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Highlights

The delivery of low-cost, low-carbon rural energy services

Energy Policy ▮ (▮▮▮▮) ▮▮▮–▮▮▮

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► We present a case study of conservation measures implemented in a diesel microgrid. ► An energy conservation and supply curve is constructed using additional measures. ► Energy efficiency and renewable energy result in cost savings and carbon abatement. ► We discuss weaknesses of energy supply and carbon abatement curve calculations

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ABSTRACT

The provision of both electrical and mechanical energy services can play a critical role in poverty alleviation for the almost two billion rural users who currently lack access to electricity. Distributed generation using diesel generators remains a common means of electricity provision for rural communities throughout the world. Due to rising fuel costs, the need to address poverty, and consequences of global warming, it is necessary to develop cost efficient means of reducing fossil fuel consumption in isolated diesel microgrids. Based on a case study in Nicaragua, a set of demand and supply side measures are ordered by their annualized costs in order to approximate an energy supply curve. The curve highlights significant opportunities for reducing the costs of delivering energy services while also transitioning to a carbon-free electrical system. In particular, the study demonstrates the significant cost savings resulting from the implementation of conventional metering, efficient residential lighting, and electricity generation using renewable energy sources.

1. Introduction

Electricity provision facilitates access to energy services that can directly address quality of life and economic opportunity for rural communities (Cecelski, 2000; Kirubi et al., 2009; Cabraal et al., 2005; Flavin and Aeck, 2005). Electricity needed for motive power, such as grinding and pumping, is not the only manner in which it can serve as a catalyst for economic activity. A study in Kenya documents the utilization of low power consumption for such economic activities as tailoring, hair salons, phone services, radio and television repair, and refrigeration for household businesses in rural Kenya (Kirubi et al., 2009). Access to electricity consistently increases the quality of services available to meet basic business and domestic needs for families, such as lighting, labor saving devices for kitchens, and information and leisure activities from TV and radio (IEG, 2008). Many of these services disproportionately benefit women and children, who are involved in domestic activities. While access to electricity services may not lessen work burdens, it improves the conditions in which domestic activities take place (Cecelski, 2000; Bose, 1993) and creates opportunities for economically productive tasks (Cabraal et al., 2005). The provision of high quality lighting cannot be underestimated, providing healthier conditions for domestic work and study, and increased security in public spaces and walkways (Jacobson and Kammen, 2007; Cecelski, 2000). Educated professionals, such as doctors, nurses, and teachers, are more willing to remain in a rural setting if they are able to access forms of modern energy (Modi, 2005). Unfortunately, there are close to 1.4 billion people without access to electricity in the world, the majority them living in rural areas (IEA, 2010).

Cost is the primary barrier to the widespread delivery of electricity. Rural users live in remote areas and often have limited capacity to pay for services (IEG, 2008). This necessitates electricity providers to determine the lowest cost means of electrification, often having to subsidize the true cost of electricity delivery. However, as many authors have pointed out, it is not the delivery of electricity that matters, but rather the provision of energy services (Cabraal et al., 2005; Modi, 2005), which underscores the need for energy providers to pay close attention to demand-side energy measures. A number of studies have examined the benefits of distributed generation and renewable energy integration as a means for increasing access to areas where grid extension might not be feasible in the near term (Kaundinya et al., 2009). However, studies quantitatively comparing costs between supply and demand-side measures for rural power systems are harder to find. In order to determine the most cost effective and appropriate rural energy system, both supply and demand-side measures must be considered.

Demand-side programs are fundamental for systems where the ongoing costs of electricity provision are high, such as diesel microgrids. While grid extension is typically the most prevalent tool utilized by governments to rapidly increase electricity access, in many cases it is more cost effective to bring electricity to isolated communities through the development of microgrids

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that generate power at or near the village location (Kaundinya et al., 2009). Tens of thousands of village-scale microgrids exist worldwide, the majority in China, Nepal, and India (Flavin and Aeck, 2005). While there are a large number that utilize micro-hydrogeneration, those that are not located in areas with adequate river resources typically rely on diesel powered generators (Solano-Peralta et al., 2009; Baring-Gould et al., 1997; IEG, 2008). Due to the low capital costs and ubiquitous diesel suppliers and service networks, diesel generators often become the technology of choice, without placing sufficient consideration on the long term volatility of fuel costs (World Bank, 2006).

Over the past 8 years, the average price of diesel fuel has more than doubled leading to sharp rises in the cost of electricity generation from diesel engines. Diesel prices for rural users are further exacerbated by the costs needed to transport the diesel fuel to isolated rural areas, often resulting in the cost doubling or tripling.[1] Addressing adequate demand-side measures can greatly reduce the costs of energy service provision in these contexts.

By looking at both the energy demand and supply for a diesel microgrid in rural Nicaragua, we show that a cost analyses that neglects energy efficiency misses the most effective means of meeting rural energy needs. Our analysis is based on actual load measurements of consumer response to the installation of conventional household meters and the replacement of incandescent bulbs with compact fluorescent lights, implemented during the period of June–August 2009. In addition, we estimate costs and benefits from a number of other demand and supply side measures that could feasibly be implemented in the future. The demand-side measures include the installation of meters, residential efficient lighting, and more efficient public lighting. The supply side measures analyzed include cost estimates for the reduction of diesel plant size and the integration of electricity generation based on wind, solar, and biomass-based fuels.

