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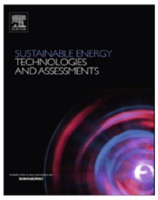

Original article

A review of sustainable energy access and technologies for healthcare facilities in the Global South

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ABSTRACT

Access to reliable, affordable and sustainable energy is essential for improving living standards, development and economic growth. From a healthcare perspective, energy is a critical parameter for delivering and improving healthcare services and life-saving interventions in the Global South. This review provides an estimation of the energy needs of different healthcare facilities as a function of patient capacity and services provided. It also presents the strengths and limitations of several energy sources that can be used to meet these needs. The review focuses on energy provision in off-grid scenarios and for satisfying peak demands of grid-connected hospitals.

The initial key observations are that fossil-fuel generators are the main energy source because of their low investment costs. However, this technology can no longer compete with the energy produced from renewable sources in terms of levelized cost of electricity (LCOE). Photovoltaics (PV) has an LCOE of 0.09 USD/kWh, versus an average 0.25 USD/kWh for diesel generators. Moreover, PV is a modular technology that can efficiently meet energy demands in an environment-friendly way. Wind turbines share many strengths of PV and yet both technologies suffer from intermittent energy sources. They must therefore be coupled with a storage system that provides continuous and stable electricity. Today, energy is mainly stored electrochemically, in the form of lead-acid batteries. However, this review shows that nickel-metal hydride (NiMH) should be used when possible for their higher energy density (200 Wh/l versus 80 Wh/l), non-toxicity, safety and simple maintenance. Alternatively, lithium-based batteries should be used when the energy density and number of cycles is a priority. Other energy production means (e.g., hydropower) and storage technologies (e.g., flywheels) are reviewed as well.

In conclusion, the optimal energy solution for medium-to-large healthcare facilities, especially for those in off-grid settings, is a hybrid system wherein the strengths of a renewable energy source coupled with efficient batteries is combined with a diesel generator to minimize the LCOE.

Introduction

Energy access is essential for improving living standards, development and growth. Today, 1.3 billion people still lack access to electricity, while the global electricity demand is growing almost twice as fast as the total energy consumption. Energy access is particularly crucial for health facilities as electricity is needed to store vaccines and perform life-saving operations [1]. Challenges such as fuel shortages, high energy costs, global warming and environmental issues must drive policies that target more affordable and sustainable energy solutions [2]. In essence, one way to overcome poverty, promote health and educational services and enhance socioeconomic development is to ensure reliable, sustainable and affordable energy for everyone. Hence, the United Nations (UN) has established "**Ensuring access to affordable, reliable, sustainable and modern energy services for everyone**" as one of its Sustainable Development Goals (SDGs) to be reached by 2030 [3]. Healthcare facilities are considered major energy consumers due to their need for reliable electricity and thermal energy supplies [4,5] for heating, ventilation, lighting, air conditioning and the use of medical and non-medical equipment [6]. Many healthcare facilities in the Global South have reduced care capabilities due to limited energy access. Despite the importance of energy issues for healthcare facilities, little attention has been given to the topic. In response, this article describes the current situation and evalu-

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ates the suitability of various energy sources for healthcare facilities in the Global South based on a set of criteria formulated by the Cooperation & Development Center's (CODEV) EssentialTech program[2] at the Ecole Polytechnique Fédérale de Lausanne (EPFL). Readers will gain insight into important considerations for choosing and managing energy systems for healthcare facilities in the Global South.

Energy access worldwide – challenges and statistics for healthcare

A country's electricity supply is an indicator of its living standards and, in the case of healthcare, the quality of services in national healthcare facilities.

Energy challenges for healthcare facilities differ for low- and high-income countries. The main challenge for healthcare facilities in low-income countries, especially those in sub-Saharan Africa, is access to reliable and affordable energy for basic vital needs [7]. Many healthcare facilities in these countries lack access to energy for basic services such as lighting, heating and the powering of medical equipment. This limits diagnostic capabilities and treatment services, reduces hours of operation to daytime hours and can result in a loss of healthcare professionals due to a lack of satisfaction (working conditions, working environment, etc.) [8]. Energy issues for healthcare facilities in high-income countries focus on improving efficiency and increasing the use of renewable energies, in order to reduce energy consumption, lower operating costs and reduce the environmental impact [9–13].

There is little reliable data on energy access in health facilities. A review led by the World Health Organization (WHO) found nationally representative data for only 14 developing countries globally, 11 of them in sub-Saharan Africa [8]. According to the 2013 Poor People's Energy Outlook, roughly 1 billion people in developing countries are without access to adequate healthcare services due to energy poverty [14]. Access to electricity—and potentially stable electricity—is the main energy challenge for healthcare facilities in the Global South that directly or indirectly affect the quality of healthcare services [7]. For instance, in Ghana, among facilities that offer routine child immunization services, 16% are limited in this endeavor by the lack of electricity or fuel to maintain the cold chain necessary for storing vaccines [15]. An unstable electricity supply can cause medical and non-medical equipment damage. Data collected from 33 hospitals in 10 countries in the Global South show that up to 70% of breakdowns are caused by voltage surges, which typically occur at the end of an outage [16]. Such events can have dramatic consequences: in 2011, a hospital in Cameroon was victim of a voltage surge from the main grid that resulted in the breakdown of 50% of its equipment (generators, medical instruments, etc.) [17]. Uninterrupted power supplies (UPS), used to protect sensitive equipment, also typically break down after only a year on average due to the poor-quality electricity supply [17].

The reliability of access to electricity supplies for healthcare facilities in some countries in the Global South are reported Table 1. The information comes from the Service Provision Assessment (SPA), a survey that evaluated the electrification of healthcare facilities in the Global South [18]. The percentage of electricity access varies depending on the type of healthcare facility. In general, larger facilities have better access to electricity.

In addition to a lack of access to a reliable electricity supply, healthcare facilities in the Global South also suffer from management-related energy issues, which directly affect the quality of the healthcare services provided. A survey conducted in four Cameroonian hospitals shows evidence of equipment damage due to a poor electricity supply, poor management of electrical installations and a lack of institutional regulations promoting energy-efficient solutions reducing the quality of services offered [17].

Table 1
Reliability of access to electricity supplies for healthcare facilities.

Country	% of facilities with access to electricity	% of facilities with stable electricity
Egypt	99	88
Ghana	71	27
Ethiopia	No data	50
Kenya	75	19
Malawi	No data	59
Rwanda	82	52
Tanzania	No data	67
Uganda	<50	<29

Classification of healthcare facilities

The most appropriate energy solution may differ from one healthcare facility to another. However, the choice of potential solutions for a facility can be improved by categorizing different types of care facilities according to their needs and challenges. This categorization is typically based on one or a combination of the following criteria: the type of healthcare services they provide, their management and ownership style, location, patient capacity, [19]. Based on the services provided and patient capacity, healthcare facilities can be divided into *hospitals* (large healthcare facilities), *health centers* (medium-sized facilities), *health clinics* (small facilities) and *health posts* [20,21].

Hospitals are the largest infrastructures in terms of patient capacity (over 120 beds) and range of services. They have full-time doctors, nurses and obstetricians as well as technical staff for the operating and maintenance of the infrastructure. Hospitals offer a large variety of services, from first aid to surgery, non-communicable disease treatment and intensive care, and house medical analysis laboratories, diagnostic equipment and storage facilities for blood and vaccines. Hospitals' average daily energy consumption ranges from 15–35 kWh, with power needs of 9 kW [20].

Health centers provide all vital services (i.e., lifesaving) such as obstetric and surgical services, and treatment for injuries and infections. They have refrigerators for vaccine storage but fewer diagnostic instruments than hospitals. One example is a lack of X-ray machines, which consume a great deal of energy. They have a lower patient capacity than hospitals (60–120 beds) and replace hospitals in smaller cities. Average energy consumption of health centers ranges from 10 to 20 kWh, with power needs of 5 kW [20].

Health clinics provide most of the vital services, such as first aid, basic surgery and obstetric services. Patient capacity can vary from 0 to ±60 beds. The staff is limited to nurses and obstetricians. Doctors from larger nearby health centers may pay regular visits, if need be. Their average daily energy consumption ranges from 4 to 10 kWh, with power needs of 2.4 kW [20].

