Technologies for heating, cooling and powering rural health facilities in sub-Saharan Africa

Matthew S Orosz, Sylvain Quoilin and Harold Hemond

Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy published online 21 August 2013
DOI: 10.1177/0957650913490300

Special Issue Article

Institution of MECHANICAL ENGINEERS

Journal of POWER AND ENERGY

Proc IMechE Part A:
J Power and Energy
0(0) 1–10

DOI: 10.1177/0957650913490300
pia.sagepub.com
SAGE

Technologies for heating, cooling and powering rural health facilities in sub-Saharan Africa

Matthew S Orosz[1], Sylvain Quoilin[2] and Harold Hemond[1]

Abstract

This paper examines technical and economic choices for rural electrification in Africa and presents the rationale for trigeneration (capability for electricity, heating, and cooling) in health and education applications. An archetypal load profile for a rural health clinic (25 $kWh_e \cdot day^{-1}$ and 118–139 kWh_t) is described, and a regional analysis is performed for sub-Saharan Africa by aggregating NASA meteorological data (insolation, temperature, and heating and cooling degree days) using correlates to latitude. As a baseline for comparison, the technical, economic (using discounted cash flow) and environmental aspects of traditional electrification approaches, namely photovoltaic (PV) systems and diesel generators, are quantified, and options for meeting heating and cooling loads (e.g. gas-fired heaters, absorption chillers, or solar water heaters) are evaluated alongside an emerging micro-concentrating solar power (μ-CSP) technology featuring a solar thermal organic Rankine cycle (ORC). Photovoltaics hybridized with LPG/Propane and μ-CSP trigeneration are the lowest cost alternatives for satisfying important but often overlooked thermal requirements, with cost advantages for μ-CSP depending on latitudinal variation in insolation and thermal parameters. For a 15-year project lifetime, the net present cost for meeting clinic energy needs varied from 45 to 75 k USD, with specific levelized electricity costs of 0.26–0.31 USD kWh^{-1}. In comparison, diesel generation of electricity is both costly (>1 USD kWh^{-1}) and polluting (94 tons CO_2 per site over 15 years), while LPG/Propane based heating and cooling emits 160–400 tons CO_2 depending on ambient conditions. The comparative analysis of available technologies indicates that where the energy demand includes a mixture of electrical and thermal loads, as in typical health and education outposts, non-carbon emitting μ-CSP trigeneration approaches can be cost-effective.

Keywords

CHP/co-generation, energy conversion/recovery, photovoltaic (PV), power generation, solar energy conversion, solar thermal conversion, diesel engine performance

Date received: 24 December 2012; accepted: 22 April 2013

Introduction

Extending energy supplies to the nearly 1.6 billion people who lack access to electricity is an enduring challenge of the 21st century, one which is implicitly connected to the unfolding impacts of climate change. In rural areas, reticulation of centralized grid infrastructure strains to keep pace with demand growth, while in urban areas power outages and "load shedding" can impair energy availability.[1] In remote areas with dispersed communities or in sparsely inhabited mountainous areas, the cost of extending the electricity grid is generally prohibitive for distances exceeding 5–10 km: utility connection fees in sub-Saharan Africa range from 20 to 1000 USD, and extension of the grid costs 3 k–20 k USD$\cdot km^{-1}$.[2–6] The levelized cost of a grid extension investment is thus a function of both distance and consumption density (demand km^{-1}), meaning that the break even point for grid extension vs. a fixed cost micro-grid at a given site will depend on distance, the surrounding population density, and their ability to pay for electricity. Chakrabarti and Chakrabarti[7] calculated this break even point for India (population density

[1]Parsons Laboratory, Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA
[2]Laboratoire Thermodynamique, Mechanical Engineering, University of Liege, Belgium

Corresponding author:
Matthew Orosz, Parsons Laboratory, Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.
Email: mso@mit.edu

$>350\,km^{-2}$, Ref. 8) and determined a distance of 16 km, below which grid extension is more appropriate than distributed generation. For sub-Saharan Africa (population density $<80\,km^{-2}$, Ref. 9) micro-grids may be preferable at a distance as close as 5 km from the central distribution grid. Regardless, energy supply often lags behind other forms of public infrastructure, such as water supply, roads, and the establishment of health and education facilities,[10] even in extremely rural areas; these latter facilities thus represent a unique case study for the application of decentralized mini-grid power systems, which is the focus of this paper. Current practices and commercially available options are presented briefly here, while the balance of the paper examines a detailed comparison of these and other possibilities for meeting facility needs.

Benefits and challenges for electrification of rural facilities

Electrification of healthcare and educational facilities is prerequisite for meeting the objectives of the Millennium Development Goals (MDGs).[11] The benefits of modern forms of energy in health facilities are well understood:[12,13] electricity is required for specialized medical diagnostic and treatment equipment (X-ray machines, ultrasound, centrifuges, etc.),[14] computers, electronic medical recordkeeping (EMR), and telemedicine programs. Supporting loads include lighting (for increased hours of operation and security), cold storage of medicines and vaccines as part of the ''cold chain'' climate control (rarely), and the powering of staff quarters, the latter having implications for the attraction and retention of qualified professionals to work in remote areas.[14–16]

Due to steadily decreasing prices of photovoltaic (PV) panels (9 $USD{\cdot}W^{-1}$ in 1987 to around 1 $USD{\cdot}W^{-1}$ in some markets in 2012, or $-7\%{\cdot}yr^{-1}$ adjusting for inflation,[17,18] solar power has inexorably become cost competitive with its traditional substitute: diesel-fueled reciprocating generators. Nevertheless, recent growth in diesel capacity in Africa has been prodigious (30% in 2008, adding $\sim$2 $GW{\cdot}yr^{-1}$).[19] As of 2002, total installed capacity of off-grid PV in Africa was no more than 125 MW,[17] and the most ambitious growth projections (including grid-tie solar PV) call for less than 1 GW additional capacity per year.[20] Balance of System (BOS) costs, including the batteries, charge controller, inverter, and structural support systems, have not declined as quickly as solar panel costs and now represent about half of installed costs.[21] Hybridization of PV and diesel in electric mini-grids is a means of reducing BOS costs and increasing the overall availability of the power.[22]

Poor reliability and lack of maintenance are persistent challenges to operating remote mini-grids at health clinics or schools.[14] A review of one UNDP-GEF project in Zimbabwe, for example, indicated that 48% of installed systems were faulty (of these faulty systems 33% had battery failure, 23% had lighting failures, and 12% had charge controller failures).[23] An extensive literature reports on the technical and non-technical reasons why clinic power systems frequently fail.[4,10,24–26] According to Energy for Sustainable Development[26]: ''It is quite possible that over half of the institutional systems installed over the past decade are not functional.'' We address this issue by treating operation and maintenance costs (O&M) with an explicit formulation in equations 1 and 2.