In order to compare the economic benefits between different measures, and to highlight the importance of methodological consistency, an estimation of an energy supply curve is constructed that includes both supply costs and the cost of conserved energy. The curve provides insight into relative benefits of energy conservation measures, and may help encourage energy providers and policy makers to rethink conventional wisdom used for making investment decisions in both isolated and grid connected systems. Well documented examples of energy systems that jointly address low-cost and low-carbon objectives, particularly in rural areas of developing nations, are rare. In a context of global warming and emerging international policy strategies for the mitigation of carbon dioxide emissions, this paper demonstrates that the transition from diesel generation to carbon-free rural electricity systems can be done while also reducing costs.

2. Nicaraguan case study

Orinoco and Marshall Point are two neighboring villages situated on the Atlantic Coast of Nicaragua, with populations of roughly 850 and 300 people, respectively. In the village of Orinoco there is a three-phase 110 kW diesel generator. Two of the phases are distributed within the village, with the third phase connecting the village of Marshall Point, located 3 km away. The distribution system provides power to a total of 186 clients, administered by the national electric company (ENEL). As of August 2009, the system received a monthly allotment of 4540 l of diesel fuel, and the plant was operated 12 h every day, running from 12 pm to 12 am.

Table 1
Estimation of total loads by source, in Orinoco and Marshall Point.[a]

	Orinoco	Marshall Pt	Total	kWh/month	%
Connected houses	121	51	172	3839	66.8
Public lighting	29	25	54	1458	25.4
Hotels	2	0	2	273	4.7
Health clinic	1	1	2	82	1.4
Churches	4	2	6	41	0.7
Schools	2	0	2	30	0.5
Carpentry shop	1	0	1	15	0.3
Communal building	0	1	1	11	0.2

[a] Consumption estimates are based on the meter readings for the month of August 2009. Public lighting estimation is based on the assumption that each light bulb is 150 W and is turned on between 6 pm and 12 am every day. In reality, many of the automatic light sensors on the street lights do not function, and many of the lights remain on for 12 h. The carpentry shop is fairly new and is not yet regularly utilized.

Over ninety percent of the consumption is residential use (lighting, TV, and refrigeration) and public illumination, with very little utilized by commercial or public buildings. Table 1 contains estimations of the loads within the community:

During the months of June–August, 2009, two demand-side measures were implemented within the microgrid. During the month of June, ENEL installed meters at each client connection, prior to which the tariff charged to each client was based on an estimation of their demand. In August the Ministry of Energy and Mines supported a request from a local non-government organization to conduct an energy efficiency campaign, focused on replacing incandescent lights with compact fluorescent lights (CFLs).

The installation of the meters resulted in a 28% reduction in the electricity load, and the installation of CFLs resulted in an additional 17% load reduction. Measurements of the load profiles before and immediately after the meter installation, as well as following the installation of the CFLs, are shown in Fig. 1. Following the diesel savings that resulted from the meter installation, grid operation was increased two more hours, to twelve hours per day.

3. Methodology

Cost estimations for additional measures were used to augment the analysis of the CFL and meter installation. There are a number of common metrics that can be used in order to compare the costs and benefits of the various measures, such as capital cost, the net present value, the internal rate of return, or the annualized energy cost. Akin to the annualized energy cost, the marginal cost of conserved energy (CCE) is a useful metric for comparing conservation with energy supply measures (Blumstein and Stoft, 1995; Stoft, 1995; Rosenfeld et al., 1993; AK Meier, 1982). CCE may be defined as the total investment cost of conservation (TCC) for the intervention, divided by the total resultant energy savings[2] :

$$\text{cost of conserved energy (CCE)} = \frac{\text{total investment cost of conservation (TCC)}}{\text{total energy savings}}$$

The total cost of conservation includes the capital costs, operation, and maintenance costs over the lifetime of the measures. A more

[1] Rural locations in many developing countries often require boat or air transport to carry fuels, resulting in fuel prices which can be as great as three times more expensive than urban areas (Personal communications in Colombia and Nicaragua).

[2] See Stoft (1995) for a detailed discussion of a more complete calculation of the cost of conserved energy, rather than the discretized, but commonly used, formula presented here.

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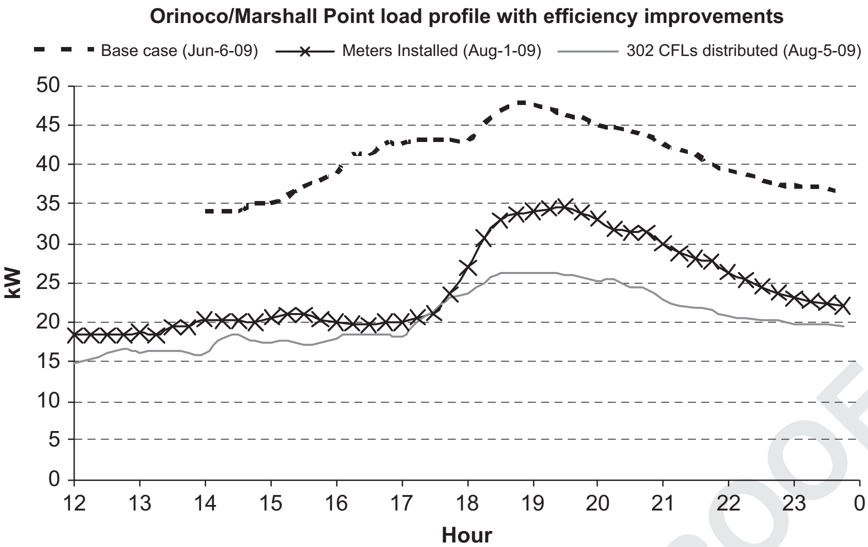