Finally, *health posts* serve mainly as storage spaces for medicine and vaccines. Medications are distributed in rural areas by different means, mostly by health operators, who walk from village to village with backpacks full of medical supplies. Some health posts also have one or two rooms for basic operations, conducted by doctors and nurses who visit the facility periodically.

Energy needs of healthcare facilities

After classifying the healthcare facility, the next step for developing an energy-management strategy is identifying its daily

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[2] http://cooperation.epfl.ch/essentialtech-en.

energy needs [22,23]. Based on this, a range of appropriate solutions can be considered. Several factors – including the size, type, location, services, number of patients, etc. – determine a healthcare facility's energy needs [24]. As such, the overall energy demand, challenges and potential energy solutions vary from one facility to another.

Depending on its size and the services a facility offers, it must have certain equipment that requires a stable power supply in order to be used, function effectively and have a long life. This equipment can be classified into three categories: *basic services* (lighting, communication, water supply, water management and HVAC equipment); *medical equipment* (equipment, devices and machines use to diagnose, treat, monitor or alleviate disease or injury) (WHO definition of medical devices [25]); and *laboratory equipment* (devices for specific health services, e.g., vaccinations and infectious diseases) [26]. To determine daily energy needs, a list of various equipment and its power needs and use time must be drawn up. Additionally, when determining how to electrify a healthcare facility, it is important to prioritize the electrification of equipment based on its criticality to patients' survival and the facility's operation. Three categories—*non-critical, non-secured* and *secured*—have been identified. *Non-critical* refers to equipment that is not critical to patient survival, such as air ventilation in the ward. *Non-secured* refers to equipment that is critical but can handle moderate voltage fluctuations of the network and short outages, often thanks to an integrated battery. Finally, *secured* refers to equipment that is critical and needs to be protected against voltage fluctuations. This prioritization helps in effectively managing electricity production and consumption during a power shortage event.

The power and energy needs for a comprehensive list of equipment are presented in Table 2. Each piece of equipment is classified according to the categories (basic services, medical equipment and laboratory equipment) and prioritization mentioned above. Additionally, each piece of equipment is sorted according to the type of facility that can most likely afford it. The data in Table 2 comes from a USAID online database [27] and the literature [8,17,28,29].

Once the energy and power needs of each type of facility have been assessed in terms of equipment and services, it is possible to examine how these needs can be met by using various energy sources in a sustainable manner, and which category of equipment has the highest potential for energy saving. A number of end-use energy analysis studies can be found in the literature. For instance, a breakdown of the energy consumption of the equipment used in a Malaysian hospital shows lighting and biomedical equipment consumed the most energy (36% and 34% respectively) [30]. According to a 2011 United States Agency for International Development (USAID) report, the major electricity consumers in hospi-

Table 2
List of equipment together with their power and estimated daily energy needs.

Basic services				
Equipment	Power (W)	Hours used per day (h)	Energy per day (Wh/day)	Prioritization
All healthcare facilities				
Lights (fluorescent)	11	6	66	Secured
Mobile phone charger	5–20	8	40–160	Non-critical
Ceiling fan (CD, AC)	30–100	10	300–1000	Non-secured
All healthcare facilities but health posts				
Water pump	100	6	600	Non-secured
Computer	15–200	4	60–800	Non-secured
Portable electrical heater	1,000–1500	4	4000–7500	Non-critical
Radio	2–30	8	16–240	Non-secured
Only health centers and hospitals				
Printer (ink, laser)	65–1000	4	260–4000	Non-secured
Small waste autoclave	600–6000	1	600–6000	Non-critical
Medical equipment				
All healthcare facilities (except health posts)				
Sterilizer (steam)	500–1560	2	1000–3200	Non-secured
Suction	24	10	240	Non-secured
Pulse oximetry	24	2	48	Non-secured
Reverse-osmosis water purifier	260–570	8	2080–4560	Non-critical
Only health centers and hospitals				
X-ray machine (dental)	200	0.5	100	Secured
X-ray machine (portable and not)	3,000–50,000	0.5	1500–25,000	Secured
Newborn incubator	420	24	10,080	Secured
Mechanical ventilator	200	10	2000	Non-secured
Ultrasound scanner	75	2–3	150–225	Non-secured
Electrocardiogram (ECG)	50–80	0.5	25–40	Non-secured
Nebulizer	180	3–5	540–900	Non-secured
Laboratory equipment				
All healthcare facilities				
Vaccine refrigerator (165 L)	40–500	4	160–2000	Non-secured
All healthcare facilities but health posts				
Microscopes	30	2	60	Non-secured
Only health centers and hospitals				
Centrifuge	600	2	1200	Non-secured
Spectrophotometer	63	1	63	Secured
Blood chemistry analyser	45	2	90	Secured
Haematology Analyser	230	2	460	Secured
Arterial blood gas (ABG) analyser	250	0.5	125	Secured

tals in India are HVAC systems, lighting equipment and water pumps, whose electricity consumption can account for 30–65%, 30–40% and 10–12% respectively [31].

In addition to electricity, a facility may also need thermal energy for heating air and water [32]. Air temperature is crucial in healthcare facilities, as patients require warmer air due to lower metabolic rates caused by physical inactivity. Hot water is also required for laundry, cleaning, bathing, washing and cooking purposes. Certain types of equipment, such as sterilizers and autoclaves for medical waste treatment, require thermal energy (as they run on high-pressure steam). Healthcare facilities' thermal energy needs may be met by direct fuel combustion, electricity (used to run heating systems) and waste heat (a by-product of electricity production by a heat engine). The fuel-powered heat engine is one of the main units of the combined heat and power (CHP) technology, presented in a following section. However, evaluating fuel-combustion technologies and heating systems is beyond the scope of the present study. Nevertheless, the next sections presents technologies to produce and store electricity.

Once the energy needs of a healthcare facility have been identified, the next task is selecting and implementing the most appropriate and effective energy efficiency measures to minimize these needs. "Energy efficiency" refers to policies, strategies and technologies designed to reduce energy consumption, carbon emissions and costs [33–35]. Energy efficiency measures for existing healthcare facilities can be simple actions such as controlling the opening and closing of windows and switching off non-essential devices when not in use. More costly measures include replacing old equipment, adding thermal insulation and using highly efficient equipment (medical and non-medical) such as chillers, pumps, boilers, lamps, etc. [6,36]. Energy efficiency measures can also be used in new healthcare facilities that are being planned or are under construction. One example is maximizing access to natural ventilation and daylight [37]. Thanks to advances in the technological innovation of medical [38] and non-medical devices [39], building materials [40], heating, ventilation and air conditioning (HVAC) systems [41] to improve energy performance, greater potential for energy efficiency in healthcare facilities exists.

Energy sources for healthcare facilities

Once the daily energy demand has been calculated, the next step is evaluating the potential technical solutions for providing sustainable energy services. For healthcare facilities located in areas where access to a grid electricity infrastructure is available, this is usually the primary energy source. Facilities in urban areas – in both developing and developed countries – are largely connected to the national grid. Off-grid energy systems include renewable energy systems, generators, micro combined heat and power systems, batteries or a combination of two or more of the above-mentioned technologies. Off-grid power systems and on-site power generation solutions must be taken into account when there is no or unreliable access to the main grid. This is mainly the case of rural healthcare facilities in the Global South. An off-grid electricity network is also the primary energy source for urban healthcare facilities during outages, which occur regularly in most African countries and worsen during armed conflicts and natural disasters. Last but not least, the off-grid network can help urban healthcare facilities satisfy peak energy demands that cannot be met by the main grid [22].

As far as renewable energies are concerned, the Global South has great potential for increasing its use of the latter due to a combination or exclusive use of abundant sunlight [42–45], biomass [46–49], water [50–52] and/or wind [53–57], depending on the geographical location. Some of the reasons for their limited exploitation include high capital costs, diffidence towards unfamiliar technologies and concerns regarding intermittent production [58,59].