Best practices for thermal energy requirements: An unmet need

In addition to electricity, the need for thermal energy, as provision of hot water or in the form of seasonal heating or cooling of a clinic or school facility, is often overlooked in the electrification literature (exceptions are Refs. 12 and 27) and in energy generation projects, despite clear impacts on operations,[24] hygiene, and nosocomial infection rates.[28] Effects of temperature and humidity on human beings vary according to the heat index[29] and include lapses in judgment and fatigue contributing to a 2% decrement in productivity per degree Celsius above 25 or below 20°C.[30] To avoid indoor temperature extremes affecting health, safety, and productivity, requirements for climate control in a medical facility are well established (see, e.g. ASHRAE, UFC Standards,[31–33]); however, in practice adherence to these standards is not reflected in the design or operation of remote health clinics in underserved areas (author's experience based on field surveys conducted for this study). This is possibly due to wide variation in thermal needs with location, cost, and design difficulties encountered in the field, or a perception that climate control is a luxury in rural areas. As a result, sourcing power for thermal needs is usually separated from the planning for electrification, and planned electricity supplies are then both inadequate and cost prohibitive for meeting thermal loads: for example, a thermal kWh obtained from electricity costs approximately 17 times more than an equivalent thermal kWh obtained from LPG (about 0.02 USD kWh^{-1} retail in South Africa in 2012[34]). Supplementary technologies deployed ad-hoc to meet thermal needs for space heating include biomass or coal combustion stoves and LPG/propane heaters.[35] LPG and/or solar thermal water heaters are generally selected for domestic water services where indoor plumbing is available, and LPG is frequently deployed for domestic refrigeration and the vaccine cold chain at health clinics.

To overcome these limitations, we propose a holistic approach where both electric and thermal loads are considered in comparing available energy systems for health clinics, presented in Section ''Technology choice for meeting electrical and thermal loads''.

Methods

Quantification of off-grid institutions for health and education

Determination of the total number of health clinics or schools operating without modern forms of energy is problematic due to sparse national reporting and a lack of any central global database with information regarding energy infrastructure at such sites. As a first-order approximation, an estimated global total can be extrapolated from existing national datasets to aggregated global data (i.e. UNESCO, World Bank metadata) containing population and percentage electrified.[36,37] Available national data correlating number of unelectrified health clinics to unelectrified populations can be averaged to derive regional per capita averages, representing the typical catchment population for clinics and schools (Table 1). In cases where explicit national data is lacking, an estimate for number of unelectrified health clinics or schools is then found by multiplying this regional per capita factor by the unelectrified population.

Demand load estimation

In order to evaluate the demand load, a profile of a representative clinic was developed through a combination of literature survey,[13,24] local inquiries with staff, estimation methods, and physical load measurements at remote clinics ($n = 11$) in Lesotho (≈27°S 29°E) operated by either the Lesotho Ministry of Health (MoH) or the U.S. based NGO, Partners in Health (PIH).

The Rapid Rural Appraisal (RRA) approach, based on methods described by Chambers,[38] was used to elicit information from professionals (e.g. nurses, doctors, teachers) stationed at rural institutions. The primary instrument was guided interviews, including a checklist of topics regarding current energy usage and practices, experiences with electrical supply and thermal conditions, and anticipated demand for future activity.

The demand load estimation approach involves quantifying the number of known unique loads, noting their instantaneous power consumption in Watts, and multiplying by the number of hours of usage to obtain Watt-hours.[13] This activity was undertaken by the clinic operators during planning for the installation of mini-grid energy systems and was supplemented in this study by modeling with the specialized online version of the software tool HOMER,[39] developed by the National Renewable Energy Laboratory and published by the U.S. Agency for International Development. This version of HOMER contains default configurations of typical health clinic equipment load inventories that can be user-modified to fit specific installations. The full equipment and lighting inventory used is described further by Orosz.[40]

Baseline load measurement. The existence of energy supplies at a subset of clinics ($n = 3$) presented an opportunity to compare the results of an audit (measured loads) in the field to typical demand load estimation methodologies. In 2009, an energy audit was conducted over a period of six weeks at three health clinics (Nkau, Bobete, and Methaleneng) using SmartWatt SW25020 logging power meters connected inline to each phase (3ϕ inverter/generator source) in the main junction box at the clinics (sampling period $= 20$ min). Two of the clinics were supplied with 1.4 kW (peak) solar PV systems paralleled with a manually transferred 30 kVA diesel backup generator; however, fuel was not supplied at these sites. At the third site (Methaleneng), only the diesel generator was operational; the data thus reflect solar-only and diesel-only configurations. The daily outputs of the 1.4 kW solar PV systems were recorded at the system controller (Mate II, Outback), and a 42-day average yield was logged for the period of load monitoring.

Estimating thermal loads with a building envelope model. To estimate the combined heating (including hot water) and cooling loads for rural health centers, we develop a simple thermal model (heat loss due to convection and air changes) for a typical clinic complex based on existing infrastructure surveyed in Lesotho, described by Orosz.[40] Two indoor set point temperature ranges are compared, the first from applicable standards[32,33] (20–25°C, modified for humidity[29]) and the second drawn from an implied 10% decrement in worker

Table 1. Estimated number of rural health and education facilities unelectrified as of 2012.