Fig. 1. Load profile before and after demand-side measures were implemented.

complete calculation accounts for the time value of money by using the levelized annual (annualized) costs, divided by the annual energy savings. The annualized costs (AC) are calculated from the present value (PV) of the costs: $AC = PV \cdot r/1-(1+r)^{-n}$, where r is the real discount rate and n is the lifetime of the intervention. This gives

$$CCE = \frac{\text{annualized cost of conservation}}{\text{annual energy savings } (\Delta E)}$$

CCE for various conservation measures can be compared with annualized energy supply costs. For example, in terms of energy services delivered, a kWh of electricity that supplies a quantity of lighting using inefficient technology would be equivalent to the reduction in demand by a kWh of electricity delivering the same lighting using more efficient technology. In both cases, a quantity of energy service is provided, one by supplying a kWh, and the other by conserving a kWh.

Table 2 summarizes various metrics for interventions to the Orinoco and Marshall Point electric system. The first two demand-side measures, meter and CFL installation, have been implemented, and the energy savings are based on actual measurements of the load changes. All other activities in the table are based on estimations, and are discussed in detail in the following sections.

The measures are ordered by increasing values with respect to the cost of conserved energy (CCE), which were calculated using each previous measure as a baseline. The supply side measures are based on *additional costs* for integration into the existing grid. For example, the costs for the 55 kW diesel generator are the additional investment costs (capital cost and installation) and do not include the cost of diesel fuel or ongoing labor and maintenance, since these costs are already being paid. The annual levelized costs were calculated using a discount rate of 8.0%,[3] and include both capital and operation and maintenance costs. The amount of total energy (kWhs) and diesel fuel that is saved is based on the reduction in demand resulting from the intervention.[4] In the case of renewable generation, the energy supplied is based on the amount of renewable energy that can be generated to offset diesel fuel consumption. It is important to note that there is a drop in efficiency of diesel engines as the load decreases. The change in diesel efficiency was modeled using HOMER, a micro-power simulation tool. The annual savings are calculated from the number of liters of diesel fuel that are saved, using a constant diesel price of $1.06.[5] The internal rate of return ~~is calculated~~ demonstrates the comparative economic value of the various measures, as well as overall economic attractiveness of the specific measure.[6]

4. Demand-side measures

The following section discusses the details of the demand-side conservation measures used in the analysis. It is worth repeating that meter installation and the introduction of more efficient residential lighting were actually implemented, while the other measures are estimations.

4.1. Meter installation

Prior to the meter installation the tariff charge was based on an estimation of the household consumption according to the appliances owned. ENEL conducted household audits to

[3] The discount rate accounts for market interest rate minus inflation (i.e. the real interest rate). In 2003, 14% was an average cost of capital in Nicaragua (World Bank, 2003), and the rates of interest between 2003 and 2009 were not dissimilar (see lending rates at the national bank: http://www.bcn.gob.ni/). However, due to the fact that many systems for rural electrification are subsidized by the government or supported by international lending institutions such as The World Bank and The Inter-American Development Bank, they would most likely have access to capital at interest rates lower than the typical market rates in the country, which is why 8.0% was chosen.

[4] Liters of diesel conserved/year $= 365$ days/year/LHV kWh/l$(P_1$ kWh/day/$\eta_1 - P_2$ kWh/day/$\eta_2)$, is the equivalent amount of diesel fuel (in liters) that was conserved, ~~either~~ through the reduction in load, where η_1 is the diesel efficiency before the measure and η_2 is the efficiency following the measure, ~~or replacement of supply~~. The lower heating value (LHV) used for the diesel fuel is 9.84 kWh/l.

[5] This fuel price is based on the average retail diesel price for 2008 (derived from data from the Nicaragua Institute of Energy, http://www.ine.gob.ni/). The diesel prices in rural areas in 2009 remained at or above this price. The authors were not able to ascertain the true cost that the government pays for the diesel fuel. While this cost is surely much lower than the retail price, it is unlikely that it would remain constant for the demand or supply side measures that have lifetimes greater than 5 years.

[6] The internal rate of return (IRR) is calculated by finding the interest rate at which the net present value of investment is equal to zero (i.e., the lifetime costs and benefits are equal). Investments where the IRR is greater than the cost of capital are typically considered attractive.

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Table 2
Summary table of demand and supply side measures in the Orinoco and Marshall Point electric grid.

