# SOX – Sustainable off-grid oxygen concentration with direct solar power

Final report: October 2017

Author: Per-Erik Eriksson, MSF Sweden Innovation Unit

Funded by: MSF OCA Sapling Nursery

Project owner: OCA

# Executive summary

The aim of this project was to explore the possibilities of producing concentrated medical grade oxygen with direct solar power during daytime and store it as compressed gas for night-time use. This could help facilitate solar power implementation in MSF by avoiding an extensive need for battery backup. An increased use of solar power would be beneficial from an environmental and social sustainability perspective (increased possibility for local actors to maintain healthcare facilities after handover).

Oxygen therapy can be a lifesaving intervention for children and neonates, as well as adults with pneumonia or hypoxemia. It is also used for anesthesia and a range of other different health conditions. In MSF projects, the use of oxygen is increasing exponentially and is projected to continue due to new treatment methods for neonates and more complex medical operations overall.

The project has investigated the current oxygen usage in MSF field projects, the current challenges and costs for oxygen provision, as well as the market availability and costs for oxygen storage solutions. Furthermore, a direct solar power solution has been tested together with a low-pressure oxygen storage prototype at the Éspace Bruno Corbé in Brussels.

The overall conclusion of this work is that the economically most promising solar powered solution would take around three years to pay-back the initial outset costs, when compared to the standard oxygen concentrators, generally powered by diesel generators. This solution consists of low-pressure storage of oxygen produced with standard concentrators — with a possible pipe distribution network connected. This option has been verified through tests in this project, but requires further development and implementation of a pipe distribution system to the patients.

The second most promising option might be high-pressure storage at larger oxygen volume needs than those originally assumed in the current project. An equipment found at the end of the project may result in a time to pay-back between three and four years, but has not been verified through our tests. The main advantage of high-pressure storage would be the transportability of the compressed oxygen in bottles for outreach movements/ambulances as well as to more remote wards in a hospital compound.

Finally, battery storage of electricity for continuous power to standard concentrators is still a valid alternative with roughly the same time to pay-back as the low-pressure storage solution. This option has been verified earlier in field projects but has the disadvantage of relying on batteries, with a limited service life and continuous replacement costs.

## Recommendations

- Develop a robust and simple pipe distribution system for oxygen to patients in field hospitals.
- Partner with the supplier of the tested low-pressure storage prototype in order to resolve some remaining development issues.
- Perform a field project test of solar powered low-pressure storage and pipe distribution.
- In combination with the suggested field test, a high-pressure filling station should preferably also be tested.

# Project timeline

**April 2016** – A conversion from diesel generator to solar power at Shamwana hospital, DRC is initiated for OCA project handover to local MoH in August 2016.

**August 2016** – Shamwana solar power installation is finalized and project is handed over. The design of the solar power system indicates a potential to find alternatives to battery storage for continuously powered oxygen concentrators.

**November 2016** – OCA and SIU jointly apply for, and receives funding for the innovation project from the MSF Sapling Nursery fund.

**January 2017** – The project is initiated with SIU as project manager and with a multidisciplinary stakeholder group from OCA and engagement from the MSF intersectional Biomed Working Group.

**January-March 2017** – A research phase consisting market research of available equipment, an assessment of oxygen needs in OCA field projects and an assessment of fuel consumption and running cost of current oxygen supply equipment.

**March-September 2017** – Setting up of a prototype for testing high-pressure storage of oxygen encounters severe problems due to a lack of available off-the-shelf system components (primarily small scale high-pressure compressors) and has to be aborted.

**April 2017** – A solar power system for testing is set up at the EBC in Brussels.

**April-May 2017** – A low-pressure storage prototype product is developed and supplied by UK-based company Diamedica.

**May-September 2017** – Testing of solar powered production and low-pressure storage of oxygen is performed without and with a minimal amount of battery back-up respectively.

**September 2017** – The Sapling Nursery project is finished and recommendations for continued development are agreed by OCA and the Biomed WG.

# Acknowledgements

The financial support from the Sapling Nursery is gratefully acknowledged, as is the support from the OCA stakeholder group for the project, the intersectional working group and the MSF Sweden Innovation Unit team. We are also very grateful to the OCB staff at the Éspace Bruno Corbé in Brussels for making the space available and for helping with many practical bits and pieces around the testing as well as to Diamedica (UK) Limited for developing and providing the low-pressure oxygen storage prototype for the tests.

Finally, the author would like to express special thanks to OCA flying electrician Ingo Kurzweil for helping to set up the solar power system during two hectic days in April and to Joel Bosrup, former OCA techlog in Maniema, DRC, who spent a whole week of his vacation in Brussels to help me with the tests.

# Table of content

# 1. Background

Solar power offers huge possibilities for increased sustainability (social, economic as well as environmental) for most MSF field operations. While this is widely acknowledged by field workers, fundraisers and energy experts in MSF, the implementation has been very slow, hampered e.g. by the need for battery storage for continuous energy supply and perceived implementation complexity. High cost has also previously been an issue but lately the cost for solar panels has plummeted.