Region	Health clinics	Primary and secondary schools	Per capita factor	
			Clinics	Schools
Americas	1200	3600	5.00E–05	1.67E–05
Africa	47,000	140,000	0.0001	0.0000328
Middle East, Central and South Asia	32,000	96,000	0.000075	0.000025
South East Asia and Oceania	6900	21,000	0.000075	0.000025

Figure 1. Three technologies for generating electricity at remote mini-grids: μ-CSP (concentrating solar power), solar photovoltaic (PV) panels, and diesel generators. μ-CSP, a solar thermal technology, is also configurable to deliver combined heating and power (CHP).

productivity according to Seppänen[30] (15–30°C, modified for humidity). Summer cooling loads include heat dissipated from electrical loads, and peak and annual thermal loads are calculated on the basis of geographically determined parameters (average temperatures and degree-days) obtained from the NASA surface meteorology and solar energy (SSE) dataset.[41]

Technology choice for meeting electrical and thermal loads

To meet the electric, heating, and cooling demand at a rural health center we compare (Figure 1; Table 2) widely used diesel generators and solar PV systems with the novel micro-concentrating solar power (μ-CSP) cogeneration system featuring single-axis tracking parabolic trough solar concentrators, an air-cooled organic Rankine cycle (ORC) power block, and sensible heat storage (detailed in Refs. 40 and 42). For μ-CSP modeling, Direct Normal Irradiance (DNI) is derived from the solar constant modified by airmass due to geoposition, overlaid by a cloudiness factor from the NASA SSE.[41] For non-imaging solar (PV or passive solar thermal) analyses, global irradiance on a latitude-tilted surface from the NASA SSE is used.

PV, diesel, and μ-CSP electricity sources can be variously combined with alternative technologies for delivering heating and cooling, e.g. LPG/Propane and solar thermal configurations (i.e. coupled with an absorption chiller). These are compared for the range of thermal loads shown in Figure 2. The configuration of a PV-LPG system where the cooling loads are handled by a vapor compression cycle (COP = 2.86, meeting ASHRAE Standard 90.1) is also considered. Average fuel costs for sub-Saharan Africa in 2012 (Diesel = 1.3 USD L^{-1}, LPG = 0.26 USD kg^{-1}) and additional assumptions of this analysis are described further by Orosz.[40] Whereas average fuel prices are used for comparison across a wide geographic area, site-specific fuel costs are more relevant to individual project technology decisions. A comprehensive analysis of fuel cost multiples for remote areas is beyond the scope of this study; however, it is important to note that these added costs may vary significantly in rural areas due to factors that include, e.g. distance from supply centers, quality

Table 2. Technologies considered for mini-grid systems to provide electricity, heating and cooling.

Technology	Input	Output electricity	Heating	Cooling
Photovoltaics (PV)	Sunlight	⊙		
Diesel generator	Diesel fuel	⊙		
Micro-CSP	Sunlight	⊙	⊙	
NH4 absorbtion chiller	Heat			⊙
LiBr absortbtion chiller	Heat			⊙
LPG-propane burner	LPG fuel		⊙	
Evacuated tube solar collector	Sunlight		⊙	
Vapor compression chiller	Electricity			⊙
Thermal storage	Heat		⊙	
Battery storage-inverter	Electricity	⊙		

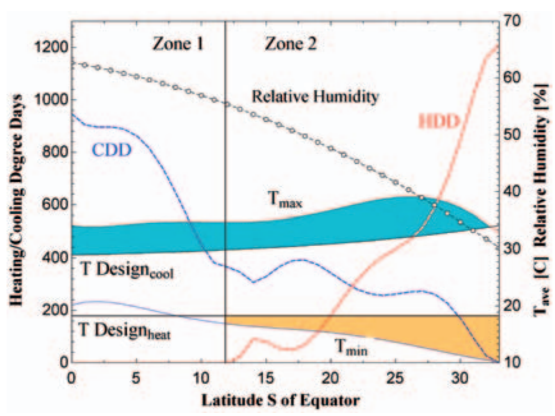

Figure 2. Latitudinal degree-day and temperature profiles for Africa based on NASA meteorological dataset. The design cooling temperature is based on Steadman's humidex.

of roads and river crossings, proximity to economic activity and fuel depots, etc. In some areas surveyed for this study, fuel supplies for health clinics were supplied by bush plane, increasing specific costs by over 100%.

Economic analysis

Financial benchmarking of the technology configurations described above is achieved with the standard discounted cash flow method.[43,44] The economic objective function is minimized net present costs (NPCs), generalized for energy systems as follows

$$\mathrm{NPC} = I_o + \sum_{t=0}^{n} \frac{O_t + M_t}{(1+r)^t} \tag{1}$$

where I_o is the initial cost of the equipment, n is the service life in years, O_t and M_t represent Operating and Maintenance costs in year t, and r is the discount rate. Operating costs are a unique function of the technology, but maintenance costs can be generalized as a function of the initial costs in two components – a constant annual service component and a linear function for repairs due to wear with age

$$M_t = \frac{f_o}{n} + \frac{f \cdot (1-a)_o}{n^2} \cdot (2t-1) \tag{2}$$

where f is the fraction of total maintenance costs with respect to initial costs, and a is a coefficient expressing the fraction of regular service costs with respect to total maintenance costs (including incremental repairs). In this study, the lifecycle annual service amount a is taken to be 0.25 of initial costs for diesel generators and chillers[45,46] and 1 for solar technologies. For diesel generators $f = 1.25$[47]; for the solar systems an average $f = 0.3$ is assumed.[48,49]