The types of energy production and storage technologies that can be directly commissioned and managed by healthcare facilities are evaluated in the following list, according to a number of criteria defined by the EssentialTech programme, at EPFL's Cooperation and Development Center (CODEV), which aims to help achieve the SDGs through the development and implementation of essential technologies in the Global South. The criteria, based on a multidisciplinary methodology developed by EssentialTech [60], address the following three complementary and interconnected aspects:

1. Technologies adapted to the local context
2. Sociopolitical factors in the value chain
3. Business model for deployment

The criteria are:

- *Safety*: The technology must comply with international norms and regulations.
- *Effectiveness*: The technology's efficacy must be proven, especially in the specific setting where it is to be deployed.
- *Durability and robustness*: Effective functioning must be guaranteed for a certain number of years.
- *Resilience to the weather environment*: The technology must be resilient to the temperatures, humidity levels and aerosol particles of a given context.
- *Resilience to the electric network*: The technology must be resilient when connected to low-quality, unreliable installations.
- *Accessibility and usability*: The technology must be easy to understand and maintain for the local population.
- *Adapted to local culture and social norms*: The technology must be accepted by the end user.
- *Marketable*: The technology must convince local users of its effectiveness.
- *Affordable*: The technology must be affordable in terms of investment costs (to purchase the technology) as well as operating and maintenance costs. These costs are often combined and referred to as levelized cost of electricity (LCOE).
- *Sustainable*: The technology must be fully maintainable, with parts produced locally.
- *Environmentally friendly*: The technology must be largely composed of environmental-friendly parts that can be easily disposed of and/or recycled.

The following sections present energy-production technologies for healthcare facilities and an assessment of their strong points and drawbacks based on the criteria presented above.

Generators

Generators run on various fuels, including natural gas, diesel, gasoline and propane. They typically power off-grid facilities and also serve as back-up power sources for grid-connected hospitals and clinics. They are the most widespread back-up energy source for healthcare facilities in the Global South. The popularity of generators is largely due to the well-established technology based on which they are designed. The advantage of using a centenary technology is low upfront capital costs, which is important in settings with limited resources. However, increasing fuel costs at the global scale and unstable fuel supply—especially during armed conflicts—to the remote areas make this technology financially less competitive than other options, especially those based on renewable technologies.

Table 3
Assessment for generators.

Criteria	Advantages and Limitations for Healthcare Centers
Effectiveness	Generators are the baseline backup energy supply for Global South healthcare facilities and are a consolidated technology.
Assembly and commissioning	Simple installation (usually); plug-n-play technology.
Durability and robustness	After one or two years they typically need repairing due to their many moving parts, especially in the warm, humid, dusty environments typical of many African and Middle East countries. In optimal operation conditions, generators are expected to withstand 25,000 operating hours [20].
Resilience to the weather environment	Moderately tolerant to high temperatures and humidity. Sensitive to dust.
Resilience to the electricity network	Generators are sensitive to voltage fluctuations and are mostly damaged by power surges and drops from the main grid, or caused by equipment such as X-ray/ radiological equipment.
Logistics	Compact technology that can be moved with moderate effort (a crane is sometimes needed, as a medium-size generator weighs several tons).
Safety	Fossil fuels are moderately to highly flammable. In an armed conflict, they can be a target for generating an explosion.
Operation and maintenance	Requires periodical maintenance, especially for refilling the lubricant oil (also performed by unskilled mechanics). However, every 100–500 h, generators need skilled mechanics. Most maintenance is done with tools and spare parts that are not adapted; hence the repairs do not last long.
Marketability	Generators are very familiar to end users in the Global South and often used in healthcare facilities.
Affordability	Although capital costs for purchase are modest, namely 0.8 USD/W, the estimated annual operating cost (fuel plus maintenance) is three times higher than PV, namely 0.56 USD/W, for a 5 kWh/day need. Maintenance is estimated at 0.0075 USD/kWh and fuel at 0.67 USD/kWh. The LCOE ranges from 0.16 to 0.34 USD/W [20].
Sustainability	Generators are often repaired using the spare parts available on the local market, though these parts are not always the most adapted.
Environmentally friendly	Noise pollution and emission of gaseous combustion products.
Recycling	Some parts of diesel generators including fuel filters, air filters, starters, batteries, cables, etc. can be reused as spare parts for other generators. Parts made of reused materials such as aluminum, steel and copper, can also be recycled.

A summary of the advantages and limitations of generators as an energy source are listed in Table 3, with respect to the selected criteria.

Solar energy

Solar-based technologies are a very promising alternative to generators due to the abundance (in hours per year) of the harvested energy source (namely the sun), especially in the Global South.

Solar-based technologies can more or less be divided into two categories: those that convert solar energy (sunlight) to thermal energy and those that convert solar energy to direct-current (DC) electricity. The first category is solar thermal, which is used to produce hot water on a small scale, to satisfy the thermal needs of healthcare facilities. The second category of solar-based technologies is photovoltaic (PV) technology, which is used mostly in rural electrification and is a promising alternative to the main grid for the electrification of healthcare facilities. To power a healthcare facility's devices, photovoltaic systems must be equipped with inverters in order to convert the DC power input to alternating-current (AC) power. However, advances in medical equipment technology allow devices to use the DC power directly supplied by PV systems. Specific medical equipment, such as vaccine refrigerators, are already designed to run on DC electricity (produced by PV). Many other devices are being redesigned to run on DC instead of AC [61].

Photovoltaics have surpassed other energy sources in terms of annual use increase in healthcare facilities in Africa in the past decade, due to improved performance and falling costs. Surveys on energy access for healthcare facilities in the Global South show that photovoltaics are currently the primary source of energy for facilities in rural settings [22]. There is a growing interest in increasing the use of photovoltaic technology in the Global South (which is still perceived as relatively new), as well as an acknowledgement of the many advantages of photovoltaics over main grid and diesel generators. Despite the increasing use of photovoltaics in the Global South, including Africa and the Middle East, the overall installed capacity is still quite limited relative to energy consumption and mostly limited to rural settings, where the main grid is unavailable and fuel transport adds to fuel costs. The main hurdles to a massive shift to photovoltaics are the technology's high upfront costs, especially in big oil producing countries where fuel availability is not an issue.

Below is a solar energy potential assessment and examples of projects in healthcare facilities in selected countries.

- *Zambia*: According to The World Bank's report on solar mapping resources in Zambia [42], the average annual global horizontal irradiation (GHI) for the country varies between 5.5 and 6.3 kWh/m^2/day. Comparing the global horizontal irradiation of Zambia with that of Germany [62] (2.7–3.3 kWh/m^2/day), the country with the most installed PV systems in the world, Zambia's high PV power generation potential could be better harnessed. Yet, this potential is not widely used in the healthcare sector. According to a USAID report in 2009 [63], only 16% of health care facilities in Zambia had solar systems. These systems are designed for lighting, vaccine refrigeration and HF radio communication. Thus, the electricity needs of laboratory equipment cannot be met through solar power. According to this report, improper design, installation, operation and maintenance are the four key cause of solar power system failure in Zambia.
- *Tanzania*: The World Bank's report on solar mapping resources in Tanzania [43] showed 83% of Tanzania's land area has annual average GHI of 4.5 kWh/m^2/day to 6.21 kWh/m^2/day in the central regions, indicating that Tanzania has high solar power potential. USAID, in collaboration with other organizations, provides solar systems for healthcare centers and hospitals often in rural areas of Tanzania. For instance, a 3.0 kW-solar photovoltaic system was installed to supply electricity to an off-grid healthcare center at the village of Mbingu in the Kilombero District. At Lugala Lutheran Hospital, solar photovoltaic systems were scaled up to 8.5 kW and supply electricity for a water pump, hospital equipment and a nursing school. A 4.8 kW-solar photovoltaic system was also installed at Mkomaindo District Hospital. Innovation: Africa, a non-profit organization, has installed photovoltaic systems in various rural clinics in the Bagamoyo district in Tanzania. Candles and kerosene lamps were the only source of light during nighttime hours. Now with solar power, these medical clinics now have their own solar-powered refrigerators to store medicines and vaccines, and healthcare services are now available at night.