Oxygen therapy is a potentially lifesaving intervention for children, neonates or adults with pneumonia and hypoxemia. It is also used for anesthesia and a range of other different health conditions. In MSF projects, the use of oxygen is increasing exponentially and is projected to continue doing that due to new treatment methods for neonates and more complex medical operations overall. MSF has so far chosen to use the small movable oxygen concentrators, developed for home-use by patients, primarily for safety reasons since high pressure gas bottles may pose fire/explosion risks if handled improperly or subjected to fire. While this is certainly important for field projects, often in conflict settings, we believed that the alternatives to the current technology should now be carefully examined. One major reason for avoiding bottled oxygen is to avoid the risks with transporting the filled bottles to the project, whereas the idea here is to have the production within the project facilities.

Movement-wide in MSF, the number of concentrators in use is believed to be at least 2,000, as of 2016 (section 3.1). Since the concentrators require a lot of energy, this is now one of the primary energy consumers in many projects, which also contributes to logistical challenges. To power a single oxygen concentrator (5 liters/minute – LPM – capacity) continuously with generator electricity, requires over 100 liters of diesel per month (section 3.2).

*Figure 1. Current normal system for provision of medical oxygen in off-grid MSF field hospitals*

This project was initiated to explore the possibilities of producing concentrated medical grade oxygen with direct solar power during daytime and store it as compressed gas for night-time use within the field project premises, thereby eliminating a major need for batteries in a solar powered MSF hospital. The inspiration came from the implementation of a solar power solution for the OCA hospital project in remote Shamwana, DRC, before handover to the local MoH. In this project, a solar power system was built for the entire hospital operation (which was downsized) after project handover. The major part of the system was required for continuous operation of a single 5 LPM oxygen concentrator. No less than 10 solar PV panels (nominal effect 250W each) and 12 lead batteries (12 V, 120 Ah each) were required for this. These batteries have a maximum lifespan of approximately three years.

*Figure 2. Solar power system for medical oxygen in Shamwana hospital after handover*

# 2. Initiation phase

The primary objective of the current project was to:

1. Survey available equipment on the market.
2. Design a solution that would serve a selected, typical project setting.
3. Assemble and evaluate potential candidate equipment for a prototype system.

This would be done under controlled conditions in order to verify the following parameters:

- Feasibility of direct drive solar power under various sunlight conditions.
- Delivered quantity of oxygen per input energy quantity.
- Quality of delivered medical grade oxygen (>90% oxygen).
- Safety in handling compressed oxygen bottles/tanks.
- Maintenance/usability.
- Cost for equipment and operation (oxygen concentration/filling plus solar energy system) compared to current solutions.

If a prototype could be assembled from off-the-shelf components, the project would aim to plan a test under field conditions in a suitable project.

A stakeholder group was formed in OCA for detailed project directions and reference, consisting of:

- Lizette van der Kamp, Biomed referent (Replaced by Séan King)
- Jaap Dominicus, Energy referent
- Jaap Karsten, Paediatrics advisor
- Marit de Wit, Health advisor, Field Support Unit
- Jaap van der Woude, Front officer, Field Support Unit

The intersectional Biomed Working Group (WG) has also been significantly involved in the discussions during the project as has also the energy referents of all OC:s.

The stakeholder group detailed the demands on a prototype basic module system as:

- Primarily aimed at a hospital operation in a rural off-grid setting (like sub-Saharan Africa).
- Capacity need approximately 10 LPM continuously (to be verified from project assessments).
- No, or minimal, use of batteries.

# 3. Research

## 3.1 Oxygen usage in field projects

Oxygen can be provided either in high-pressure bottles (or liquefied in developed contexts) or via oxygen concentrators. MSF has chosen to use standard concentrators as the primary method, complemented with high-pressure bottles in certain contexts. There are no overall statistics of the current usage volumes, neither from concentrators nor bought in bottles, since patient prescriptions are not registered and follow-ups like for other drugs are not made.

Statistics from OCA, compiled for this project, shows that the number of concentrators is increasing exponentially. The number delivered from Amsterdam Procurement Unit (APU) to the projects has increased from 14 in 2005 to 31 in 2010 and 161 in 2015, see Figure 3. In addition, OCA estimates that around 30% extra are purchased locally (either concentrators or bottles) due to import, supply or energy limitations. The total number of concentrators in service currently is also shown in the graph, with the assumption of 5 years' service life.