Levelized costs are calculated as NPC amortized over the lifetime (15 years) energy production of the equipment, using a discount rate of 4%, the mean discount rate from a 2001 survey of 2160 economists for problems involving a long-term environmental component (in this case creating new energy infrastructure in the context of climate change).[50] Equipment costs were estimated from manufacturer data for materials and current retail prices for equipment and fuels. PV panel 2012 wholesale prices in sub-Saharan Africa were approximately 2–3 $\mathrm{USD{\cdot}W^{-1}}$,[20,26,51] while diesel generators are available at 0.2–1.6 $\mathrm{USD{\cdot}W^{-1}}$ depending on size, features, and accessories.[4,48,52] The cost of deep cycle sealed lead acid batteries in 2011 remained above 150 $\mathrm{USD{\cdot}kWh^{-1}}$,[24,48,53,54] while for sub-MWh systems the cost for sensible thermal storage at 150°C in a cylindrical tank quartzite pebble bed ranges from 20 to 100 $\mathrm{USD{\cdot}kWh}t^{-1}$.[40]

Results

Target health and educational institutions

We estimated that in the 115 countries with 1.46 billion unelectrified citizens, there exist over 87,000 remote medical facilities and 260,000 unelectrified primary and secondary schools (Table 1). Regionally these unelectrified institutions are concentrated in sub-Saharan Africa (over 180,000) where an average of 32% of the population has access to electricity. Globally the largest single nation by unelectrified institutions is India (over 47,000), despite having over 66% of the population connected to the grid.

Rapid rural appraisal results

The Lesotho health clinics surveyed in this study were similar in operational capacity and physical attributes, with typically three to five health workers seeing 50–100 patients per day in poorly insulated masonry (concrete block) and wood joist, corrugated iron roof facilities with an average footprint of 200 m^2. Interviews with health workers revealed a strong preference for greater access to energy regardless of the electrification status of the facility. Additionally, four of the clinics (MoH) reported that previously installed (via a World Bank program) solar PV panels had been stolen, and six reported that previously installed solar hot water heaters had broken down. At the time of evaluation (July–September 2009) three of the clinics (PIH) were equipped with 3ϕ 1.4 kW PV energy systems installed by the Solar Electric Light Fund (SELF), and of those, two were equipped with backup 3ϕ diesel generators (30 kVA). The clinics are seasonally heated by coal-burning stoves or LPG heaters, and a mixture of LPG and solar hot water heaters are in use.

Baseline load determination

Demand estimation (Section "Demand load estimation") results in a modeled electrical load of 20 $\mathrm{kWh{\cdot}day^{-1}}$ for typical operational and staff uses; however, we propose the accommodation of 25% future growth in demand, i.e. a target clinic load demand of 25 $\mathrm{kWh{\cdot}day^{-1}}$ (2.2). The annual target for 330 days of operation per year is thus 8250 kWh of electricity for the alternative technologies compared. For peak power output, we derive a scaled load curve from the averaged measured load curves of Figure 3 which indicates a nominal output of 2 kW and peak capacity of 5 kW.

The average output of the 1.4 kW solar PV arrays during the measurement period was 6.3 $\mathrm{kWh{\cdot}day^{-1}}$ The measured average clinic demand load curves at sites with PV systems for weekdays (6.8 $\mathrm{kWh{\cdot}day^{-1}}$) and weekends (5 $\mathrm{kWh{\cdot}day^{-1}}$) are shown in Figure 3. The load factors (LF, percent of full capacity used)

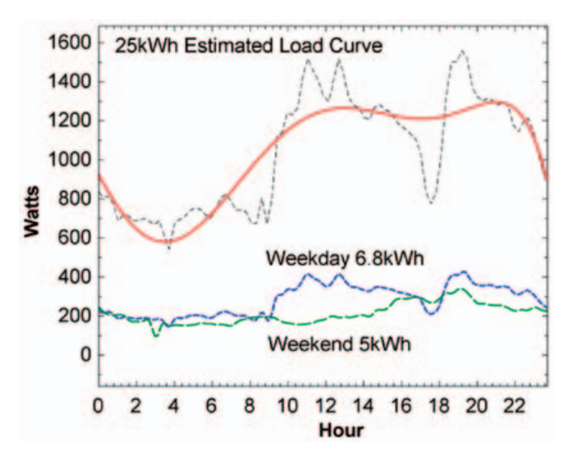

Figure 3. Measured and estimated health clinic load profiles. Average weekday (blue) and weekend (green) load curves are extrapolated to fit the load curve corresponding to the estimated target of 25 kWh day^{-1} (red).

for the PV systems were 107% and 79% for weekdays and weekends, respectively (essentially 100% combined). The load curves for the diesel-only site ranged from 2 to 5 kWh·day^{-1}, with a load factor below 3% (Figure 4).[47,54]

For thermal loads, latitude in particular is a global driving parameter (Figure 5). Average thermal loading (either heating or cooling) of 118–139 kWh$_t$·day^{-1} was estimated, with peak loads ranging from approximately 45 W m^{-1} in clinic buildings at the equator to nearly 60 W m^{-1} in latitudes from 20 to 30 degrees.

The various combination of electrical and thermal technologies appropriate for powering rural health clinics (shown in Table 2) were modeled and sized to meet the load specification of 25 kWh$_e$ and 118–139 kWh$_t$ day^{-1}. The ranking of technology options by NPC and levelized cost is illustrated in Figure 6, with bars indicating variation due to climate factors. The estimated NPC for supplying electricity to remote health clinics and maintaining indoor climate between 20 and approximately 25°C (depending on relative humidity) at the archetypal African clinic ranges from 50 k USD near the equator to a local maximum of 55 k at 5–6°S (mainly Congo, DRC, and Tanzania) and a local minimum of 44 k USD at latitudes 10–15°S (approximately parts of Angola, Zambia, Tanzania, and Mozambique) over a 15 year project lifetime.

Discussion

Health clinic electric load profile

The load estimate of 25 kWh·day^{-1} for a archetypal health clinic facility generally agrees with previously published clinic power needs estimates,[16,24] although further data collection at clinic sites having relatively unconstrained power supplies (e.g. continuously fueled generators) would be informative. During the monitoring period, the PV system energy supply was exhausted almost daily, usually tripping the low battery voltage protection late at night or in the early morning. In one instance, this feature had been defeated (presumably to extend operating hours), but this resulted in premature, and costly, battery failure.