- *Rwanda*: According to GeoSUN Africa's (a spin-off of the Centre for Renewable and Sustainable Energy Studies (CRSES) at the University of Stellenbosch) solar map, the [44] majority of Rwanda's land has an annual average GHI of more than 4.5 kWh/m^2/day. In some areas, this figure exceeds 5.4 kWh/m^2/day. Considering Rwanda's high PV power generation potential, the Solar Electric Light Fund (SELF) in collaboration with Partners in Health (PIH) (two non-profit healthcare organizations) equipped five health clinics in Rwanda with 3.4–4.3 kW solar photovoltaic systems. These clinics provide healthcare services to approximately 400,000 people. The systems supply electricity for laboratory equipment (microscopes, blood analysis machines, centrifuges, portable X-ray machines and sterilization devices). They also supply electricity for refrigeration, telecommunications and computers (patient records, etc.). The local staff was also trained in system installation and maintenance.
- *Haiti*: In most of Haiti, the annual GHI ranges from 5 to 7 kWh/m^2/day. This value even reaches 8 kWh/m^2 day in some regions [45]. Considering the country's enormous potential to switch to solar energy, the world's largest solar-powered hospital – with over 1800 solar panels on its roof, each capable of generating up to 280 W – has now opened. PIH who collaborated with the Solar Electric Light Fund (SELF) to install small-scale photovoltaic systems in rural Rwanda, scaled this technology for this 300-bed hospital. According to the hospital's design and construction director, the main challenge was in the design and engineering.

Advantages and limitations of photovoltaic systems are listed in Table 4.

Wind energy

Wind is a renewable and, depending on the geographical location, abundant source of energy [56]. Wind turbines can be divided into a number of categories based on their capacity. Mini and small wind turbines ranging from 1 to 100 kW are mainly used for off-grid rural electrification and can be used extensively in homes and in small communities. Medium and large size wind turbines with capacities ranging from 100 kW to several megawatts can be used both for on-grid electrification (through connection to the main grid) or off-grid electrification [66]. Small wind turbines with a diameter of less than 15 m (usually 7 m) require relatively low wind speeds (typically between 3 and 4 meters per seconds, or m/s) for activation, and can thus be employed as an energy source in off-grid healthcare facilities, whereas larger turbines are not used for urban hospitals, mainly because the urban environment prevents wind energy harvesting due to the turbulence created by nearby buildings. It is worth pointing out that with moderate wind, namely greater than 4.5 m/s, the energy harvested is greater than that produced by a PV installation of the same price, though they require more maintenance than a PV array [67].

Although countries with lower wind energy potential cannot make wind energy-based solutions part of their long term energy plan, they can benefit from a smaller-scale production potential of their limited wind energy resources for rural electrification purpose. Countries with medium wind energy potential, whose average wind speed ranges from 5 to 7 m/s at 50 m above sea level, can harness wind energy by installing small and medium scale wind turbines to electrify off-grid rural areas.

Table 4
Solar energy assessment.

Criteria	Advantages and Limitations for Healthcare Centers
Effectiveness	Intermittent energy source that requires storage for electricity at night, if not coupled with other energy sources. Photovoltaics are already a mature technology whose price per kWh is still dropping. It is the best solution for promoting healthcare facilities' energy independence from the main grid. However, PV installation is still limited, particularly in urban hospitals. It is easily interfaced with small appliances, such as battery chargers and lighting that can runs on DC electricity. PV is modular and can easily adapt to energy requirements.
Assembly and commissioning	Installation requires specific knowledge of PV, especially for connection to the facility's electrical network, which requires a DC/AC inverter. Additionally, PV modules are at risk of theft and in some cases need dedicated countermeasures.
Durability and robustness	Robust technology as there are no moving parts. PV modules are certified for 25 years against any kind of atmospheric agent. Performance may decline more rapidly in tropical climates. The DC/AC inverter is the weak link of PV installation, even though it is certified for up to 10 years. High temperatures and humidity can impact its lifespan.
Resilience to the weather environment	Tolerant to high temperatures and humidity, although PV module efficiency decreases with temperature. In tropical environments, accelerated aging due to water ingress may somewhat reduce the lifespan.
Resilience to the electricity network	PV installations are insensitive to voltage fluctuations from the main grid.
Logistics	Photovoltaics installation is complex. Once installed, they cannot easily be moved.
Safety	The technology is considered to be quite safe. Future research and development (R&D) should focus on making modules that are resistant to shocks produced by detonations. PV modules on flexible substrate could be a good solution, though less efficient.
Operation and maintenance	Requires little, relatively simple maintenance (mainly cleaning the PV modules, especially in dusty environments with little rain. Once installed, it is easy to operate and monitor. Nevertheless, in case of damage or broken parts, certain expertise is required to fix it.
Marketability	Still a new technology for most end-users. Advantages could be overshadowed by the high upfront costs.
Affordability	Investment costs have been decreasing steadily for the past twenty years and are now down to less than twice those of diesel generators, ranging within 1.5–4.3 USD/W [64]. Maintenance costs are much lower than those of diesel generators, at approx. 0.1 USD/W [26]. LCOE is approx. 0.9 USD/kWh for an annual irradiation of 2400 kWh/m^2/y, a value attained by African countries with high GHI [64].
Sustainability	Difficulty finding spare parts on local markets. Potential for a local business startup (installation companies). Local production of PV modules and inverters is not currently an option (in Africa; only moderate industrial capacities in the wealthy part of the Middle East, particularly the United Arab Emirates.
Environmentally friendly	Renewable energy without toxic materials (except solar cells containing cadmium). Greenhouse-gas emissions only in the production phase.
Recycling	PV modules can also be partially recycled; especially the protective glass. Aluminum and semiconductor materials can be recovered and reused [65]. However, recycling remains a challenge on the African continent.

With the growing use of wind energy in the Global South, it is interesting to evaluate this technology's advantages and limitations (Table 5) for possible future development.

Combined heat and power (cogeneration)

Combined heat and power (CHP) systems combine the production of electricity and a heat recovery unit to provide electricity and heating for medium and large infrastructures [69]. Cogeneration is a promising solution for simultaneously reducing both greenhouse gas emissions and costs. CHP plants run on different type of fuels, such as natural gas (most common), diesel, gasoline, community solid waste and biomass. A CHP fueled with natural gas decreases energy and carbon emissions by 20%, relative to a traditional gas plant and gas boiler [70]. A more advanced and promising cogeneration is tri-generation, typically known as a combined cooling, heating and power (CCHP) system, which also cools buildings, in addition to heating and powering them. Micro- and mini-combined heat and power (with an electric power output of 50–1000 kW [71] respectively) are in keeping with the idea of cogeneration and have a wide variety of uses, such as in hotels, offices, health centers, hospitals and so on. The heat released during the electricity production is used to warm a building or heat water. The heat can also be used to produce more electricity. CHP systems are mainly customized to satisfy the user's heating requirements as, technically speaking, it is easier to transport electricity than heat.

Table 5
Wind energy assessment.

Criteria	Advantages and Limitations for Healthcare Centers
Effectiveness	Intermittent energy source throughout the day, which requires energy storage and/or another reliable energy supply source for healthcare facilities. Wind energy is a mature technology, though R&D activities seek to further improve it. Wind is abundant at high elevations and scarcer in proximity to settlements, such that harvesting in remote locations is optimal. Consequently, wind cannot be used as an additional energy source for urban hospitals. The AC output can be directly injected into the facility's electrical network.
Assembly and commissioning	Installation is rather complicated and requires expert engineers. Risk of theft of small wind turbines is lower than for PV modules.
Durability and robustness	Robust technology, as wind turbines are built to last for over 20 years with proper and regular maintenance. Warranties between 2 and 10 years.
Resilience to the weather environment	As wind turbines are mounted in areas with a certain wind potential, high temperature and humidity are not an issue.
Resilience to the electricity network	Wind turbines connected to a grid require an inverter to stabilize the voltage from the wind turbines. Inverters also reduce the sensitivity to voltage fluctuations from the main grid.
Logistics	Small wind turbines are mounted with a tilt-up pole and can be dismantled and relocated relatively easily. Medium wind turbines are more difficult to relocate.
Safety	The technology is considered to be quite safe.
Operation and maintenance	Wind turbines require regular maintenance, mostly to lubricate rotating components. Rotor blades may need adjustment every two years. To increase their lifespan, expert technicians must do maintenance with appropriate parts. Once installed, they are easy to operate and monitor.
Marketability	Its advantages could be overshadowed by high upfront capital costs. Acoustic and vibration issues, which could pose a major problem for wind turbines near healthcare facilities.
Affordability	Investment costs of some 1.3–2.3 USD/W for onshore plants [64], with maintenance costs as low as 0.1 USD/W [20]. LCOE ranges from 0.06 to 0.12 USD/kWh [64].
Sustainability	Difficulty finding spare parts on local markets. Potential for a local business startup (installation companies). Small wind turbine production is easier to set up than PV.
Environmentally friendly	Renewable energy without toxic materials and polluting emissions.
Recycling	About 80% of wind turbine systems including parts made of recyclable material such as steel and copper which can be recycled. However, the blades are not easy to recycle as they are made from composite materials [68]. The blades can be converted to other uses, e.g., benches, as was done in the Netherlands, or shredded into small pieces and burned as fuel, as a cement factory in Germany does.