	Capital cost	Lifetime (year)	Annualized cost ($/year)	kWh/day electricity saved or supplied	Liters/day of diesel saved	Estimated annual diesel savings	Internal rate of return (%)	Cost of cons. or supplied (annualized) energy ($/kWh)
Meter installation	$4350	10.0	$648	115	33	$12,726	293	$0.02
CFL installation	$1030	2.0	$577	50	14	$5581	528	$0.03
Smaller street lights	$3240	7.0	$622	46	13	$5101	157	$0.04
Biogas	$13,500	10.0	$4012	43	22	$8690	49	$0.26
Reduce diesel plant capacity	$23,000	5.0	$5760	58	24	$9157	28	$0.27
Wind turbine (class 2)	$61,557	15.0	$7767	54	22	$8500	10	$0.39
Replace street light sensors	$322	0.3	$1352	9	4	$1468	23	$0.42
Solar PV	$92,300	20.0	$9501	33	14	$5579	2	$0.78

determine the power rating of each appliance coupled with an estimate of the number of hours that each appliance would be utilized. The time of use estimates were based upon the assumption that most of the appliances would be in use for the full operation of the grid. Because the consumers were aware that their tariff charge was not reflective of the actual amount of energy that they consumed, there was very little motivation within the community to conserve electricity. When the diesel plant would start during the day, the majority of loads would immediately come on. For example, light bulbs (the majority being incandescent bulbs) in houses and churches were frequently left on when the plant started in the afternoon.

Operators of microgrids may choose not to install household meters, often due to the capital outlay and operational costs. However, the costs of the meters can be transferred to the clients through a small charge bundled into the monthly bills.[7] There may be additional ongoing costs to the energy provider caused by the need for a person to take monthly measurements of the meter and additional administrative time for calculating monthly charges. However, in the case of Orinoco and Marshall Point, meter reading was added to the tasks of one of the salaried workers, so there were no additional labor costs for ENEL. It should be noted that there are important social components of successful metering, such as insuring that the clients trust the accuracy of the meters as well as the ability of the meter reader.[8] In addition, it is important that tamper resistant meter technology is chosen.[9]

Following the installation of the electric meters, the peak load dropped by 30% from close to 50 kW down to 35 kW, and the load profile took on the more familiar bell-shaped curve with an evening peak due to the loads from household lighting, as shown in Fig. 1. The savings in diesel fuel that resulted from the decreased consumption allowed the administrators to increase the operation of the diesel grid by two hours every day. The estimated cost of conserved energy was 0.02 $/kWh,[10] with an IRR of 293%, showing the strong economic rationale for installing meters.

4.2. Efficient residential lighting

Fluorescent lights typically provide the equivalent light output as incandescent bulbs while consuming only 25% of the electricity, with five to eight times longer operating lifetimes (Hong, 2002). However, barriers to widespread adoption include higher upfront costs, prevalence of poor quality brands, lack of awareness of the economic advantages, and lack of availability in rural communities (Kumar et al., 2003; Gadgil and De Martino Jannuzzi, 1991). The Nicaraguan Ministry of Energy and Mines (MEM) agreed to support an energy efficiency campaign in Orinoco and Marshall Point, in August of 2009. The MEM donated 330 15 W CFLs and 165 brochures describing methods for household energy conservation. Household owners who had incandescent light bulbs were offered the opportunity to remove two of their incandescent light bulbs in exchange for two 15 W CFLs.[11]

In an electric system where the marginal production cost is subsidized (i.e. money is lost with each unit of energy produced) it is economically rational for the provider to look for ways to reduce consumption, while maintaining the same level of energy service to the clients. The estimated cost for purchase and installation of each bulb was $3.12. Using a conservative bulb lifetime estimate of 2 years,[12] the estimated cost of conserved energy for the CFL campaign was 0.03 $/kWh, resulting a 17% reduction in demand. The CFL installation provided the most attractive financial investment, with an IRR of 528%.

Due to the economic advantages of CFLs and the existing distribution chains of the bulbs in developing countries, policy strategies such as educational campaigns may help increase the rate of adoption in rural areas (Kumar et al., 2003), and the actual distribution could be left to local store owners and entrepreneurs. In addition, it is important to fully understand the barriers to adoption of energy efficiency in every community setting (Jaffe and Stavins, 1994).

[7] ENEL charges a monthly meter rental fee of $ 0.59.

[8] In the neighboring town of Bluefields, several clients questioned whether or not their meter was accurate, but independent measurements by the author confirmed its accuracy.

[9] There exists anecdotal evidence from neighboring communities that individuals could be hired to tamper with older types of meters so that they underrepresented the true consumption.

[10] A lifetime of 10 years and a cost of $25 per meter was used, with a $50 transport cost to the village.

[11] In order to insure that all houses had the opportunity to receive two CFLs, and to account for broken/malfunctioning bulbs, the NGO provided additional CFLs.

[12] The CFLs have a manufacturer stated lifetime of 7000 hours. This is usually calculated as the expected lifetime for 50% of the manufactured bulbs. If we assume a usage of 5 h/day, this would give a lifetime of 3.8 years. However, since we do not yet have empirical data on the lifetime of the bulbs used (brand-name Liya), a conservative lifetime estimate of 2 years was used.

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4.3. Energy efficient public lighting

Public lighting is an important aspect of rural energy systems, increasing security and mobility during the evening hours (Cecelski, 2000). It is estimated that the public lighting in Orinoco and Marshall Point currently accounts for over 25% of the daily load. This consumption can be reduced by providing more appropriate levels of illumination on public walkways and increasing the reliability of the individual photo-sensors that are used to automatically turn on each light after dark.