It is interesting to note that the estimation methods (e.g. HOMER) focus on operational loads whereas in practice off-design loads are routinely observed. At the audited health clinics, only about 3 kWh day^{-1} was consumed during the operating hours (8 a.m.–5 p.m.) of the clinic, which indicates that on average only 33% of the available energy is used for strictly defined operational purposes. This could indicate a mismatch between equipment sizing procedures and actual operational needs, an implicit clinic staff preference for allocating energy towards personal uses, or a combination of the two.

At the investigated sites, estimated loads exceed measured loads by a factor of three, which could be anticipated given the LF = 99% for the PV systems, i.e. the energy systems are undersized compared to demand and the load curve reflects an adjustment to limited capacity. In the case of the diesel-only site the fuel supply, rather than the generator capacity, is the limiting factor. The diesel-only site was allocated 205 L fuel per month, equivalent to 3 kWh·day^{-1} at the part load conditions represented by their peak load curve (Figure 4).

As shown in the inset of Figure 4, the fuel consumption rate of a diesel generator decays exponentially towards its optimum efficiency at full load. Given that a diesel generator's nameplate capacity must exceed the peak load, we observe that under normal, part-load operating conditions dictated by the shape of the demand load curve, even appropriately sized diesel generators will exhibit poor fuel economy during periods of low demand (night time, weekends, etc.). Over-sizing the generator exacerbates this characteristic and severely degrades the fuel economy of the diesel plant. The tendency to over-size generators is possibly due to a relative scarcity of reliable, low RPM small-capacity (<10 kVA) engines, a "more is better" or "room to grow" rule-of-thumb approach in sizing, and the negligible capital cost of installed capacity in comparison to the high lifecycle cost of operating a diesel plant. Two deployment strategies which could address this problem include (1) operating smaller generators in parallel or (2) cycling a larger generator to charge a battery bank while supplying loads with an AC inverter. In this study, the latter configuration, which is rarely practiced, is shown to reduce the NPV of electricity costs by over 50%.[22] These costs, however, are still more than double the levelized cost of electricity from solar PV systems.

Despite their high lifecycle costs, diesel plants offer several advantages in micro-grid applications: they

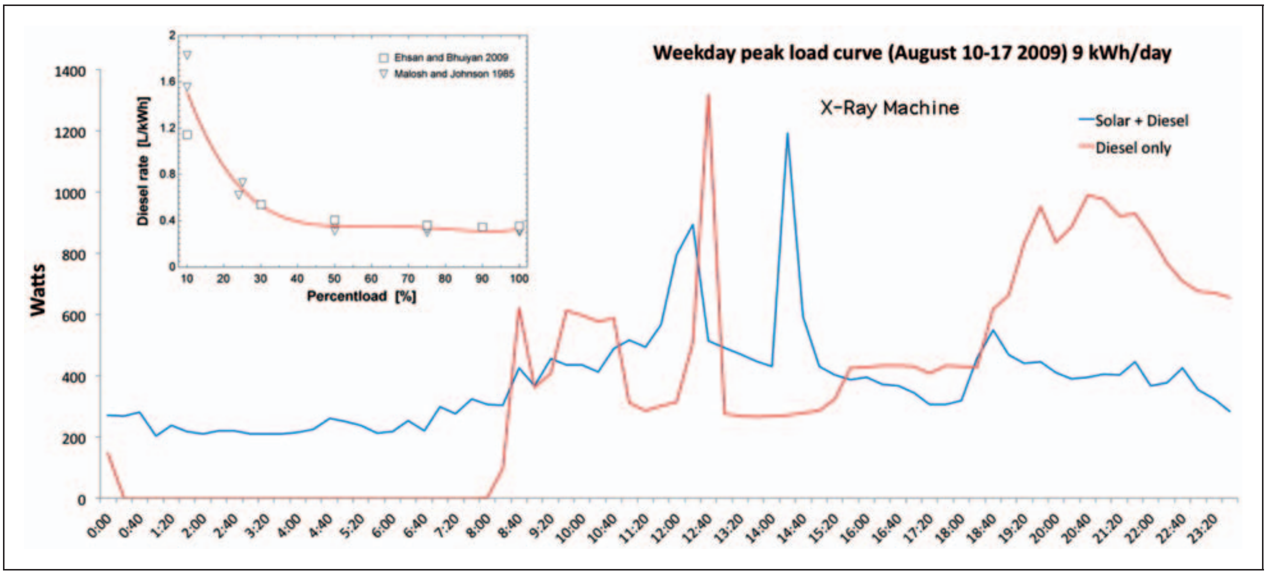

Figure 4. Measured PV and diesel clinic loads with part load fuel economy derived from Refs. 55 and 56.

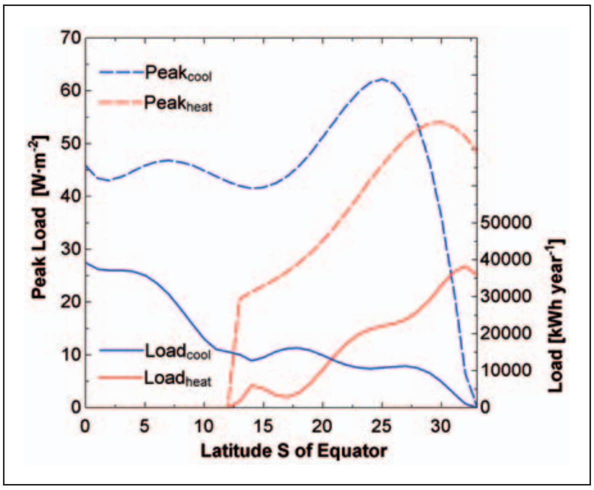

Figure 5. Latitudinal variation in Heating and Cooling Loads and Peak Capacity.