Cogeneration technology is spreading rapidly in the high-income world in three sectors: industry, commercial/institutional and district heating and cooling systems (DHC) [72]. Developed countries rely on integrated CHP plants, particularly in the healthcare sector, as healthcare structures require significant and reliable electricity supply and have a high thermal load. In the United Kingdom and the United States, for example, CHP plants that provide heat and power for health centers and hospitals have capacities ranging from a hundred kilowatts to several megawatts. In middle-income countries, CHP and CCHP pilot projects have already been implemented in some countries, such as India, Brazil [73] and Iran [74,75]. CHP and CCHP systems have great potential in the Global South, as these systems are financially advantageous wherever main-grid electricity is more than 2.5 times more expensive than fossil fuel [70] and heating and/or cooling needs are considerable, i.e., more than 5000 h/year. Table 6 assesses this technology based on chosen criteria.

Small hydropower

This technology is divided in two categories: the storage type, which involves the construction of a dam, and the run-of-river type, which does not require a significant water reservoir. A third classification exists, based on the plants' power range: large hydropower plants and small hydropower plants. "Small" hydropower refers to power capacity that can reach 10 MW, and is normally divided into mini-hydro (up to 1 MW), micro-hydro (up to 500 kW) and pico-hydro (up to 50 kW) [51]. Whereas mini-hydro tends to be grid connected, micro- and pico-hydro are normally used for off-grid applications and could potentially be used for healthcare facilities. More than 150 countries have hydropower resources, meaning that even very poor countries can meet part of their electricity needs through hydropower.

Global hydropower capacity is currently at about one third of the world potential capacity. Thus there is potential to increase the proportion of hydropower technology. In African countries, though solar energy is the largest renewable energy resource, large hydropower systems are the most economically renewable energy solutions for development, particularly in sub-Saharan Africa [77]. The Democratic Republic of the Congo and Ethiopia are the two countries with the highest economically feasible hydropower capacity. In countries rich in water sources, like those in West and Central Africa, small hydropower plants are a viable solution for the energy needs of healthcare centers and clinics. A number of running and completed projects exist in Ethiopia, Uganda, Rwanda, Mozambique, Nepal, the Democratic Republic of Congo and many other developing countries. For instance, a 60 kW hydropower plant that was the only source of electricity for a hospital in a small rural village in Uganda was upgraded to 300 kW. This increase in capacity allowed the hospital to sell its surplus electricity to around 800 customers, including 400 households and 194

Table 6
Combined heat and power assessment.

Criteria	Advantages and Limitations for Healthcare Centers
Effectiveness	New technology mostly used in developed countries and some developing ones like India. Potential fuel-to-energy conversion efficiency of up to almost 80% [70]. No network electricity distribution losses as CHP is installed at the end-user's premises. Great flexibility in choosing the system's power capacity (from 1 kW to 500 MW). CHP providing less than 1 MW of power are made from standard pre-assembled modules.
Assembly and commissioning	CHP installation requires engineering experts.
Durability and robustness	Not enough data available at present (in the developing world, first installations in India, Iran and Brazil). Flexible choice of the cheapest fuel type available. Different types of fuel can be used in a single CHP.
Resilience (local environment)	No major issues expected regarding humidity and temperature.
Resilience (local electrical network)	CHP chosen to improve the quality of the electricity supply and heating in countries with regular power outages.
Logistics	Difficulty relocating a CHP as it is connected to the electrical network and heating system of the healthcare facility.
Safety	CHP is powered by fossil fuels, all of which are inflammable.
Operation and maintenance	Need for regular maintenance. Relatively easy to operate and monitor.
Marketability	For now, uncommon in the Global South. Opportunity for urban hospitals to sell the surplus energy to the neighboring households.
Affordability	Investment and operating/maintenance costs varied from one type of CCHP to another. LCOE varied from 0.06 to 0.11 USD/kWh [76]. Investment were a larger percentage (50–80%) of total costs (depending also on the fuel type).
Sustainability	Difficulty in assessing the sustainability of the technology, in terms of developing a local business.
Environmentally friendly	Reduction of greenhouse gas emissions due to high fuel-to-energy conversion efficiency.
Recycling	Various parts of a CHP plant components, such as gas turbines, steams turbines and generator parts, can be reused. Some gas turbine parts that can be recycled include rotor, blades and fuel nozzles.

Table 7
Small hydropower assessment.

Criteria	Advantages and Limitations for Healthcare Centers
Effectiveness	Advantages: continuous and reliable energy source, which makes it a preferred option for healthcare facilities near rivers. Limitations: Only adapted to rivers whose flow is constant throughout the year, for instance those in equatorial Africa. Not a scalable technology. Maximum power capacity determined by the river's characteristics. Power output is modest, with a maximum capacity of approx. 100 kW (for healthcare facilities).
Assembly and commissioning	Micro-hydro is complex to implement and requires expert engineers. The AC electricity produced can be directly connected to the facility network.
Durability and robustness	The technology is quite robust and normally lasts for over 25 years [78,79]
Resilience (local environment)	Resistant to high humidity and temperatures.
Resilience (local electrical network	Resistant to voltage fluctuations from the main grid.
Logistics	Impossible to relocate the installation, which is optimized for the specific characteristics of the river.
Safety	Safe technology as there is no fuel or water accumulation in a reservoir (which could cause flooding in case of destruction).
Operation and maintenance	Need for regular yet simple maintenance [78]. Easy to operate and monitor.
Marketability	New technology for end users in Africa, which prevents full exploitation.
Affordability	Investment costs range from 1 to 3.5 USD/W. Operation and maintenance costs are within 2–2.5% (of investment costs)/year for large plants and within 1–6 %/year for small plants. The LCOE for large plants ranges from 0.02 to 0.06 USD/kWh, whereas LCOE for small plants ranges from 0.03 to 0.12 USD/kWh [64,80]. Small hydropower is therefore an interesting option for both supplying grid and off-grid rural electrification in water-rich regions.
Sustainability	Potential for a local business startup, as many components can be manufactured using local materials [78].
Environmentally friendly	Renewable technology. No polluting emissions. Little impact on the ecosystem as there is no flooding of dry land (versus storage-type hydroelectric).
Recycling	Partial recycling possible.

small businesses, in proximity to the hospital. Rwanda's rural communities, which hardly have access to grid power, also benefit from micro hydropower projects. For example, a 200 kW micro hydropower plant provides electricity to over 800 households as well as various schools, health centers and small businesses in a rural district. A small-scale hydropower plant (75 kW) for rural communities in Mozambique, a project begun in 2005, provides electricity to a 200-household village, a health center, a school, two maize mills and shops [50]. Evaluation of hydropower technology for the selected criteria is reported in Table 7.

Energy storage systems

Solar and wind power are two promising renewable energy sources for healthcare facilities across the African continent and the Middle East. The energy throughput can fluctuate greatly in a short timeframe due to the nature of the harvested energy. As such, the excess energy produced during production peaks must be stored, so as to be readily available when the demand exceeds the production. This is called "peak-shaving," and it is done both at the level of the main grid (in developed countries that use different energy production technologies) and at that of the individual healthcare facility, especially in off-grid facilities in the Global South. In urban hospitals connected to the main grid, an electricity storage system not only handles the excess energy production from renewables; it also provides a continuous supply at times of outages and helps harmonize different energy sources to maximize their lifespan (protection from voltage surges and drops) and minimize the energy bill.