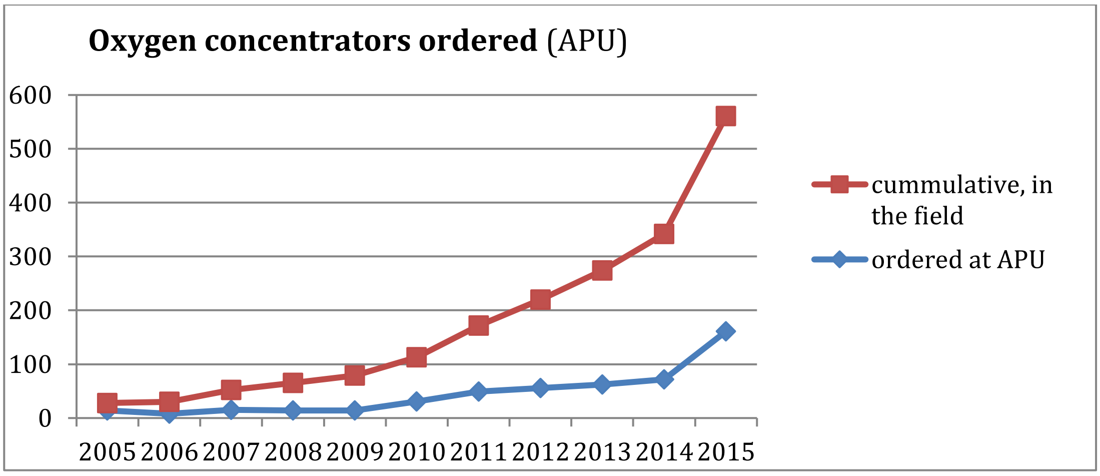

*Figure 3. Exponential growth usage of oxygen concentrators in MSF-OCA (data: APU – Amsterdam Procurement Unit). Cumulative quantity in the field is calculated by assuming an equipment-lifetime of 5 yrs.*

Based on the Logistics Reporting in OCA, an estimation was made of oxygen usage, based on reported concentrator runtime hours for 4 sample projects in 2016. In addition, a detailed study was carried out during four weeks in March-April 2017 at the Mweso hospital project in DRC (OCA), providing an estimate of actual oxygen volume usage in relation to concentrator runtime hours (maximum delivery capacity). This is summarized in Table 1.

The conclusion of this is that the original estimates from the Shamwana project of roughly 10 LPM continuous usage (out of the maximum 12 LPM based on runtime) seems to hold – and the data seems reasonably scalable with the size of the hospital (in number of beds) for a general hospital operation. The Mweso study indicates that the concentrators in service are used at an average of 75% of their full capacity. The exception in the table – Haiti-Cruo – is a specialized neonatal hospital and is also partly supplied with locally purchased bottled oxygen. However, it should also be noted that most of this data is not validated well enough to be used for any general conclusions on oxygen usage in MSF. Still, for the current project, it serves as a basis for sizing the prototype equipment as a basic module with 10 LPM continuous capacity or 14.4 $m^3$ of oxygen (>90% concentration) per 24 hours.

*Table 1*

| **Project** | **Total capacity based on runtime/year** (m3/year) | **Capacity** (LPM) | **Actual usage** (LPM) | **Size hospital** (# of beds) |
|---|---|---|---|---|
| **DRC – Shamwana** | 6,200 | 12 | | 70 |
| **Haiti-Cruo*** | 12,000 | 23 | | 250 |
| **Afghanistan – Helmand**** | 60,000 | 113 | | 700**** |
| **DRC – Mweso***** | | 50-64 | 35-45 | 250 |

* Haiti-Cruo also uses oxygen bottles
** Filtered data by Biomed back-officer OCA; some strange high- and negative numbers are taken out. Not completely reliable data
*** From detailed survey Jan-April 2017
**** Uncertain figure

## 3.2 Energy use and running cost estimates

The energy consumption of the oxygen concentrators is significant. In Table 2, the power draw for the two standard types of concentrators in MSF as well as the one used in the tests in this project are listed.

*Table 2*

| **Type** | **Capacity* (LPM)** | **Effective capacity @ >90% oxygen concentration (LPM)** | **Specified power at effective (>90%) capacity (W)** | **Power draw per LPM** >90% (W)** | **Energy per $m^3$ oxygen >90% (kWh)** |
|---|---|---|---|---|---|
| **DeVilbiss 525** | 5 | 5* | 312* | 62* | 1.04* |
| **AirSep Newlife Intensity 10 LPM (MSF current standard)** | 10 | 9 | 590 | 66 | 1.09 |
| **AirSep Newlife Intensity 8 LPM** | 8 | 7 | 410 | 59 | 0.98 |

**) For the AirSep Newlife Intensity concentrators, according to the specifications[1], the produced oxygen may have concentration <90% at full capacity. This has been verified in the tests whereas the corresponding performance of the DeVilbiss concentrator has not been tested.**) This applies only at effective full capacity operation.*

As can be seen in Table 2, the three concentrators are fairly similar in power consumption per produced volume of concentrated oxygen. For an estimation of energy needs we can therefore assume that roughly 1 kWh is consumed per $m^3$ of oxygen produced (1 $m^3$/hour corresponds to 16.7 LPM). If the concentrator is delivering less than this amount to patients, see previous section, the energy consumed per $m^3$ of oxygen will be higher.

---

[1] http://www.chartindustries.com/Respiratory-Healthcare/Stationary-Oxygen-Concentrator/NewLife-Elite-Intensity

The least expensive way of supplying the power is most likely always via the power grid – but in a majority of MSF's field project this is not available at all or not sufficiently reliable. Most current concentrators are therefore presumably supplied by diesel generator power. In this project, the presumed scenario is a hospital project in an off-grid location. Therefore, the cost for power supply is based on the fuel cost for diesel generators.

Unfortunately, there are currently no reliable estimates within OCA of the typical fuel consumption for generators per delivered kWh. Therefore we need to estimate from manufacturer data and some specific field observations.

The fuel consumption of an SDMO 9KM generator (8.6 kW capacity and MSF standard) at optimal operation (100% load) is 0.36 l/kWh according to manufacturer specifications[2]. At 50% load, the specification says 0.49 l/kWh. However, the generators are often run at even lower loads, especially for oxygen concentrators (and lights) at nights. The estimate from the Shamwana hospital project was that the average consumption of the generators was at least 0.6 l/kWh, i.e. an average load below 50% of generator capacity. This seems likely, since there was not sufficient battery backup for the hospital at night-time for shutting off the generator. According the OCA energy referent, an acceptable average would be 0.5 l/kWh, which will be used here for the cost estimate.