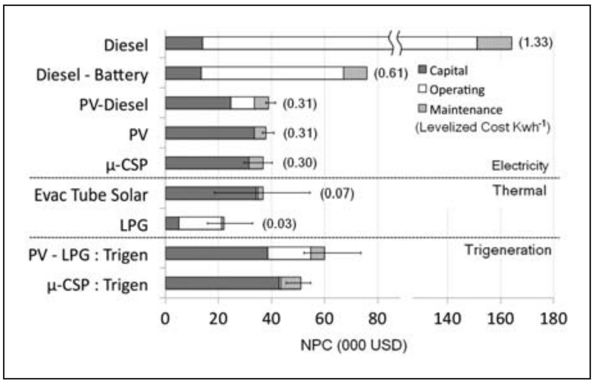

Figure 6. Net Present Cost (NPC) of distributed generation technologies meeting a typical clinic specification (25 kWh$_e$, 118–139 kWh$_t$·day^{-1}, 330 days·year^{-1}). Latitudinal variance due to thermal loads is indicated by bars where appropriate.

are quickly dispatchable (energy on demand), have a high power availability (>90%) and power quality, are commercially available in capacities of 2.5 kVA to several MVA, use a common pay-as-you-go fuel with a global supply chain, occupy a small footprint compared with renewable energy equipment, and are perceived as robust and well understood by local technicians. The low initial cost of a diesel generator compared to renewables is also a decisive factor.

Alternative technologies cost comparison

While the exact NPC and LCOE results illustrated in Figure 6 are highly sensitive to initial parameters (location, climate, building construction, thermal efficiencies of equipment, cost of inputs, discount rate, etc.), the relative ranking of approaches involves less uncertainty and provides sufficient basis for general inferences: at the time of this study, PV is more economical than diesel for electricity generation, and LPG is more cost-effective than passive evacuated tube solar collectors for thermal loads. The evaluation of μ-CSP is complicated by localized variation in DNI; in practice, it tracks close to PV for electrical generation and is generally more economical than LPG for thermal loads.

The lowest cost trigeneration solution critically depends on the local solar resource and the extent of heating and cooling loads (Figure 5). μ-CSP with trigeneration using an LiBr-H_2O chiller is more cost-effective at latitudes with strong to mild cooling demand from 0 to 20°S, and photovoltaics combined with an LPG-fired NH_4-H_2O chiller and hydronics offer similar economies at higher heating loads found >20°S (Figure 7). Photovoltaics combined with LPG heating and vapor compression cooling likewise become cost-effective at latitudes beyond

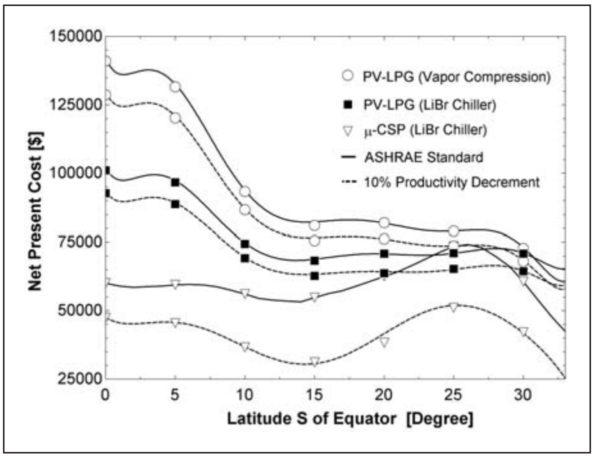

Figure 7. Variation of Net Present Cost (NPC) with latitude for μ-CSP and PV-LPG trigeneration systems meeting a 25kWh$_e$ and 118–139 kWh$_t$ day^{-1} load profile (20–25°C ASHRAE standard) and a thermal load profile with indoor comfort requirements relaxed to an implied 10% decrement in worker productivity (15–30°C Winter-Summer).

20°, where cooling loads represent a smaller fraction of the overall energy demand. To the extent that specific locations within the study area experience the fuel supply cost penalties discussed in Section "Technology choice for meeting electrical and thermal loads", however, the cost differential with respect to μ-CSP in Figure 7 is conservative.

Compliance with indoor comfort standards has implications for cost-benefit analysis. Planners may weigh outcomes at existing facilities against the need to allocate resources to other important objectives, such as, e.g. building new facilities for currently underserved populations. In this analysis, the relaxation of indoor comfort standards to permit an implied 10% decrement in worker performance has a relatively minor effect on the project NPC where thermal loads are primarily met through LPG, due in part to the discounted future costs of fuel. By contrast, relaxing the indoor temperature requirements can significantly (>30%) lower the cost of the μ-CSP trigeneration configuration, where the thermal loads over the project lifetime impose an initial cost in installed capacity. The effect of these tradeoffs on relevant operational outcomes (patient care or educational attainment) is a topic proposed for further research.

Conclusions

The deployment of energy systems at remote institutions is essential to support high quality health care or education services. To date, installation of energy infrastructure at these sites has proceeded largely without the benefit of consistent guidelines for sizing equipment or determination of load profiles, performance or cost comparison with respect to normal variation in climate or solar irradiance. Diesel generators are frequently deployed in micro-grid applications without consideration of operating costs or fuel economy. At the investigated health clinics, the rated capacity of the diesel generators were oversized compared to average demand by a factor of roughly six, possibly due to a hedging strategy against future demand expansion. Unfortunately, such a strategy leads to an operating regime with extremely poor fuel economy and increased fueling costs. In addition to these concerns, a lack of provision for operating and maintenance needs over time has resulted in a high level of attrition (estimated at over 50%) at micro-grid installations in remote areas of developing countries.

In this paper, we apply a consistent load estimation methodology and an assessment of heating, cooling, and electrification technologies for the case of an achetypal remote African health clinic serving 50–100 patients per day with a staff of 3–5 health workers. An electrical specification for 25 kWh$_e$·day^{-1} and thermal loading of 118–139 kWh$_t$·day^{-1} (meeting ASHRAE standards) was developed using a simple building envelope heat loss model and parameter correlations based on historical geographic meteorology data.

Using commonly available technologies, we find that the lowest cost configuration is sensitive to the extent of heating as compared to cooling loads. At latitudes beyond 20°S, a PV system with LPG-based hydronic heating and cooling via an NH_3-H_2O or vapor compression chiller is cost-effective, but emerging technologies such as μ-CSP (using an LiBr chiller) can be more economical depending on local thermal parameters and input costs.