In terms of technological development, some of the storage systems are consolidated by decades of development, whereas others remain at pre-industrialization stages. More specifically, pumped-hydro tends to be mature and commercialized technology, as are certain type of batteries (electrochemical storage), like lead-acid batteries. Others battery technology (sodium-based, lithium and nickel-based batteries) are commercialized for other end-user applications than healthcare facilities in the Global South. Flywheels and compressed air energy storage (CAES) technology (mechanical storage) are in the demonstration/deployment phase. Finally, electrical storage systems (double-layer capacitor and superconducting magnetic energy storage) and chemical storage systems (including hydrogen and synthetic natural gas) are still in the R&D phase [81,82]. The latter two technologies are suited to small-scale systems in terms of electricity demand, whereas pumped hydro and CAES technologies are mainly used for high-power systems, as their storage capacities range from several hundred megawatt hours (MWh) to several gigawatt hours (GWh).

Batteries

The capacity of battery storage systems ranges from one kWh to a few thousand kWh. Their discharge time ranges from a few seconds to several hours or days depending on their discharge power rate [82]. Batteries' extensive discharge time makes them suited to both energy and power applications. In off-grid scenarios, batteries could be integrated into energy systems, either for storing excess electricity for future consumption or balancing fluctuations from solar and wind-based energy systems' power output [83]. Batteries could also be used to enhance the reliability of the electricity network for grid-connected systems. It is worth pointing out that the charge state of a battery should ideally be maintained at 20–80% to thoroughly exploit the battery lifetime [83,84].

Four major types of batteries – **lead-acid batteries, nickel-based batteries, lithium batteries and sodium-based batteries** – are either currently being used in healthcare facilities in the Global South, or could be interesting replacements in the near future. The technical characteristics of these types of batteries and an assessment relative to the selected criteria are presented below. The "assembly and commissioning" and "sustainability" criteria were not included here; instead we added a "performance" criterion, which we found to be more relevant when evaluating the potential for battery use in healthcare facilities in the Global South. In addition to the aforementioned criteria, the "performance" criterion also addresses the technical features of batteries.

Sodium-based batteries

Sodium-based batteries are by far the highest installed battery capacity worldwide [62,64]. Sodium-based batteries include Sodium Sulphur batteries (NaS) and Sodium Nickel Chloride batteries (NaNiCl). Formerly their power capacity ranged from 50 kW to 100 MW whereas today they can be purchased with a power value of as low as 1 MW and an energy value of as low as 6–7 MWh [82,85]. As such they are mainly used for grid stabilization. Despite the high cost of Sodium-based batteries, their potential in off-grid applications in the Global South is interesting, particularly because of their resistance to high temperatures and low maintenance needs. Typically, the internal temperature of these batteries must be maintained at about 300 °C, which necessitates a devoted heat source and the use of a portion of the stored energy. The NaNiCl have a performance similar to NaS batteries, but with fewer safety issues. Table 8 summarizes the advantages and disadvantages of this type of battery.

Table 8
Sodium-based battery assessment.

Criteria	Advantages and Limitations for Healthcare Centers
Effectiveness	Sodium-based batteries are a several decade-old technology and are mainly fabricated and used in Japan. Nevertheless, their potential for use in the Global South is great due to low maintenance, good performance, safety and environmentally-friendly technology.
Performance	Sodium-based batteries have excellent energy densities (150–300 Wh/l) [82,85]. The acceptable depth of discharge is about 80%. They have a number of cycles between 2500–4500 [82,84]. Response time is very fast (milliseconds). However, the energy required to maintain the internal temperature at 300 °C lowers their efficiency.
Durability and robustness	The declared lifespan is approx. 10 years, though this may be optimistic, as for other battery technologies.
Resilience (local environment)	Sensitive to temperatures higher than 70 °C [85], 60 °C [84], if properly used.
Safety	These batteries are designed to be reliable and safe. They are resistant to shocks, fire, short circuits and flooding, according to the NGK Insulators, LTD product features [86] and are thus an interesting option not only in the Global South but in all regions affected by armed conflict.
Operation and maintenance	Extremely simple to maintain.
Marketability	Not currently used in the Global South.
Affordability	Moderately expensive technology, ranging from 350 to 600 USD/kWh [85,87,88].
Environmentally friendly/recycling	Sodium-based batteries can be potentially fully recycled.

Lithium-based batteries

Lithium-based batteries rank second for batteries in total installed capacity but had the highest market share in recent years [87]. The high, specific energy of Lithium-based batteries (80–200 Wh/kg) compared to other types of batteries makes them highly suited for use in consumer products, such as mobile applications (i.e., cellphones and laptops), which require minimal physical space. This technology also had by far the largest percentage increase of installed capacity for grid-connected storage (up to tens of MWh) from 2013 to 2014 [87]. Their use as energy storage units by small, private renewable installations is becoming more widespread. However, as these products are designed for developed countries, their cost is still largely beyond the means of Global South countries. For small-scale, off-grid use, when volume and weight are of greater concern than price, Lithium-ion batteries could become the preferred storage system. Consequently, they are a potentially viable storage system for healthcare facilities and refugee camps. The advantages and limitations of Lithium batteries are listed in Table 9.

Table 9
Lithium-based battery assessment.

Criteria	Advantages and Limitations for Healthcare Centers
Effectiveness	Lithium is still a new technology, especially in terms of its potential as energy storage for small and medium renewable installations.
Performance	Lithium batteries have excellent energy density (200–400 Wh/l) [82,85], which makes them an interesting option for refugee camps, for instance. The acceptable depth of discharge is 80%. They outperform all other battery types in terms of number of cycles (up to 10,000) [82,85]. Discharge time can vary from seconds to weeks. They are resistant due to memory effect.
Durability and robustness	Lithium batteries have a declared lifespan of about 20 years, according to manufacturers. Although they are more resistant to high temperatures and can support more discharge cycles than other batteries, their lifespan in the field is expected to be considerably lower than that purported by manufacturers.
Resilience (local environment)	Sensitive only to temperatures higher than 75 °C [84] if used properly. This makes them a good option for use in many African countries and in the Middle East.
Safety	Lithium's reactivity with air and humidity at high temperatures raises serious safety concerns. Its metal oxide electrodes are thermally unstable. Hence the battery needs a monitoring unit to prevent overcharging and over-discharging [82]. The constant need for monitoring makes them a more complex technology.
Operation and maintenance	Lithium batteries are essentially maintenance free.
Marketability	No use in the Global South at present.
Affordability	Moderately expensive technology at more than 600 USD/kWh [85,88].
Environmentally friendly/recycling	The lithium battery is an environmentally friendly technology. However, the recycling rate is still low (50%).

Lead-acid batteries

Lead-acid batteries are the third most used storage technology in terms of installed capacity. Their low cost is their main advantage relative to other types of batteries. Their main disadvantages are their short life and low specific energy (approx. 50 Wh/kg). Their electrical power ranges from 10 kW to 100 MW, and their discharge time ranges from a few minutes to several hours or days [85]. Their primary use is energy management, to support intermittent PV systems [85,87]. Lead-Acid batteries operate well between 0 °C and 40 °C [85]. Technically speaking, there are two types of lead-acid batteries: vented (or flooded) and sealed. Vented lead-acid batteries are preferred for their robustness, number of cycles and long life. Sealed ones (also called valve-regulated lead-acid (VRLA) batteries) require no maintenance because, unlike flooded ones, do not require regular refilling with deionized water. The choice between the two types is determined by use and the environment. The advantages and limitations of lead-acid batteries are listed in Table 10.

Nickel-based batteries

Nickel-based batteries are the second most used type of battery in the Global South, though the overall installed electrical capacity is not comparable to that of the lead-acid type. There are two types of nickel-based batteries: Nickel-Cadmium (NiCd) and Nickel-metal hydride (NiMH). Nickel-Cadmium batteries are a consolidated technology (on the market for over a century) and are available both sealed (which are maintenance-free but have lower electrical capacity) and vented (which have additional electrical capacity). Nickel-Cadmium batteries tend to discharge more easily than lead-acid ones. As such, applications that allow for regular recharging (e.g., in combination with a photovoltaic installation) should be favored. NiCd batteries can be stored in a discharged state for long periods. However, as they have memory effect, they need periodic full discharges. They also have high self-discharge behavior and require recharging after storage. Nickel-Metal Hydride (NiMH) batteries are a much younger and better-performing technology (particularly in terms of energy density) than NiCd. They are especially suitable for storing photovoltaic electricity in sunny countries because of their energy density, high performance in warm climates and lack of toxic elements. NiMH batteries suffer less from memory effects but like NiCd have high self-discharge behavior. The advantages and limitations of nickel-based batteries are listed in Table 11.

