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Methods

The challenge of making reliable carbon abatement estimates: the case of diesel microgrids

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Abstract

Carbon abatement cost curves can help guide policy decisions related to cost effective carbon mitigation. Carbon abatement cost curves are often presented at the national or international level, aggregating mitigation measures across local and regional scales. In this paper, we show how the microgrid optimization model, HOMER, can be used to construct a micro-level carbon abatement cost curve and may be used to explore conservation and supply measures at the local level. As an example, we highlight the subtle challenges of estimating the carbon reduction and abatement costs in a diesel microgrid. Most carbon mitigation measures decrease the load on the diesel generator, and thus its efficiency. It is critical to understand how energy efficiency and conservation measures impact diesel plant efficiency, to insure a net reduction in emissions. It is also important to understand how revenue streams may be impacted by certain mitigation efforts, a point that is rarely addressed in most macro-level abatement curve analyses. In the case of electricity systems, demand-side conservation measures can lead to savings by consumers and revenue loss to utilities. The electricity rate structure may need to be altered in order to compensate profit-making utilities, and encourage investment in conservation. In the case of a subsidized electric system, where the utility is losing money on each unit of energy generated, energy conservation results in savings to both the utility and the consumer.

Keywords: Carbon abatement, abatement cost curves, microgrid

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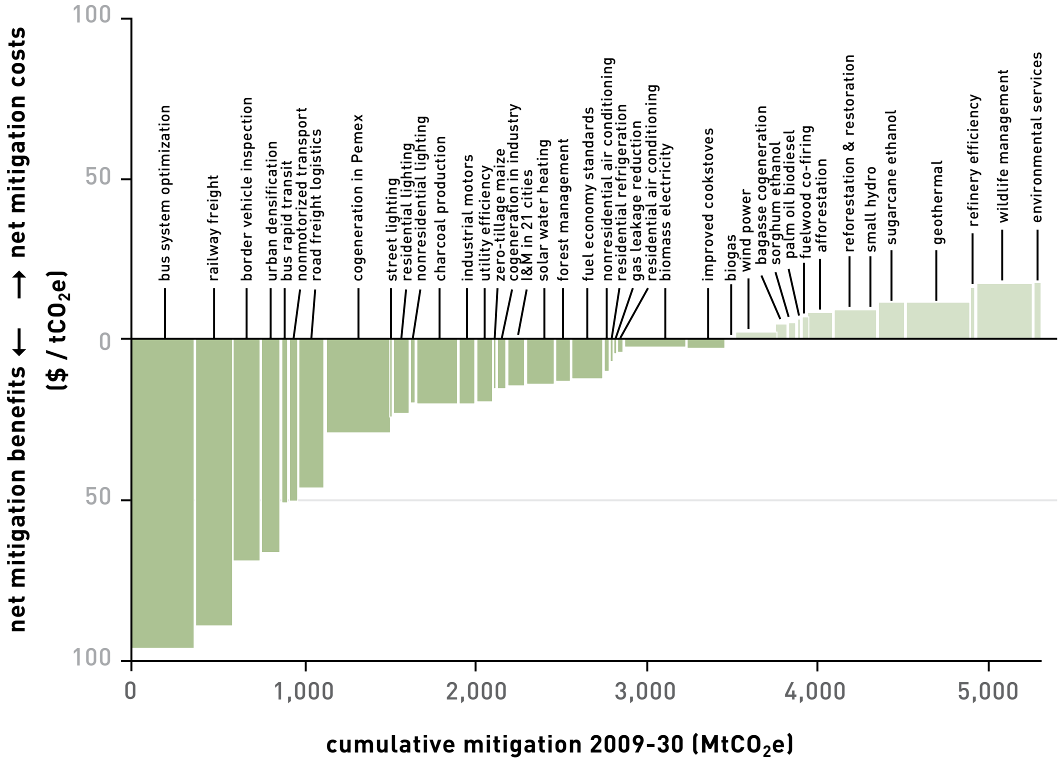


Figure 1: Economy wide carbon abatement cost curve for Mexico (Johnson ***et al.***, 2009).
Legend: The width of each box represents the total emissions reductions resulting from the intervention, relative to a business as usual (BAU) baseline. The height of the box represents the amortized cost to society, in $ per tonne of CO_2 equivalent. Boxes below the x-axis represent net savings relative to the BAU case. The estimations are based on an 8 percent discount rate, and project lifetimes of 20 years.