In Orinoco and Marshall Point there are a total of 54 public street lights. While there are several CFL lights used for public lighting in Marshall Point, the majority of the lights are 150 W, 220 V high pressure sodium (HPS) bulbs. In the communities of Orinoco and Marshall Point (where there are no vehicles) the public lighting is utilized for illumination of walkways and public spaces. Low pressure sodium (LPS) bulbs have higher efficiencies than HPS bulbs at a given wattage, though they provide poor color rendering. For example, manufacturer data from Sylvania state that a 55 W LPS bulb has an average efficiency of 140 lm/W, compared to 90 lm/W for a 150 W HPS bulb. In places where color rendering is not important, such as walkways, the community members could replace the HPS bulbs with LPS bulbs. Replacing the 150 W high pressure sodium bulbs with 55 W bulbs would result in a 40% decrease in illumination, but a 65% drop in energy consumption. In order to discern the utility loss to the customers, several demonstration lights should be installed in order to test public preferences. In addition, 55 W fluorescent lights, or HPS lights, could replace the higher power HPS lights in places where color rendering is desired, but less illumination would be satisfactory.

Technicians at ENEL have made unverified claims that the lifetimes of the photo-cells is typically on the order of 3 months, resulting from the high salinity and humidity of the coastal environment. Due to the remote location of the communities, as well as time lags and bureaucratic hold-ups between light sensor replacements, there are several approaches to addressing the problem of non-functioning sensors. ENEL has experience in other communities retrofitting the public lighting system with a photo-sensitive switch that controls the entire lighting system, rather than separate ~~ones~~ for each bulb. This requires additional capital investment to set up a parallel wiring system for the bulbs, but once it is installed it is much easier to manage the replacement of a single sensor. The second approach would be for the energy provider to take account of the large fuel costs resulting from failed sensors (when the sensors fail, the light remains on during the daylight hours) and prioritize having a stock of sensors at each microgrid and replacing the sensors as soon as they fail. An individual sensor retails for five dollars, so it would pay for itself after only 11 days of use.[13]

5. Supply side measures

There are a number of modifications that can be made on the supply side to an existing diesel system in order to decrease the fuel consumption, while still meeting demand. The options include increasing the efficiency of the diesel machine by making sure that it is better matched to the loads, integrating other generation sources to supplement the diesel production, or switching the fuel from petroleum based diesel to other combustible fuels such as biomass-based oil or gas.

[13] This assumes the grid is operated during 6 h of daylight, and the marginal production of the diesel generator is 0.43 $/kWh (based on the performance of the Orinoco generator, and diesel at 1.06 $/l).

5.1. Resizing the capacity of the diesel plant

Fuel savings can be achieved by proper matching of a diesel generator to the load (Baring-Gould et al., 1997; Hunter and Elliot, 1994). The average efficiency of a diesel generator varies with load; there is an initial amount of fuel consumed in order to overcome frictional and electromechanical losses and begin turning the generator before the first kWh of electricity is produced. Therefore, the average efficiency, (total kWh produced divided by total kWh of fuel consumed) is highest when the generator is running close to its greatest output.

Utilizing HOMER, a micro-power optimization model, we calculated the potential fuel and dollar savings if the current 110 kW sized generator were to be replaced with a 55 kW generator. Table 3 shows the decrease in fuel consumption and the increase in efficiency resulting from changing to a smaller engine. The load of 197 kWh/day is the resulting load following the implementation of the more economic conservation measures; as demand-side measures decrease the total load, the diesel engine becomes less efficient. The replacement with a smaller diesel plant could result in a potential savings of 24 l per day, with an IRR of 28%.

5.2. Displacement of diesel using wind and solar energy

There are numerous successful, village-scale micro-grids that utilize intermittent renewable energy technologies, such as wind or solar photovoltaics (PV), used to supplement diesel systems (Flavin and Aeck, 2005; Baring-Gould et al., 2003; Illindala et al., 2007). Due to the intermittency of some renewable energy sources and the expense of energy storage, it is common for such systems to utilize diesel generators to meet the base loads, supplemented by wind or solar. When the PV or wind generators are producing power, the diesel generator experiences a decreased load and reduces its output based on voltage or frequency control. As mentioned in the previous section, diesel systems operate most efficiently when running at greater loads, therefore such hybrid systems require a careful technical and economic analysis to determine the optimal level of renewable energy integration, where the fuel savings from renewable integration are not mitigated by decreased diesel performance. The simplest systems, which do not typically require additional diesel control equipment, are those that are sized so that the diesel system never falls below 30–40% of its maximum load (Baring-Gould et al., 2003; Hunter and Elliot, 1994).

The cost effectiveness of wind or solar integration is sensitive to lifetime estimates of fuel cost trends, as well as the wind and solar resources. The case study area has moderate solar resources and marginal wind resources (4.6 kW/m^2/day solar resources and class 1–2 wind regimes). Table 4 shows lifetime cost estimations for the integration of wind or solar PV into the Orinoco and Marshall Point microgrid. As can be seen in the table, lifetime costs for wind generation decrease considerably when located in better wind resources.

It is important to note that the supply costs are sensitive to the particularity of this case study. The grid is currently operated from noon to midnight, resulting in a need for battery storage in

Table 3
HOMER simulation results for a 55 kW plant versus a 110 kW plant.