Table 10
Lead-acid battery assessment.

Criteria	Advantages and Limitations for Healthcare Centers
Effectiveness	Mature technology heavily employed in the Global South.
Performance	Lead-acid batteries are the oldest type of rechargeable batteries. Their performance does not match that of other, more-advanced battery types. Modest energy density compared to the other types of rechargeable batteries (50–80 Wh/l) [82,85]. The number of cycles is also modest compared to other battery types and can vary greatly (200–2000) [82,85].
Durability and robustness	Battery life can be as long as 20 years according to manufacturers. In the Global South, environmental factors may reduce this to as little as two years due to high temperatures and maintenance issues.
Resilience (local environment)	Sensitive to temperatures of 40 °C and above [85], which negatively impact their electrical capacity and life.
Safety	The presence of lead, a toxic material, is a major safety issue along with sulphuric acid they contain. The hydrogen produced during the chemical reaction is also highly inflammable. However, in normal operation conditions, there are no issues of lead contamination, exposure to battery acid or high-level hydrogen leakage. Lead-acid batteries should be protected from sparks and temperatures of more than 200 °C, which could ignite the hydrogen-oxygen mixture inside the battery.
Operation and maintenance	The vented or flooded lead-acid batteries require regular refilling with deionized water, which can be an issue depending on its availability at healthcare centers, especially those far from urban centers and with limited resources. Sealed ones require little and easy maintenance.
Marketability	Widespread technology, easily marketable.
Affordability	Low-cost technology ranging from 100 to 300 USD/kWh [20,82,88].
Environmentally friendly/recycling	Disposal and recycling of lead-acid batteries is a well-established, successful process (recycling potential of up to 80%) in the developed world. However, this is still not the case on the African continent, where the culture of recycling is in its infancy. Moreover, lead-acid batteries can potentially contaminate groundwater sources if not properly disposed of.

Flywheels

Flywheels (also known as inertia wheels), which store excess electricity in the form of kinetic energy (stored on a spinning rotary disk) are a viable option at the building scale and for off-grid power systems. Their power ranges from 10 kW to 100 MW [85]. Because of their short discharge time they are mainly used for their power quality (e.g., for stabilizing electrical network and regulating frequencies). They are used more specifically to protect sensitive instruments like X-ray/MRI machines and CT scanners against voltage oscillations from the grid. Flywheels are also being used for

Table 11
Nickel-based batteries assessment.

Criteria	Advantages and Limitations for Healthcare Centers
Effectiveness	NiCd is a mature technology, whereas NiMH is a relatively new technology. Nevertheless, both types are used much less than lead-acid batteries due to their higher cost.
Performance	Ni-based batteries have less electrical capacity than lead-acid ones. However, they outperform lead-acid ones on all other criteria. The energy densities of NiCd and NiMH batteries are 15–80 Wh/l and 80–200 Wh/l respectively [82]. The depth of discharge is 80%. The number of cycles is 1500–3000 for NiCd and 600–1200 for NiMH [82].
Durability and robustness	Ni-based batteries live longer than lead-acid ones (up to 20 years according to manufacturers). However, life expectancy is much lower in the Global South for the same reasons as lead-acid ones.
Resilience (local environment)	Sensitive only to temperatures higher than 60–70 °C [84]. This makes them a much better option than lead-acid batteries, particularly in many African countries and the Middle East.
Safety	They are among the safest batteries and thus preferable in Global South countries.
Operation and maintenance	Ni-based batteries normally require little and simple maintenance, except for vented NiCd, which require regular refilling.
Marketability	Rare technology in the Global South but with high marketability potential.
Affordability	Expensive technology at approximately 850 to 1000 USD/kWh [88].
Environmentally friendly/recycling	The cadmium contained in NiCd batteries is toxic and polluting, whereas NiMH batteries are environmentally friendly (approximately 75% recyclable) though recycling remains a challenge in the Global South.

Table 12
Flywheel assessment.

Criteria	Advantages and Limitations for Healthcare Centers
Effectiveness	Flywheels are a recent technology and are being increasingly used to provide a continuous electricity supply in the Global South.
Performance	The minimum power capacity of flywheels is 1515 kVA. The advantages are no significant energy loss (with almost unlimited storage time) and enormous potential in terms of the number of cycles (approx. 200,000 deep cycles). Moreover, energy can be stored or dispensed regardless on how the cycle is performed. Simple monitoring of the charge state.
Durability and robustness	Warranty is usually 10 years, but life expectancy is over 20.
Resilience (local environment)	Resistant to high temperatures and humidity, even those in Global South countries.
Safety	Flywheel safety is still subject to engineering research. At present, its safety for use in the Global South has not been assessed.
Operation and maintenance	Little maintenance required (every six years for the Powerthru's product).
Marketability	New technology with limited applications in the Global South as yet.
Affordability	High investment costs of 0.25–25 USD/W and an LCOE at about 1000 USD/kWh [88,89], but moderate operation and maintenance costs (500 USD/year).
Environmentally friendly/recycling	No toxic or polluting materials, greenhouse gas emissions or no water use; little noise pollution.

Table 13
Hybrid energy systems assessment.

Criteria	Advantages and Limitations for Healthcare Centers
Effectiveness	Hybrid systems are becoming a reality in many African and Middle East countries, notably urban hospitals, which are connected to the main grid but also have a PV systems and a backup reciprocating engine.
Durability and robustness	Long lifetime for each component, as they are customized based on detailed specifications.
Resilience (local environment)	Resistance depends on the sensitivity of each element of the micro-grid.
Safety	No particular safety concerns beyond the ones already mentioned for each technology.
Operation and maintenance	Low maintenance and operating costs; high costs for the reciprocating engine, which operates only when necessary (reduced maintenance and extended lifetime due to minimized use and hence reduced operating costs).
Marketability	A combination of traditional (diesel generator) and new energy (PV/battery) sources is more easily implemented than strictly renewable/new energy technologies.
Affordability	Moderate-to-high capital costs (around 7 USD/W) for PV and reciprocating engines, batteries excluded. With lead-acid batteries, the total operating and maintenance costs at 0.3 USD/W [20].
Environmentally friendly	Reduced greenhouse gas (GHG) emissions and noise pollution thanks to environmentally-friendly renewables.

data protection purposes, for instance Children's Hospitals and Clinics of Minnesota in the United States is replacing the lead acid batteries used for backup power in their data centers with flywheel storage systems. Though the upfront cost is higher than for electrochemical batteries, their low maintenance costs and long life make them less costly (per kVA) over their lifetime. Their potential use during outages on the main grid and as a continuous electricity supply for urban hospitals makes them a viable future option.