The cost for fuel per liter at the project locations is unfortunately another unknown, primarily due to limited follow-ups of transportation cost specifically for the fuel. In the Katanga mission in DRC, the assumed diesel cost in 2016 was 1.1 €/l, which was the purchase cost in Lubumbashi. The transport from Lubumbashi to Shamwana (3-6 days each ways on MSF trucks) added roughly 1 €/l to that cost. Whether or not this is representative for the actual fuel cost at field project location in OCA is unknown – but for this study, an estimated 2 €/l will be used for calculations. Further, a cost for maintenance and depreciation of generators could be included – but this is ignored here, since it is assumed that a generator would be needed for other equipment in the project and as back-up power.

In conclusion, based on the assumptions above, we can assume that the average fuel cost for producing 1 $m^3$ of oxygen would be approximately 1€. Converted to a fuel cost for one concentrator, this would mean that the yearly fuel cost to power a DeVilbiss 525 concentrator would be approximately 2,700 € and for an AirSep Newlife Intensity 10 LPM (at 9 LPM capacity), 5,200 €, i.e. several times the concentrator investment cost. This is at full capacity of the concentrators, so in reality, the figure would be somewhat higher (see previous section).

## 3.3 Market assessment of oxygen storage equipment

The overall conclusion from the market assessment is that none of the equipment suppliers interviewed have thoroughly considered the possibility of using solar power for their equipment. Some of them have had questions about this from clients – but there seems to be almost no ongoing commercial development anywhere in the world.

The project started with the objective of primarily finding equipment for oxygen generation combined with high pressure compression (bottle filling stations), see figure 4. An extensive market search was performed and a number of suppliers were identified (see Annex A). However, it fairly quickly turned out that the packaged small-scale solutions from all manufacturers found at that stage would be at too high a cost (too long pay-back time) compared with our current technology. The primary reason for this is presumably that the concentrators are produced for a large homecare market, whereas the oxygen generator stations are small series equipment for

---

[2] http://www.sdmo.com/EN/Products/PPR/Power-gen-products/T9KM

hospitals. For the equivalent oxygen production capacity, the oxygen generators are normally 3-6 times more expensive than the concentrators. Most often they also require significantly higher power input. It should be noted that the guaranteed concentration of oxygen from the generators may be somewhat higher than from the standard concentrators, but the latter still meet the >90% specification within MSF.

In addition, the high-pressure compressors add even more to the price of a complete system for oxygen filling. There is a very limited supply of such compressors, since medical oxygen requires completely oil-free compressors. A further factor is presumably that the investment cost is normally compared only with the relatively high cost of bottled oxygen supply – not with the cost using standard oxygen concentrators, since this is normally not considered as the primary alternative outside MSF.

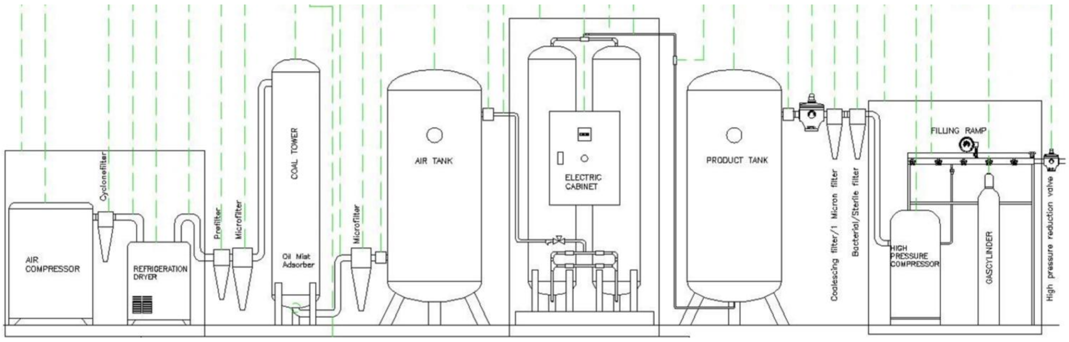

*Figure 4. Schematic drawing of an oxygen generators and filling station. Note that all steps up until the product tank are in principle included in a standard oxygen concentrator.*

An attempt was therefore made to find a stand-alone high pressure compressors that could match the oxygen concentrator specifications in production volume and output pressure. Unfortunately, it was not possible within the timeframe of the current project to get one for testing purposes, due to a combination of delays of market introduction for a new compressor from one manufacturer and too short time for delivery from another.

Towards the end of the project, we found one more manufacturer that is particularly interesting for a potential follow-up project. They may be able to supply both an oxygen generator and a compressor at 10 LPM capacity at lower prices (see the lower end of the price range in the table below) and with a relatively low power consumption. Potentially, there may also be another couple of interesting alternatives to this supplier. It should also be noted that one of the suppliers has a larger capacity generator, 70 LPM, with a more attractive pricing per produced volume, which may be interesting for our larger scale projects. The power requirement for this equipment is 7 kW.