1. INTRODUCTION

Due to the global nature of climate change, greenhouse gas mitigation tends to focus on national and international level policies. However, moving from macro-level planning to implementation will require understanding local scale environmental, social and economic dynamics in order to implement beneficial mitigation projects.

There has been an increasing amount of literature on both methodologies and weaknesses for carbon accounting for various projects (Ekins *et al.,* 2011; Pearson, 2007; Searchinger *et al.*, 2008). In this paper we focus on one particular tool for carbon mitigation analysis and planning, the carbon abatement cost curve, which can help guide policy decisions related to cost effective carbon mitigation. To date, these tools have been primarily used for national or international (i.e. macro-) level planning. We seek to explore the nuances of constructing these curves at the local, or micro-level, highlighting the case of isolated electric systems that are powered by a diesel generator.

The electricity sector currently comprises the largest source of greenhouse gas emissions (IPCC, 2007). However, close to 1.4 billion people do not currently have access to electricity (AGECC, 2010). It has been estimated that close to 12 GW of new generation will likely come from isolated microgrids within the next 20 years; it is expected that many of these systems will be powered by diesel generators (Bazilian *et al.*, 2011).

In order to support efforts of governments, entrepreneurs, and various development actors, we outline a methodology for evaluating the relative carbon reduction potential and financial benefits from conservation and supply measures, using a popular microgrid modeling tool called HOMER. There are numerous cases described in the literature that address the use of HOMER for analyzing the optimal design of rural microgrids (e.g. Lambert *et al.*, 2006; Zhu & Yang, 2012). Therefore, we demonstrate the utility of HOMER for exploring the sensitivities of emission reduction interventions and how HOMER can be used to construct community level carbon abatement cost curves in diesel microgrids.

We use HOMER costs and emissions to analyze two specific aspects of carbon mitigation measures: cumulative emission reductions and the ramifications of electricity rate structure and ownership on abatement costs. The first aspect, emissions reduction, is of course fundamental. The second aspect, exploring the financial ramifications of interventions, is critical if policy makers are going to design effective policies

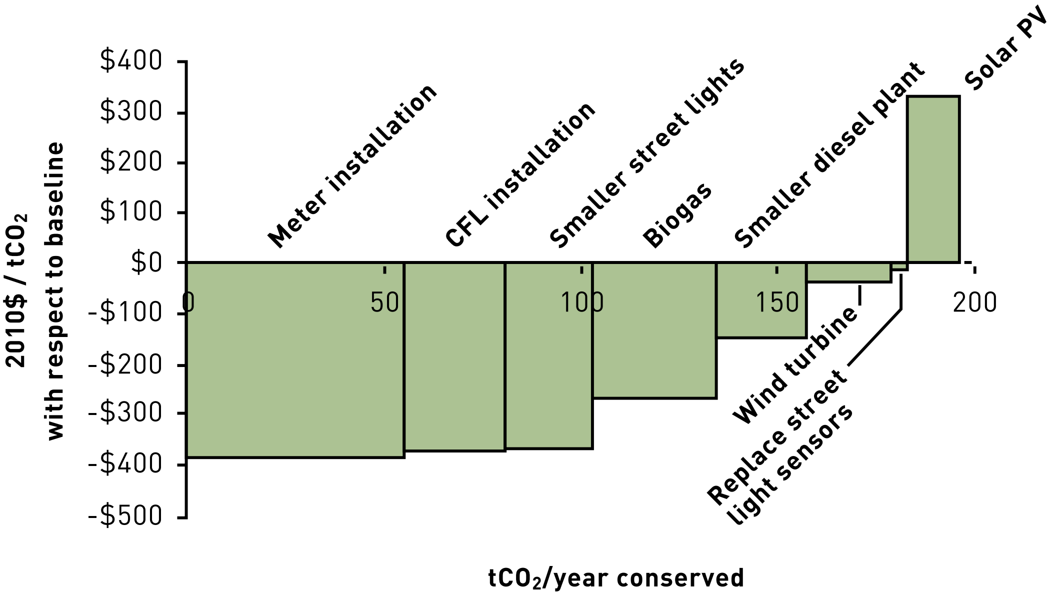


Figure 2: Community level carbon abatement cost curve (Casillas & Kammen, 2010).
Legend: The width of each box represents the cumulative emissions reductions resulting from the intervention, relative to the emissions of the previous intervention. The height of the box represents the annualized lifetime cost to the implementing agency, in $ per tonne of CO_2. Boxes below the x-axis represent net savings.

targeting beneficiaries in rural areas, where electricity rate structures can vary widely.