The advantages and limitations of this technology listed in Table 12 come mostly from the Beacon power and Powerthru3 (flywheel manufacturers) websites.[3]

Hybrid systems

In areas where energy from the main grid is of poor quality or is unreliable, healthcare facilities must be equipped with decentralized power sources. As both generators and renewable energy sources have benefits and drawbacks, the best solution is to combine both systems, so as to maximize the benefits and compensate for the drawbacks. Such hybrid-energy systems can include a generator, a PV and/or wind installation and/or hydropower and energy storage systems. This specific set of resources is optimal because renewable resources can respond to all demand peaks that cannot be handled by the main grid. Outside demand peaks, renewable energy systems charge storage systems, namely battery banks. During outages, renewable energy systems and the battery bank supply the necessary electricity. During prolonged outages where both stored energy and electricity from renewable resources is not sufficient, generators can be employed. Thus, generators can be sized to cope only with emergency situations, so that operating costs can be minimized and their lifetime greatly extended. A combination of PV/wind farms, generators and batteries typically has the least LCOE (USD/kWh), due to sizing optimization of PV/wind farms and battery bank (high capital costs), and optimum generator usage (high operating and maintenance costs). However, a different combination of energy sources might be better for a given set of geographical and economic factors. To maximize usage of a combination of intermittent energy sources, such as solar and wind energy, the design of the hybrid system must take meteorological and seasonal weather conditions into account. To optimize the hybrid system, i.e., custom sizing of each energy source, simulation software such as HOMER can be used. A comparison was made of different configurations of hybrid energy systems for rural health clinics in six regions of Nigeria [90]. The optimum configuration was selected based on each region's renewable energy potential: in the south and southwest, the optimal solution was PV systems, diesel generators and batteries. In other areas wind was also included. Another hybrid system case study was a health center in Umm Jamal (Mafraq Governorate area) in Jordan, which operated 24 h/day with 55 kWh/day electricity demand and a 5.9 kW peak demand. A hybrid system consisting of a 20 kW PV system, a 10 kW diesel generator and 108 kWh batteries was determined to be the optimal electrification option [91]. In Rwanda, solar/diesel generator/battery hybrid systems have been designed to provide electricity for rural health clinics. Before the installation of hybrid systems, the rural clinics in question had been powered by 11 kW generators. Now, more than 90% of their power comes from solar energy. Hybrid energy systems are also a promising option for large healthcare facilities, like hospitals located in rural areas. One example of such a facility is a 157-bed hospital in a low-income region of southern Tanzania, with a 160-kWh daily electricity consumption. The hospital's hybrid energy system consists of a PV system (18 kW capacity) and diesel generators (33.6 kW and 23 kW capacity); 40% of their electricity need is met by the PV system [21].

Advantages and limitations of the hybrid system are listed in Table 13.

Conclusion

Healthcare facilities need access to reliable, affordable, sustainable energy in order to provide quality healthcare services. Facilities with no or an unreliable grid connection, like those in remote areas, must be equipped with on-site energy-production

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[3] http://beaconpower.com/; http://www.power-thru.com/.

systems to meet the Sustainable Development Goals of affordable energy and good health for all.

The choice of the most adequate energy-production solution depends on several factors. To begin, it depends on the healthcare-facility's characteristics in terms of size (number of patients), location and services. The location determines whether access to the electricity grid is available or not, which renewable energy source has the highest exploitation potential and the availability of affordable fuel provision. Moreover, an energy-management strategy can identify minimum energy needs and optimize facilities' energy consumption.

Healthcare facilities need both electrical and thermal energy to provide effective service. They are also among the largest energy consumers and need both a stable and continuous energy supply. Energy provision is even more challenging in conflict regions and rural areas without access to the national electrical grid. This review focused mainly on electrical-energy-production technologies as they can also be used for heating, because electricity requirements are generally more demanding than heating, and because their impact on the environment can be largely optimized.

Currently, the most commonly used energy source, as a backup in grid-connected hospitals and rural healthcare centers, is fuel generators. This choice is preferable, given the low investment costs, end-users' familiarity with this technology (which is similar to a transport-vehicle engine) and the unfounded belief in its easy reparation, cheap fuel and easy installation and relocation. However, as this has review highlighted, this is not necessarily the best choice in regions with an abundant supply of at least one renewable energy source and where climate conditions can rapidly age the generator. Additionally, generators are a risky choice in regions where fuel is scarce and/or expensive due to the distance from the supplier. To conclude, generators are noisy and environment-unfriendly technologies. For all these reasons, healthcare facilities in the Global South should steer towards other energy sources, notably renewable ones.

Solar energy offers massive and, as yet, unexploited potential for many countries in the Global South according to the high GHI values. Solar energy can be used both to produce electricity with photovoltaic modules and hot water with solar-thermal modules. Solar-thermal is a very simple technology to build (in terms of availability of parts and manufacturing) and the output (i.e. hot water) can have an important impact on patient conditions. Photovoltaic technology is more complex and expensive, which explains end-users' mistrust. However, this mistrust is unfounded when one considers the steadily falling prices of this technology over the past twenty years. Though investment costs are still higher than those of generators, this fact is overshadowed by the many advantages this renewable and sustainable technology offers. Its modularity, which that can effectively meet the energy demand, simple maintenance, cost-free operation, longevity and environmental friendliness are just a few of the advantages. Even given other limitations, such as the need for a storage system for the balancing intermittent production and the complexity of relocating an installation, PV technology is one of the most promising energies for the Global South.

Wind is another renewable and sustainable energy with high exploitation potential in certain regions of the Global South. Wind energy has many of the same advantages and drawbacks as solar energy, namely high investment costs but low maintenance and zero operation costs, the fact that it is an intermittent energy source and yet an on-site clean technology, resilience to weather conditions and theft. Although wind energy is less modular than solar energy, commercial wind turbines have powers ranging from a few hundred watts to a few megawatts, meeting the energy demand of different types of healthcare centers. Wind turbines must not be built near buildings, so as to take full advantage of the energy source. Finally, the danger of rotating blades and the complexity of relocation constitute some of the challenges related to wind energy.

Hydropower technology is the preferred choice for water-rich regions like countries in central Africa such as Ethiopia, Uganda, Rwanda and the Democratic Republic of Congo. Hydropower installations can meet the energy demands of healthcare facilities thanks to different commercial run-of-river solutions, from pico-hydro to micro-hydro. This renewable, clean energy is not intermittent, like solar and wind, though comparable in terms of investment costs. However, the installation is rather complex to build and impossible to relocate.

Combined heat and power plants run on different types of fuels, but are much more efficient than conventional generators. In fact, in addition to the electricity generated, they exploit the heat produced to warm up the buildings. It is an expensive technology in terms of investment costs, and can only be afforded by big hospitals in medium-income countries like India, Iran and Brazil. It becomes financially advantageous wherever main-grid electricity is more than 2.5 times more expensive than fossil fuel and heating needs exceeds 5000 h per year. Future developments may make this technology accessible to low-income African countries as well.

As mentioned above, a number of renewable technologies have the drawback of being intermittent, which is an incompatible for healthcare facilities. Therefore, energy-storage technologies are required in order to the store electricity excess during production peaks and provide electricity during production lows. The most mature storage technology, besides large dams, is electrochemical storage, namely batteries. The four main types of batteries – **lead-acid batteries, nickel-based batteries, lithium batteries and sodium-based batteries** – have been reviewed. Lead-acid batteries are the oldest type of rechargeable batteries and are heavily employed in the Global South. However, their performance does not match that of more-advanced batteries such as nickel-based batteries. In particular, Nickel-Metal Hydride (NiMH) batteries have more than twice the energy density of lead-acid batteries, and are particularly suitable for storing photovoltaic electricity due to high performance in warm climates and little maintenance. Also, they do not contain toxic materials. The drawback is the higher cost (twice that of lead-acid), which, nonetheless, is expected to drop with technology improvement and increased use in the coming years.

When volume and weight are of greater concern than cost, especially for small-scale and off-grid use, lithium-ion batteries are the preferred storage solution. This is the case for temporary healthcare facilities and refugee camps. This technology is outstanding for energy density (up to 400 Wh/l) and number of cycles (exceeding 10,000). They are maintenance free, but need constant monitoring and have safety issues because of lithium reactivity to air. Finally, sodium-based batteries are not currently used in the Global South, but are interesting candidates due to low maintenance, good performance (with energy densities up to 300 Wh/l) and up to 4500 cycles, no safety issues, resilience to high temperatures and environment-friendly technology. The main drawbacks are large investment costs and no compact products commercially available.

Among other types of energy storage, flywheels (mechanical storage) are increasingly being used to provide continuous electricity supply in order to protect sensitive equipment like X-ray machines and CT scanners against voltage oscillations from the grid. The maximum number of cycles, up to 200,000, outperforms any electrochemical storage. Moreover, it is insensitive on how cycles are performed.

Hybrid-energy systems can include a generator, a PV and/or wind installation and/or hydropower and energy storage systems. Hybrid-energy systems combine different energy technologies so as to maximize the benefits and minimize the drawbacks. During prolonged outages where both stored energy and electricity from renewable resources is not sufficient, generators can be employed. Thus, generators can be sized to cope only with emergency situations, so that operating costs can be minimized and their lifetime greatly extended.

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