Unexpectedly, low pressure storage technology – that had not been the primary focus at the beginning of the project – turned out to be very interesting and could furthermore be verified through the tests. Although there is basically no such product on the market currently that would fit the needs in this project, the only available commercial supplier, Diamedica, assembled a prototype for our test purposes. This does not fit the demand on storage capacity currently – but can relatively easily be developed to do so.

In Table 3, the different equipment options are summarized for an assumed continuous consumption of 10 LPM of oxygen. The direct solar power is assumed to be available for 8 hours per day on average and thus the production capacity during that time needs to be 3 times higher for the first three alternatives than for the last two with constant power supply. An investment interval is given for each system option based on market prices supplied by the manufacturers, excluding the solar power system needed. In Table 4, advantages and disadvantages with each technology option are listed.

*Table 3*

| System | Suppliers, examples | Stage | Capa-city | Storage volume | Power requi-rement | Equip. investment (excl power system) |
|---|---|---|---|---|---|---|
| Concentrators + low-pressure storage (6-10 bar) | Diamedica, (Global Good, FreO2) | Proto-type tested | 3*10 LPM (20 LPM stored) | 1600 liter/day storage (6 bar) | 1.5-2 kW | €8-12,000 (excl piping) |
| Concentrators + high-pressure compressor (150 bar) | Rix, Novair, Özcan Kardesler, CanGas, Wenling etc | Not tested | 3*10 LPM (20 LPM stored) | 64 liters storage | 2.5-3 kW | €15-25,000 |
| Oxygen generator + high-pressure (150 bar) | AirSep, Novair, Özcan Kardelser, CanGas, etc | Exists | 30 LPM (or 10 + 20 LPM) | 64-96 liters storage | 3-6 kW | €20-40,000 |
| Concentrator + solar power + batteries (cont. power supply) | AirSep | Exists | 10 LPM | Batteries (approx 20*12V/ 120Ah) | 5-600 W | €6,000 (backup needed) |
| Concentrator + generator (cont. power supply) | AirSep | Stan-dard | 10 LPM | Fuel | 5-600 W | €2,000 (backup needed) |

*Table 4*

| System | Advantages | Disadvantages |
|---|---|---|
| Concentrators + low-pressure storage | • High volume delivery to patients for peak needs<br>• Relatively inexpensive and robust equipment<br>• Relatively low safety risks<br>• Low operation cost | • Bulky gas storage<br>• Requires pipe system for distribution (or small tanks with short duration) |
| Concentrators + high-pressure compressor | • High volume delivery to patients for peak needs<br>• Easy handling of supply to different wards<br>• Usable for outreach/ambulances<br>• Efficient storage of oxygen<br>• Low operation cost | • Additional safety issues for gas handling and storage<br>• Relatively advanced compressor<br>• Medium investment cost |
| Oxygen generator + high-pressure (packaged) | Same as above | Same as above plus:<br>• High power demand<br>• High investment cost |
| Concentrator + solar power + batteries (cont. power supply) | • Relatively easy handling of supply to different wards<br>• Low safety risks<br>• Relatively low investment cost | • Limited volume delivery for peak needs<br>• Battery storage costly and needs regular replacement |
| Concentrator + generator (cont. power supply) | • Relatively easy handling of supply to different wards<br>• Relatively easy to increase system capacity by adding concentrators<br>• Low safety risks<br>• Low investment cost | • Limited volume delivery for peak needs<br>• High running cost<br>• Continuous fuel supply logistics required<br>• Ecologically unsustainable |

In addition, it can be noted that the pipe delivery system required (or almost required) for the low pressure storage system has advantages in terms of patient comfort as well as infection control, since the concentrators would not be moved between and operated close to patients. On the other hand, a simple but robust pipe system would have to be developed/identified and implemented in field project hospitals.

Furthermore the storage systems may also be interesting for a generator power solution, since a more efficient generator usage during daytime can lower fuel consumption per produced volume of oxygen. If there is sufficient battery backup capacity for other nighttime power consumption, the generators can then be kept off for the night.

## 3.4 Safety

There are always a certain number of safety considerations and precautions to be taken around handling high concentration oxygen, since the oxygen will increase the combustion in a potential fire (while not being a flammable gas itself). Open fire, smoking and oil/grease should always be avoided – this is the case for concentrators also.

When compressing oxygen, the safety issues are even more important, primarily for the following reasons:

- The amount of stored concentrated oxygen in one place will increase and potential leakage is difficult to detect.
- Piping used to supply patients from a storage tank or cylinder may be susceptible to leakage.
- High pressure storage of any gas poses a potential danger, should the pressure cylinder or valves rupture.

These safety issues were raised as a major concern at the initiation of the project. However, through the course of the project it has become evident that the risks should not be a factor for not pursuing the proposed development route. Bottled oxygen is still used in a large proportion of MSF projects and the safety risks seem to be reasonably mitigated – even though the handling also involves transportation of the high pressure bottles to the project locations.

However, no proper protocol for the handling and use of oxygen cylinders currently seem to exist in any of the sections. There is an OCP document that outlines a procedure, including how ready bottled oxygen should be procured and transported (which is not applicable in this project). This document seems to be a well formulated and complete procedure description and could most likely be agreed upon, for example by the Biomed WG, and implemented as an intersectional standard procedure.