Plant capacity	load kWh/day	L/day	kWh/l	Efficiency (%)
55 kW plant	197	80	2.46	25.0
110 kW plant	197	104	1.90	19.3

Table 4
Lifetime costs for wind/solar integration into Orinoco/Marshall Point grid.

Technology	Capacity (kW)	Lifetime (year)	Capital cost	Levelized cost ($/year)	kWh/day	$/kWh
Wind turbine (class 1)[a]	10	15.0	$55,557	$7066	22.0	$0.88
Wind turbine (class 2)[b]	10	15.0	$61,557	$7767	54.0	$0.39
Solar photovoltaics[c]	10	20.0	$92,300	$9501	33.4	$0.78

[a] 15 year lifetime, ARE 442 wind turbine, class 1 wind data typical of case study area (Weibull probability distribution, $f(v)=k/c(v/c)^{k-1}\exp[-(v/c)^k]$ where v is wind velocity with parameters $k=2.4$, and $c=4.8$ at height of 25 m). The system uses Trojan L16 batteries with a nominal capacity of 17 kWh.
[b] Same as above, with wind characterized with Weibull distribution parameters of $k=2.4$, $c=6.5$ at 25 m, and a battery bank with a nominal capacity of 69 kWh.
[c] Solar photovoltaics estimated at 20 year lifetime, horizontal average solar radiation of 4.6 kWh/m^2/day, with 86 kWh of nominal battery capacity.

Table 5
Lifetime costs and production values for an anaerobic digester.

System lifetime (years)	10
Daily filtered gas production (kWh/day)	221
Electricity generation (kWh/day) from biogas	43
Present value of capital cost	$13,500
Present value of labor for O&M ($2000/year)	$13,420
Net present cost	$26,920
annualized cost	$4012
Annualized energy cost ($/kWh)	$0.26
IRR	49%

order to capture the energy generated by the wind or sun before the grid is in operation, which contributes to slightly elevated system costs. In the class 2 wind regime, greater battery storage is needed. Possible solutions to decrease energy storage costs include running dispatchable loads such as ice-production or water pumping.

5.3. Displacement of diesel using biogas

There have been a number of studies demonstrating the economic benefits that rural users can attain through the incorporation of agricultural residues into their local energy systems (Gowda et al., 1995; Parikh, 1985; Romijn et al., 2010). Some of the most common sources of energy generation utilizing biomass derived fuels include wood gasification, biogas production through anaerobic digestion, or oil extraction from plants. All of these biomass derived fuels can act as direct fuel substitutes or supplements to diesel powered engines. In order to demonstrate the potential cost benefits that may be derived from creating a locally available, less expensive diesel substitute, an example calculation is provided based on the production of methane gas from the anaerobic digestion of existing agricultural residues. The system design costs and production values are based on a recently constructed biogas system constructed on a dairy farm in Costa Rica (Arias, 2009). The costs, shown Table 5, do not include the costs of a diesel generator, since diesel generators can be run in a duel fuel mode, operating with up to 90% methane and 10% diesel (Tippayawong et al., 2007).

6. Discussion

6.1. Energy supply curve

Fig. 2 displays an estimation of a “supply curve”[14] for conserved and supplied energy for the Orinoco and Marshall Point microgrid. The vertical access displays the annualized production cost of energy for supply measures and the cost of conserved energy for conservation measures (the final column of Table 2). The width of each step in the curve represents the total possible kWhs conserved or supplied by each measure. For example, the first step on the left signifies that up to 115 kWh of electricity from diesel generation can be saved at an annualized cost of 0.02 $/kWh from the installation of meters, followed by another 50 kWh for 0.03 $/kWh with the installation of CFLs.

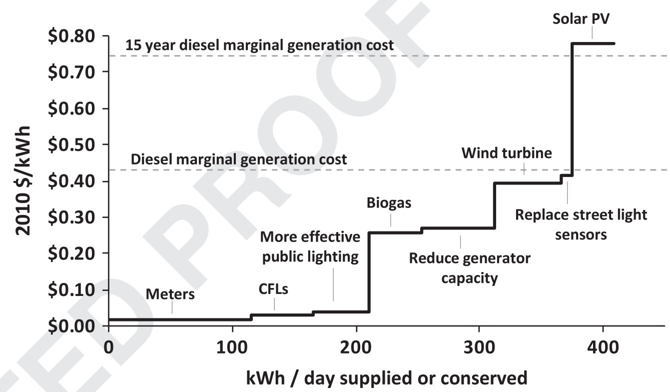

Fig. 2. Energy supply curve.

The lower dotted line represents the estimated marginal production cost of 0.43 $/kW for a 110 kW diesel engine operating at 25% efficiency, and utilizing diesel fuel at a cost of 1.06 $/l. Relative to this diesel cost, all measures that lie below this line could be implemented at cost savings. However, this may not be the most relevant comparison since it compares an estimate of today’s marginal generation costs with the annualized production costs for other measures that have lifetimes ranging from 0.3 to 20 years. Especially for the cases of wind and solar (~~with 20 and 15~~ year lifetimes, respectively) a more appropriate comparison price for these measures might therefore be the average marginal diesel generation cost over an equivalent lifetime.

