reveals. Keeping them visible separately makes it easier to identify where performance is being lost and what type of intervention is required.

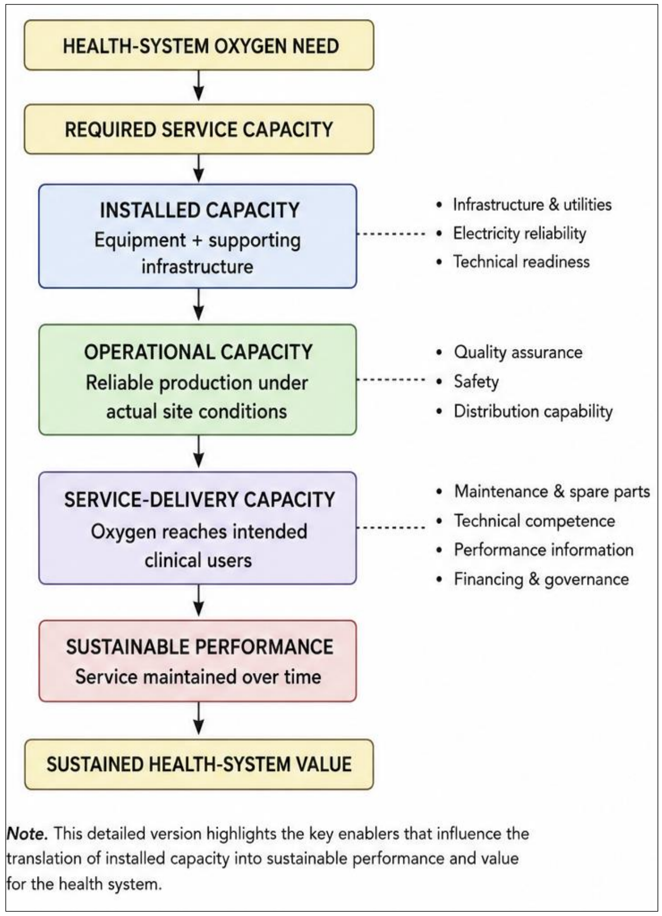

Fig 1 : From Installed PSA Capacity to Sustainable Oxygen-Service Performance

The figure represents analytical performance boundaries rather than maturity levels or a formal asset-management framework. The factors shown between boundaries illustrate conditions that may enable or constrain the conversion of technical capacity into sustained oxygen-service value.

VII. STUDY LIMITATIONS

Several limitations should be considered when interpreting the findings.

First, the assessment represents conditions observed during a defined period and therefore provides a cross-sectional view of assets whose reliability and performance evolve over time.

Second, actual production, downtime, and maintenance histories were not equally complete across all installations. This limited quantitative comparison between nominal capacity and realized output.

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Third, newly deployed and rehabilitated assets were at different stages of their lifecycle. Direct comparison between the two groups should therefore be made cautiously.

Fourth, the study focused on technical and organizational asset performance rather than patient-level clinical outcomes, formal cost-effectiveness, or total lifecycle cost.

Fifth, the four performance states used in the analysis were derived from cross-site interpretation and were not subjected to formal maturity-model or psychometric validation. They should therefore be understood as analytical performance boundaries rather than standardized categories.

Finally, confidentiality requirements required removal of contextual information that might otherwise help explain some differences between individual installations.

Future studies should examine PSA performance longitudinally and link equipment condition, electricity, maintenance expenditure, actual production, quality, downtime, service interruptions, and lifecycle costs. Such work could also test whether the performance-boundary distinction is transferable to other infrastructure-dependent healthcare assets.

VIII. CONCLUSION

The assessment of nine hospital-based PSA installations suggests that medical oxygen production assets cannot be adequately evaluated through equipment functionality alone.

The oxygen generator remains central to the system, but the service it provides depends on infrastructure, electricity, maintenance, quality assurance, distribution, safety, technical competence, information, and organizational arrangements.

The distinction between **installed capacity, operational capacity, service-delivery capacity, and sustainable performance** provides a useful way of interpreting these dependencies without introducing another formal asset-management framework.

- These states represent different boundaries from which performance can be observed.
- Installation confirms that technical capacity exists.
- Operational performance determines whether that capacity can be used reliably under real conditions.
- Service-delivery performance determines whether the resulting oxygen reaches the intended users.
- Lifecycle performance determines whether that service can be preserved over time.
- This changes the interpretation of investment success.

Installation and commissioning remain important milestones, but they represent the beginning rather than the endpoint of performance management. Technical capacity must remain usable, oxygen quality must be assured, distribution must remain available, and the technical, human, financial, and organizational conditions required to preserve service must continue throughout the useful life of the asset.

The relevant unit of performance is therefore not only the PSA generator, but the **oxygen service sustained by the complete asset system**.

Lifecycle optimization should seek to minimize the loss of value between **installed technical capacity and sustained clinical service**.

The practical question for healthcare asset managers is no longer simply:

Does the asset work? but: **Does the asset continue to deliver the service for which the health system invested in it?**

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