# 4. Tests

All practical tests of equipment were performed at OCB's Éspace Bruno Corbé (EBC) in Brussels.The EBC is a very good place for testing and demonstration, since many MSFers pass through the center for trainings. The only disadvantage was the slightly unpredictable Belgian sun…

*Poster at Brussels/Charleroi airport.*

## 4.1 Solar power test setup

The solar power system was designed to produce a steady solar power output of 1.1 kW (AC at 220V) over as many hours as possible over the day. The reason for this was that all equipment found require a constant AC power to operate properly and the design power was for one 10 LPM oxygen concentrator and a corresponding high pressure compressor.

This can be achieved with a tracking system, which always orients the panels directly towards the sun. But since solar PV (photovoltaic) panels have now become relatively inexpensive, it is cheaper to have an overdesigned PV panel array with fixed positions and an optimized orientation to achieve the same purpose. From initial measurements, it was determined that the geometry of the setup should be to orient half the panels directly to the east and half to the west, all at a 60 degree inclination, see figure 5.

*Figure 5. Solar panel orientation, used for the tests*

This way, the morning and evening sun can be captured relatively early and late respectively and the same panel surface will be exposed to the sun also at noon. The resulting output power from the panel chargers on a completely clear in May is shown in figure 6, which verifies this setup. This is not the highest possible energy output over the day from a certain number of PV panels. That would be achieved with all panels facing south. But since the load we design for here is constant over the day, the high output at midday would be partly unused and the morning and evening power output would have been too low compared to the load.

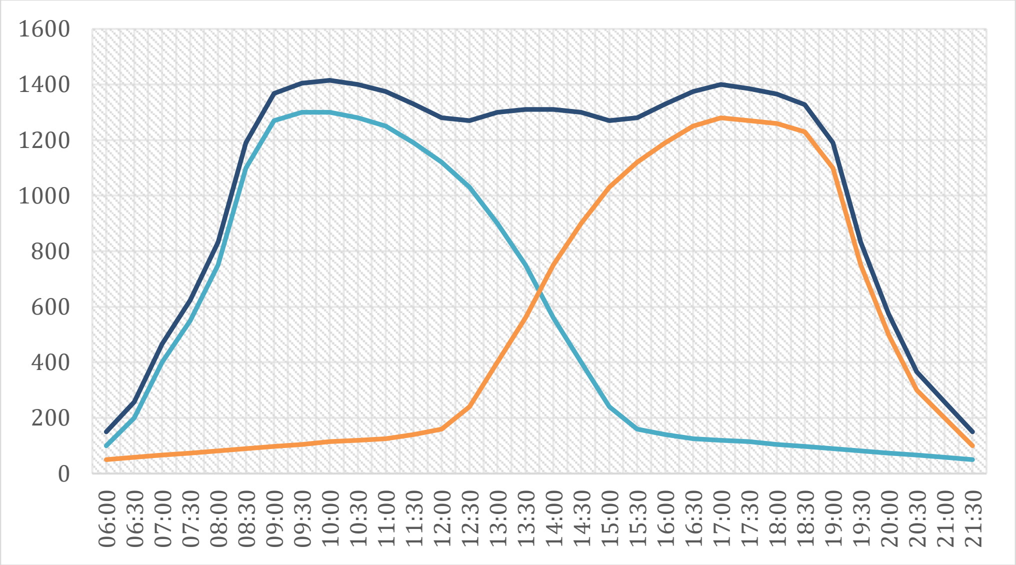

*Figure 6. Solar panel power output through charge controllers on a clear day in May at EBC in Brussels. The light blue curve shows the east side output and the orange the west side output. The curves are slightly curtailed both in the morning and evening due to some shading fences and buildings.*

Through simulations with the System Advisor Model from the National Renewable Energy Laboratory, USA[3], it has been concluded that this system setup is near optimal for most locations. In Brussels, the optimal angle should potentially have been two degrees of less inclination to increase the output slightly at noon, whereas in equatorial locations (Nairobi, Kenya and Manaus, Brazil were simulated), the inclination should be closer to 65 degrees to achieve the “flat” output power curve for a maximum number of hours. This also yields approximately the same power output and number of hours as in Brussels (in May), so the tests there are a good indication also for equatorial locations. However, in equatorial locations the increased number of hours is not as significant.

We used 12 polycrystalline PV panels with a nominal maximum output of 275 W each, connected three in series and two (times two) batches of three in parallel. From the panels, the charge current passes the two MPPT solar chargers (Victron 150V/35A, one for each side) into either the batteries or the supercapacitor, set up as a 48 V system. From there, the inverter (Victron Phoenix 48V/3000VA) creates pure sinewave DC at 220V, 50Hz. The setup is shown in figure 7.

---

[3] https://sam.nrel.gov/

*Figure 7 – Solar charge controllers, inverter and control panel for test setup.*

Due to the system losses, the maximum delivered power on the AC side is approximately 1.1 kW with the solar charge curve in the figure above, during approximately 10.5 hours in May in Brussels (approximately 8.5-9 hours year round in equatorial locations according to the simulations).