Since there is no way of divining the average price of oil over the next 15 years, one rational method by which one can guarantee an average diesel price over this time frame would be to borrow money at a given interest rate (8% to remain consistent with the discount rate used for other calculations) and purchase 15 years worth of diesel fuel at today’s diesel price. The resulting annual loan payments can be used to represent an attainable fuel price over the next 15 years.[15] At an initial diesel price of 1.06 $/l and an 8% interest rate, the marginal diesel generation cost

[14] See Stoft, 1995 for an explanation why this curve is different from a classical economic supply curve.

[15] If today’s cost of fuel is C, then the annual fuel cost for a project of lifetime n, with a loan taken at an interest rate of i would be: Annual fuel price $=C\cdot n\cdot i/1-(1+i)^{-n}$

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becomes 0.76 \$/kWh, which is represented by the upper dotted line in the figure. While it might be argued that a more economically rational choice would be to wait until the current marginal diesel price (the lower dotted line) exceeds the annualized cost of a measure before investing in it, there may be other motivations for earlier investment, such as reducing carbon emissions as soon as possible.

After the equivalent of 408 kWh of diesel generation have been conserved or supplied, without any increase in demand, then the system would be running with 100% renewable energies, resulting from the energy efficiency measures, resizing of the diesel system, supplementation of diesel fuel for biogas, as well as integration of wind and solar.

6.2. Taking into account energy savings

Typical analyses using CCE do not take into account the value of the economic savings that might occur from an investment. Estimating a supply curve without displaying the values relative to a baseline has the advantage that it remains general by not relying on energy prices, and can be useful for various utilities and changing prices since the generation costs are not embedded in the calculations (Stoft, 1995; AK Meier, 1982).

However, it is worthwhile to analyze how the costs and ordering change when the monetary savings to the utility are taken into account. Savings for both conservation and renewable energy supply measures result from the avoided cost of diesel fuel, and can be calculated as the *marginal generation cost* × *saved energy*.

Table 6 shows the how the investment values, from the utility perspective, change with proper accounting for diesel savings and tariff loss. The second to last column in the table is the annualized energy cost relative to the marginal generation cost. The negative values signify savings. An ordered curve of the energy costs would appear the same as that shown in Fig. 2, simply shifted down by 0.43 \$/kWh.

A conservation measure may or may not be attractive to a utility. This will depend on the value of the energy generation costs relative to the tariffs they charge, and any regulatory incentives that they may face. Where the utility is making a profit on each unit of energy (i.e., tariff is priced above the marginal generation cost), the implementation of a conservation measure will result in revenue loss, unless appropriate regulatory incentives are provided to the utility (e.g., the lost revenue could be accounted for with a tariff increase). However, if the utility is actually taking a loss on each unit of electricity sold (which is often the case in rural electrification schemes), then energy conservation measures would result in cost savings. The lost revenue can be approximated as the *marginal tariff rate* × *saved energy*.

Taking into account the tariff can shift the relative attractiveness of an investment in supply or conservation. Investment in renewable energy supply in a diesel grid results in savings from reduction in diesel fuel consumption, without any revenue loss from decreased demand. The attractiveness of investment in conservation must be balanced between diesel savings and tariff loss.

In the case of the Orinoco and Marshall Point microgrid, the system is heavily subsidized. The tariff system is a two-part tariff in which the client pays a fixed rate for any consumption below 15 kWh, and a marginal rate of 0.26 \$/kWh for consumption above 15 kWh. Therefore, with a marginal generation cost of 0.43 \$/kWh (i.e., a loss to the utility for each unit of energy generated), energy conservation is attractive.

The final column in Table 6 takes into account the loss in tariff revenue from the conservation measures. It can be seen that reducing diesel plant capacity and replacing the street light sensors shift to become net costs with the current tariff schedule.

Table 6
Summary table showing annualized energy costs relative to baseline diesel generation supply and tariff schedule for the Orinoco and Marshall Point electric grid.

	kWh/day electric saved or supplied	Annual tariff loss (\$/kWh)	Liters/day of diesel saved	Estimated annual diesel savings	Annualized energy cost (\$/kWh)	Annualized energy cost w/diesel savings (\$/kWh)	Annualized energy cost w/diesel savings and tariff loss (\$/kWh)
Meter installation	115	\$10,894	33	\$12,726	\$0.02	−\$0.41	−\$0.15
CFL installation	50	\$4763	14	\$5581	\$0.03	−\$0.40	−\$0.14
Smaller street lights	46	\$4382	13	\$5101	\$0.04	−\$0.39	−\$0.13
Biogas	43	\$0	22	\$8690	\$0.26	−\$0.17	−\$0.17
Reduce diesel plant capacity	58	\$5525	24	\$9157	\$0.27	−\$0.16	\$0.10
Wind turbine (class 2)	54	\$0	22	\$8500	\$0.39	−\$0.03	−\$0.03
Replace street light sensors	9	\$846	4	\$1468	\$0.42	−\$0.01	\$0.25
Solar PV	33	\$0	14	\$5579	\$0.78	\$0.35	\$0.35

Table 7
Summary table of estimations of carbon mitigation impacts from demand and supply side measures in the Orinoco and Marshall Point electric grid (UAC = unit abatement cost, BAU = business as usual).