Given sufficient DNI resources, our analysis indicates a potential role for μ-CSP trigeneration at remote outposts with substantial (and predominantly cooling) thermal requirements. The NPC was calculated as a function of latitude with variation due to aggregated climate factors affecting the available insolation, ambient temperature for heat loss and heat rejection, and the heating and cooling load throughout the year based on degree days and maintenance of a 20–25°C indoor temperature profile modified by the humidex (humidity heat index). NPC for μ-CSP with trigeneration varied from 60 k USD at the equator to about 45k USD at the southern tip of Africa, with a local maximum of 75 k USD at latitudes of 24–27°S. Relaxation of the indoor comfort standard to an implied 10% decrement in worker productivity (15–30°C humidex modified indoor temperatures) can reduce the NPC of a μ-CSP mini-grid by over 30%. The effect of indoor temperature on relevant social impacts at remote institutions is a proposed topic for further study.

For standalone electricity generation, PV-solar is both cost-effective and mature. Unlike a PV-LPG hybrid, μ-CSP is a completely renewable trigeneration approach, and the technology is comparatively simple and scaleable using manufacturing methods already available in sub-Saharan Africa. Finally, although beyond the scope of this study, in the context of diminishing LPG costs, further investigation of the potential synergies of LPG and solar thermal hybrid systems (e.g. incorporating waste heat recovery in an ORC) is warranted.

Finally, the type of engineering cost-benefit analysis presented here is an important prerequisite for systematic energy planning in support of rural health and education missions, and should ideally be supplemented with demand-side conservation, improved energy efficiency (e.g. increased building insulation), and project sustainability metrics, e.g. CO_2 avoidance.

Funding

This work was supported by the U.S. Fulbright Fellowship and Switzer Environmental Fellowship programs and the MIT Energy Initiative Seed Fund [award number 015728-020]. It was made possible through collaborations with the Government of Lesotho's Appropriate Technology Services and Ministry of Health and with Partners in Health.

Acknowledgements

Participatory assessments (and the ensuing technology design and testing phases) were conducted by a team of collaborators from the NGO STG International, the Massachusetts Institute of Technology, the University of Liege, and the Appropriate Technology Services.

References

1. The World Bank. *Rural energy and development: improving energy supplies for 2 billion people, best practice paper 15912*. Washington, DC: Author, 1996.
2. The International Bank for Reconstruction and Development. *Powering up: costing power infrastructure spending needs in sub-Saharan Africa, Africa infrastructure country diagnostic, background paper 5 (phase II) 61811*. Washington, DC: Author, 2009.
3. Saghir J. *Energy and poverty: myths, links, and policy issues, energy and mining sector board 37481*. Washington, DC: World Bank, 2005.
4. Deichmann U, Meisner C, Murray S, et al. *The economics of renewable energy expansion in rural sub-Saharan Africa, technical paper 5193*. Washington DC: The World Bank, 2010.
5. Foley G. *Photovoltaic applications in rural areas of the developing world, technical paper 304*. Washington, DC: Joint UNDP World Bank Energy Sector Management and Assistance Programme, 1995.
6. Krause M and Nordstrom S. *Solar photovoltaics in Africa: experiences with financing and delivery models, monitoring & evaluation report 2*. New York: UNDP Global Environment Facility, 2004.
7. Chakrabarti S and Chakrabarti S. Rural electrification programme with solar energy in remote region – a case study in an island. *Energy Policy* 2002; 30: 33–42.
8. Republic of India 2011 Census, "Maps of India". http://www.mapsofindia.com/census2011/population-density.html (accessed 10 May 2012).
9. Naude W. *World development report, technical report*. Washington, DC: World Bank, 2009.
10. Brew-Hammond A. Challenges to increasing access to modern energy services in Africa, background paper, forum of energy ministers of Africa. In: *Conference on energy security and sustainability*, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, 30 March 2007.
11. United Nations. Millennium development goals, http://www.un.org/millenniumgoals/ (2000, accessed 10 May 2012).
12. Cabraal R, Barnes D and Agarwal S. Productive uses of energy for rural development. *Ann Rev Environ Resour* 2005; 30: 117–144.
13. Burman K, Lilienthal P and Kline D. Web-based solar photovoltaic hybrid design tool for rural clinics in Africa. In: *Proceedings of ISES solar world congress 2009: Renewable energy shaping our future*, 11–14 October 2009, Johannesburg, South Africa. Washington, DC: International Solar Energy Society (ISES), 2009, pp. 910–919. NREL Report No. CP-7A4-48573.
14. The World Bank. *The welfare impact of rural electrification: a reassessment of the costs and benefits, IEG impact evaluation 45400*. Washington, DC: Author, 2008.
15. Ezzati M, Bailis R, Kammen D, et al. Energy management and global health. *Ann Rev Environ Resour* 2004; 29: 383–419.
16. Kirubi C, Jacobson A, Kammen D, et al. Community-based electric micro grids can contribute to rural development: evidence from Kenya. *World Dev* 2009; 37: 1208–1221.
17. Moner-Girona M, Ghanadan R, Jacobson A, et al. Decreasing PV costs in Africa. *Refocus* 2006; January/February: 40–45.
18. Krugman P. Here comes the sun. *The New York Times*, 6 November 2011, p. A25.
19. Sales of diesel gensets reach new highs, African review of business and technology, http://tinyurl.com/dieselafrica (2008, accessed 25 March 2012).
20. Goncalves D. *The solar PV gold rush to South Africa*. CA, USA: Frost & Sullivan, 2011. http://tinyurl.com/d4ajcbl (2011, accessed 25 March 2012).
21. Bony L, Doig S, Hart C, et al. *Achieving low-cost solar PV: industry workshop recommendations for near-term balance of system cost reductions, technical report*. Snowmass, CO: Rocky Mountain Institute, 2010.
22. Rehman S and Al-Hadhrami L. Study of a solar PV-diesel-battery hybrid power system for a remotely located population near Rafha, Saudi Arabia. *Energy* 2010; 35: 4986–4995.
23. Chigwada J. Paper presented at the workshop on financing mechanism and business model for PV project, cited in Krause 2004, May 2003, Pretoria, South Africa.
24. USAID. *Powering health: energy management in your health facility*. Washington, DC: United States Agency for International Development, 2011.
25. Joint UNDP World Bank Energy Sector Management and Assistance Programme. *Photovoltaic applications in rural areas of the developing world, technical paper 21992*. Washington, DC: Author, 2000.
26. Energy for Sustainable Development. *Study on PV market chains in East Africa, World Bank study*. Africa, October 2003.
27. Kammen D and Kirubi C. Poverty, energy and resource use in developing countries: focus on Africa, 2008. *Ann NY Acad Sci* 2008; 1136: 348–357.