## Batteries and supercapacitor

The objective of the project is to not use batteries as storage of electricity. However, the solar panels produce a stable current in virtually any insolation (provided that there is a load) but the voltage they produce depends on the light intensity (they are a "current source"). The inverter is only capable of handling a voltage between 38 and 66V. The $V_{oc}$ (open circuit voltage) of the panels is a multiple of 37.9V ($V_{oc}$ per panel) per panel and the MPPT regulator is able to convert the panel voltage into a suitable charge voltage. But to enable its' (the MPPT regulator) functioning it needs a battery or other buffer. Two options for this were tested:

- 4 Optima Yellow top 2.7 car batteries @ 12V, 38 Ah
- Eaton XLM-62R1137-R supercapacitor @ 62V and 69 Wh storage capacity

The batteries were selected to be able to handle high charge currents, but not to provide a very significant storage. The supercapacitor does basically the same but has the advantage of a long life, a good temperature resistance, no maintenance and no toxic waste. However, it has also the disadvantage of a low storage capacity and a relatively high price. With the supercapacitor, the power will cut after only about a minute, whereas with these batteries it can keep operating roughly 15 minutes.

This is important, for example in the early morning, when the sun generates enough power to charge the supercapacitor or battery. When they reach a certain voltage, the oxygen production system would start. But the power that the solar panels can generate is not enough and the voltage drops very quickly and consequently the system stops. This will repeat itself until the sun intensity is sufficient. The same will happen in the evenings when the solar panel charge drops. These problems could be handled with e.g. a timer, a light intensity meter or a thermometer. The more difficult problems arise on a partly cloudy day. With batteries (as they have a higher capacity to store energy) the on-off sequence will be less frequent compared to the capacitor.

But in that case, every time the batteries would go through a discharge-charge cycle, which is not good for their life expectancy. If the equipment is not very sensitive to frequent starts and stops, the supercapacitor would be the best choice. This is most likely the case for e.g. a future direct solar power air conditioning solution. With the oxygen production equipment, it is more challenging since there is a certain start-up time before the oxygen concentrator/generator starts generating high enough concentration of oxygen. It is also not clear how frequent starts and stops will influence the life expectancy of the equipment. For this type of equipment, it is therefore recommended, for the time being, to use either a certain battery capacity or a manual restart procedure (after verifying that no clouds will interrupt operation for some time). Another potential solution for completely avoiding batteries could be a hybrid system with the combination of a supercapacitor and a small generator with autostart, which would only run a very limited part of the time/days in a location with fairly secure insolation.

The total cost for the solar power system with the batteries, as specified here, was €5,500 (excluding VAT), including all cabling and remote monitoring equipment. With the supercapacitor replacing the batteries, the corresponding cost would be €6,200. The MPPT charge controllers and the inverter are oversized, so the same system could be designed for a higher power output by adding only more solar panels. Thus the system cost at different power output, to be used for cost comparison of alternatives later on, can be assumed to be approximately:

*Table 5*

| **Maximum AC output (W)** | **System w batteries (€)** | **System w supercapacitors (€)** |
|---|---|---|
| 1,100 | 5,500 | 6,200 |
| 2,200 | 8,500* | 9,900* |
| 3,300 | 12,000** | 14,100** |
| 4,400 | 15,300** | 18,100** |

*) Battery and supercapacitor capacity has been scaled up according to system output power.
**) Inverter capacity has also been scaled up.

The solar power equipment used in the tests has been demounted and packed into a transportable box with the components still connected – the SOX BOX – which remains stored at EBC in Brussels the rest of 2017.

## 4.2 Oxygen generation and storage setup

The oxygen generation and storage equipment used in the tests was a prototype low-pressure storage system from Diamedica, developed from their currently available small volume storage solution. Normally, this product is used as back-up oxygen supply to keep running their anaesthesia machines in case of power failures. The systems consist of a standard oxygen concentrator, a small compressor and separate storage vessels of 120 litres.

The current prototype is installed in a plastic pallet box with an additional storage vessel installed, see figure 8. Oxygen provided by the oxygen concentrator (AirSep Newlife Intensity 8 LPM) is passed through the compressor and stored in the aluminium vessels at 6.5 bar. As used here, the power required for the system is 600 W, 220V AC. At 6.5 bar there is a storage capacity of approximately 1500 litres taking 3.5 hours to fill at full, 8 LPM, concentrator capacity. At 6.5 bar, the concentrator and the compressor are programmed to stop automatically and will then restart when the pressure in the vessels has dropped to 4 bar. These settings are adjustable.

The oxygen output from the storage vessels can be adjusted up to approximately 20 LPM flow and 2 bar pressure at present. The oxygen is delivered through a standard plastic pipe, as used normally from concentrators or flow-splitters to patients.

The function of the prototype has been verified through a series of tests, including:

- The function of the system stop-start functionality at full tanks/half-full tanks and at power cuts respectively
- Start-up time for output oxygen to reach >90% concentration (also tested with an AirSep 10 LPM concentrator)
- Oxygen concentration output at various concentrator delivery flows (also tested with an AirSep 10 LPM concentrator)

*Figure 8. The Diamedica prototype low-pressure oxygen system. The top of the oxygen concentrator can be seen to the left and the upper of the two storage vessels at the right. In the pallet box, the compressor is also installed. The prototype further contains a unit for handling varying quality grid power or 12 V solar power direct input – but these features were not used in the current tests.*

The stop-start function at continuous power supply was verified to work properly – but when the power was shut off from the solar power system, the compressor kept running due to a built-in battery back-up. This will need to be changed.