	Annualized cost (\$/year)	Liters/day of diesel saved	tCO_2/year abated	Unit abatement cost (\$/tCO_2)	UAC relative to BAU (\$/tCO_2)	UAC relative to BAU with tariff loss (\$/tCO_2)
Meter installation	\$648	33	32	\$20	−\$377	−\$135
CFL installation	\$577	14	14	\$41	−\$356	−\$114
Smaller street lights	\$622	13	13	\$48	−\$349	−\$107
Biogas	\$4012	22	22	\$183	−\$214	−\$214
Reduce diesel plant capacity	\$5760	24	23	\$250	−\$147	\$95
Wind turbine (class 2)	\$7767	22	21	\$363	−\$34	−\$34
Replace street light sensors	\$1352	4	4	\$366	−\$32	\$211
Solar PV	\$9501	14	14	\$677	\$279	\$279

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6.3. Carbon abatement potential

Due to the link between carbon dioxide emissions and climate change, it is urgent to find the most economic means for delivering low-carbon energy services, especially to those marginalized populations who will be the most vulnerable to climate shocks (Bierbaum and Fay, 2010; Casillas and Kammen, 2010). The unit abatement cost (UAC) of a carbon mitigation option can be calculated as

$$\mathrm{UAC} = \frac{\text{Annualized cost of the investment}}{\mathrm{tCO_2/yrabated}}.$$

The marginal abatement cost relative to a baseline scenario is a commonly used metric for determining the economic attractiveness of a mitigation option:

$$\mathrm{MAC} = \frac{\text{Annualized cost of the investment}}{\mathrm{tCO_2}\text{ abated}} - \mathrm{BAU\$/tCO_2}$$

Similar to the discussion with CCE, the marginal abatement cost relative to a baseline scenario loses an aspect of generality since it now has the energy price embedded in the calculation. We also run into the issue of the loss of tariff revenue for conservation measures, compared to carbon-neutral supply measures.

Q1 Table 7 shows the carbon abatement costs that result from the reduction of diesel combustion in the Orinoco and Marshall Point microgrid. This is a first order approximation, and does not take into account the imbedded emissions associated with the lifetimes of the technologies. The second to last column shows the unit abatement costs relative to the baseline diesel generation scenario, and the final column takes into account the tariff loss of conservation measures.[16]

7. Conclusions

Cheap capital costs and the prevalence of well developed supply chains make diesel generators a common choice for providing power to isolated communities. However, the long term volatility of diesel prices and the negative environmental externalities resulting from the production of carbon dioxide provide two important reasons for reducing diesel dependency in these electric systems. This study demonstrates that there are many currently available opportunities for rapidly and cost effectively transitioning to the delivery of low-carbon energy services in rural communities. In order to make the persuasive case to policy makers, government officials, and funders, it is critical to present the costs and benefits of the decisions in consistent and rigorous manners. Several important metrics include capital cost, ongoing fuel costs, risk of future fuel price volatility, the internal rate of return, carbon mitigation benefits, and savings relative to the current baseline.

Energy conservation and supply curves provide a simple graphical tool in which planners can compare the relative economic benefits between conservation and supply measures for delivering energy services to rural users. One shortcoming is that the curves obscure the capital costs and lifetime of the different measures. In addition, these curves are typically displayed in a manner that neglects to highlight the revenue loss between conservation and supply measures.

This paper presented the costs and savings that may be attained through the implementation of various demand and supply side measures, based on a particular microgrid in a village in Nicaragua. Prioritizing the use of efficient public and residential lighting, as well as installing meters in order to provide users with more accurate consumption information, can result in large monetary savings as well as carbon abatement, with low capital investment costs. When the revenue lost from tariff collection is accounted for, some supply measures look more favorable relative to conservation measures. It is clear that there is abundant, low-hanging fruit in the form of both conservation and renewable energy generation that government and private utilities should rapidly implement in order to increase energy access and decrease costs.

Appendix A. Supplementary materials

Supplementary materials associated with this article can be found in the online version at doi:10.1016/j.enpol.2011.04.018.

[16] $\mathrm{MAC} = \mathrm{UAC} - \frac{\mathrm{marginalgenerationcost(\$/kWh)}}{\mathrm{tonsCO_2/kWh}} = \mathrm{UAC} - 397\,\$/\mathrm{kWh}$, Tariff adjusted MAC for conserve. Measures: $= \mathrm{UAC} - (\text{marginal generation cost } (\$/\mathrm{kWh})/\ \mathrm{tonsCO_2/kWh}) + (\text{marginal tariff loss}(\$/\mathrm{kWh})/\mathrm{tonsCO_2/kWh}) = \mathrm{UAC} - 397\,\$/\mathrm{kWh} + 242\,\$/\mathrm{kWh}$a, where $\$/\mathrm{kWh\ electric} = (\$/\mathrm{l})(\ \mathrm{l/kWh})(1/\eta)$, and $\mathrm{tCO_2/kWh\ electric} = (\mathrm{tCO_2}/\ \mathrm{l})(\mathrm{l/kwh}\ )(1/\eta)$. Based upon a diesel cost of 1.06 \$/l, the U.S. Environmental Protection Agency carbon intensity value for diesel of 2.688 kg CO_2/l, lower heating fuel value of 9.84 l/kWh, diesel engine efficiency of 0.2525, and a marginal tariff price of 0.26 \$/kWh electric.

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