28. Axel K, Ingeborg S and Günter K. How long do nosocomial pathogens persist on inanimate surfaces? A systematic review. *BMC Infect Dis* 2006; 6: 130.
29. Steadman R. The assessment of sultriness. Part I: a temperature-humidity index based on human physiology and clothing science. *J Appl Meteorol* 1979; 18: 861–873.
30. Seppänen O, Fisk WJ and David F. Cost benefit analysis of the night time-ventilative cooling in office building. In: *Proceedings of the Healthy Buildings 2003 Conference*, Singapore, vol. 3, 7–11 December 2012, Healthy Buildings 2003, Inc., Singapore.
31. ASHRAE. *Standard 62, ventilation for acceptable indoor air quality, technical report*. Atlanta, GA: American Society of Heating, Refrigerating and Air Conditioning Engineers, 2007.
32. ASHRAE. *Standard 55, thermal environmental conditions for human occupancy, technical report*. Atlanta GA: American Society of Heating, Refrigerating and Air Conditioning Engineers, 2010.
33. Dalton J, Gott J, Hartford S, et al. *Unified facilities criteria (UFC) design: medical military facilities*. USA: Department of Defense, 2012.
34. Liquefied petroleum gas safety association of southern Africa, fuel prices March 2012, http://www.lpgas.co.za/page34/page34.html (2012, accessed 25 March, 2012).
35. Taele B, Gopinathan K and Mokhutsoane L. The potential of renewable energy technologies for rural development in Lesotho. *Renewable Energy* 2007; 32: 609–622.
36. World Bank, "World databank". http://databank.worldbank.org/data/views/variableSelection/selectvariables.aspx?source=world-development-indicators (2012, accessed 15 December 2012).
37. UNESCO institute for statistics data centre, http://www.uis.unesco.org/Pages/default.aspx (2012, accessed 15 December 2012).
38. Robert C. Rapid rural appraisal: rationale and repertoire. *Publ Adm Dev* 1980; 1: 94–106.
39. Lambert T, Gilman P and Lilienthal P. Micropower system modeling with HOMER. In: FA Farret and M Godoy Simoes (eds.) *Integration of alternative sources of energy*, ch. 15. John Wiley & Sons, Inc., 2006, www.poweringhealth.org (2006, accessed 15 January 2012).
40. Orosz M. *Thermosolar and photovoltaic hybrid systems for distributed power applications*. PhD Thesis, Massachusetts Institute of Technology, Cambridge, MA, 2012.
41. NASA Atmospheric Science Data Center. Surface meteorology and solar energy, http://eosweb.larc.nasa.gov/ (2012, accessed 15 January 2012).
42. Quoilin S, Orosz M, Hemond H, et al. Performance and design optimization of a low-cost solar organic Rankine cycle for remote power generation. *Solar Energy* 2011; 85: 955–966.
43. Miller D and Hope C. Learning to lend for off-grid solar power: policy lessons from World Bank loans to India, Indonesia, and Sri Lanka. *Energy Policy* 2000; 28: 87–105.
44. Chaurey A and Kandpal TC. A techno-economic comparison of rural electrification based on solar home systems and PV microgrids. *Energy Policy* 2010; 38: 3118–3129.
45. Bartel T, Butz L, Butz T, et al. *Costs of utility distributed generators, 1–10 MW twenty-four case studies, technical report* (1007760). Palo Alto, CA: Electric Power Research Institute, 2003.
46. Lilly DA. *Analysis and performance of gas-electric hybrid chiller systems*. MS Thesis, Georgia Institute of Technology, May 1998.
47. Jimenez A and Olson K. *Renewable energy for rural health clinics, technical report*. Golden, CO: National Renewable Energy Laboratory, 1998.
48. IRENA. *Concentrating solar power, technical report 2 (Renewable energy technologies: cost analysis series)*. Bonn, Germany: IRENA, 2012.
49. National Renewable Energy Laboratory. *Distributed generation renewable energy estimate of costs*. Golden, Colorado: National Renewable Energy Laboratory, 2012.
50. Guth J. Resolving the paradoxes of discounting in environmental decisions. *Transnatl Law Contemp Probl* 2009; 18: 95–114.
51. Yaholnitsky I. PV panel wholesale prices in South Africa, personal communication. Director, Bethel Business and Community Development Center, March 2012.
52. Kozlowski D. Onsite options, facilitiesnet, http://www.facilitiesnet.com/energyefficiency/article/Onsite–Options–1679# (2002, accessed 25 March 2012).
53. Aabakken J. *Power technologies energy data book, technical report 620-39728*. 4th ed. Golden, CO: National Renewable Energy Laboratory, 2006.
54. Tetra Tech. *Assessment of backup power needs for selected laboratories in Mozambique, final report 620-39728*. Arlington, VA: Author, 2010 [Prepared for Association of Public Health Laboratories, APHL].
55. Malosh J and Johnson R. *Part load economy of diesel-electric generators, final report*. Fairbanks, AK: State of Alaska Department of Transportation and Public Facilities, Division of Planning, Research Section, 1985.
56. Ehsan M and Bhuiyan S. Dual fuel performance of a small diesel engine for applications with less frequent load variations. *Int J Mech Mechatron Eng* 2009; 9: 30–39.