The time it takes for the concentrator to reach >90% oxygen concentration was tested with different intervals of power breach. The result was that it invariably takes 4-5 minutes until it has stabilized above 90%, regardless of the time it has been shut off. The same result was also achieved with the 10 LPM concentrator. Even for a 15 seconds shut-off time, this applied. For very short stops, the concentration will not drop all the way down to the normal air 21% due to the internal tank in the concentrator – but still to 40-50%. Therefore it can be concluded that frequent short power-cuts will affect the concentration in the storage tanks and should be avoided. For example, the oxygen from the concentrator could be vented out and the compressor started with a 4-5 minutes delay.

The output oxygen concentration was also tested at various delivery flows for the two concentrator models, with the following results at normal room temperature:

*Table 6*

| Oxygen flow (LPM) | AirSep 8 LPM, concentration (%) | AirSep 10 LPM, concentration (%) |
|---|---|---|
| 2 | 98 | 98 |
| 4 | 96 | 97 |
| 6 | 95 | 96 |
| 7 | 93 | 95 |
| 8 | 89-90 | 94 |
| 9 | | 92 |
| 10 | | 89-90 |

As can be seen, the concentration tends to fall below the MSF minimum (90%) at full capacity operation. This is in correspondence with AirSep's specifications for these models. Thus in order to have a guaranteed quality in the pressure vessels, especially if there would be a few stops and starts during the filling procedure, it is recommended to run the concentrators a little below full capacity, c.f. section 3.2. This should also be noted for oxygen delivery from the concentrators directly to patients.

On the whole, the low-pressure storage prototype from Diamedica worked well during the tests. It is assembled from well proven components. For a full-scale use of the system, however, the storage capacity would need to be upgraded to be able to contain at least one day of oxygen production – and possibly with extra capacity to cover the need for rainy days. This can be done by adding more pressure vessels of the same type or having one significantly larger. A possibility that has not yet been tested is to use large storage balloons that could be either inside a container or a robust storage room in order to avoid mechanical damage.

Unfortunately, as has been mentioned previously, it was not possible to test and verify any high pressure compressor within the current project time. This is unfortunate, since we would have preferred to see and test that type of more advanced equipment in action.

# 5. Results and conclusions

Returning to the table with the different system options from Section 3.3, we can now evaluate the complete economic implications of the different options, except maintenance cost:

*Table 7*

| System | Capa-city | Equip. invest-ment, excl power system) | Solar power invest-ment | Yearly running cost (excl mainte-nance**) | 3 year operation (invest + running cost) |
|---|---|---|---|---|---|
| Concentrators + low-pressure storage (6-10 bar) | 3*10 LPM (20 LPM stored) | €8-12,000 (excl piping) | €8,500-10,000 | - | €16,500-22,000 |
| Concentrators + high-pressure compressor (150 bar) | 3*10 LPM (20 LPM stored) | €15-25,000 | €12,000 | - | €27-37,000 |
| Oxygen generator + high-pressure (packaged) (150 bar) | 30 LPM (or 10 + 20 LPM) | €20-40,000 | €12-20,000 | - | €32-60,000 |
| Concentrator + solar power + batteries (cont. power supply) | 10 LPM | €6,000* (backup needed) | €5,000* | €1,500 (3 year battery replacem.) | €15,500 |
| Concentrator + generator (cont. power supply) | 10 LPM | €2,000 (backup needed) | - | €5,200 (fuel) | €17,600 |

*) Batteries already included in equipment investment

**) Maintenace cost is naturally important, especially for the more advanced options but at this point we lack data and experience

From the table, it is evident that the pay-back time for both the solar powered concentrator and low-pressure storage system and the solar and battery powered concentrator can be as short as three years.

The high-pressure storage systems will take from five years up to around ten years to pay-back (for the packaged generator/filling station systems). At the lower end, this could potentially be a possible solution but even that might be too long for the time horizon of normal MSF projects. A potentially interesting alternative could be a combination of a low-pressure storage system and a small high-pressure storage complement. Another highly interesting option is available for larger projects, as mentioned in section 3.3. At a total investment cost, including the solar power system, of around €50,000, there is an available equipment for producing 70 LPM of oxygen and compressing 50 LPM. Compared with generator powered concentrators, this would give a pay-back time of between three and four years.

Between the low-pressure and battery storage solutions, the major differences are the need for a piping system for the former versus the negative (environmental) impacts of the replaced batteries plus the additional cost over more years for battery exchange for the latter.

By also including the environmental effects of diesel combustion (primarily the contribution to global warming) in generators – and the solar power alternatives contribution to increased sustainability of a healthcare facility after an MSF project handover, it should be clearly evident that one of the two solar powered alternatives would be preferable.

However, if MSF anyway chooses to continue primarily with generator power, the oxygen storage solutions are anyway interesting for more optimal generator usage and the possibility of not running them during e.g. the night.

Based on the conclusions above, the following recommendations can be made:

- Develop a robust and simple pipe distribution system for oxygen to patients in field hospitals.
- Partner with the supplier of the tested low-pressure storage prototype in order to resolve some remaining development issues.
- Perform a field project test of solar powered low-pressure storage and pipe distribution.
- In combination with the suggested field test, a high-pressure filling station should preferably also be tested.