2. CARBON ABATEMENT COST CURVES

Carbon abatement cost curves share a close relationship with economic supply curves. In the economics literature, marginal abatement cost (MAC) curves follow from the production theory of firms (Klepper & Peterson, 2006; McKitrick, 1999). A firm-level supply curve shows the quantity of a product that the firm is willing to produce for a given price. In a competitive market, a firm's decision to produce or not to produce is determined by its marginal costs. A profit-maximizing firm will only be willing to operate where the marginal cost to produce an additional good is less than or equal to the price of the good. A sector wide supply curve shows the amount of goods that will be supplied to a market for a given price.

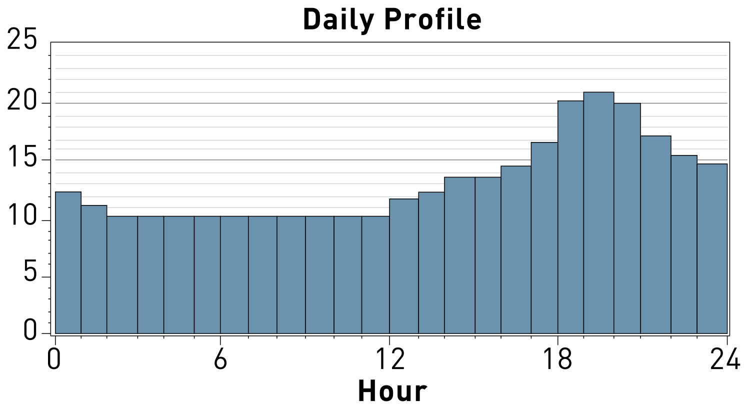
In recent years, a number of macro-level estimations of supply curves for carbon abatement have been created for national and global economies (Ekins *et al.*, 2011), where the firm is most likely a government or society. The supply curve is comprised of mitigation interventions over various sectors, such as electricity, transportation, or forest management. The costs are annualized costs to society, often net of taxes and subsidies, averaged across each given sector. Macro-level curves will have a different nature from micro-level curves (McKinsey & Company, 2009, p. 40), which may focus on a specific sector, under specific circumstances (such as a diesel microgrid). Due to the disaggregated nature of the costs in a micro-level curve, it can be presented more easily from the perspective of either the consumers or providers of a service.

There is some ambiguity in the direct analogy to the marginal cost curve of a single firm that is basing its production decisions on its marginal costs. Therefore, in this paper we will refer to the curves as abatement cost curves, rather than marginal abatement cost curves.

The World Bank and the management consulting firm McKinsey & Company have each produced a number of national-level supply curves for carbon abatement. These curves can serve as useful starting points for policy makers to approximate where the cheapest carbon reductions can take place in an economy, even though they do not highlight how benefits will be distributed. Figure 1 shows an example of an economy wide carbon abatement cost curve for Mexico (Johnson *et al.*, 2009).

The authors of the Mexico study highlight the fact that there are large uncertainties in many of the assumptions that were used to estimate both the costs and resulting emissions reductions. Estimations must be made for many values that are difficult to predict, such as future fuel prices, rates of technology adoption, and growth in demand.

Based on a wide number of metrics, not just reduction of greenhouse gases, policy makers will need to prioritize mitigation interventions in various sectors. Other evaluation metrics include environmental effectiveness, cost effectiveness,



Average (kWh/d)	312
Average (kW)	13
Peak (kW)	25
Load factor	0.52

Figure 3: Daily load profile used in the HOMER model simulation
Legend: Daily load profile based on load profiles measured in rural villages. The hypothetical community has an existing diesel grid powering 150 houses, with 25% of the daily load coming from residential lighting.

distributional and equity effects, and institutional feasibility (IPCC, 2007, p. 751). Actual implementation of a policy intervention will require a detailed estimation of the potential social, environmental, and technical interactions, requiring analysis to move from the macro-level to the micro-level. For example, residential lighting, an intervention in the Mexico cost curve, will have a range of costs and impacts depending on whether or not the consumers are rural or urban, wealthy or poor, or connected to a central or isolated grid. Also, the beneficiaries targeted by policy makers may be electricity producers, product manufacturers, or consumers. In short, the devil is in the details.

Correctly characterizing the scale of the carbon mitigation potential in rural microgrids can be important, especially with the increasing availability of carbon credit funds that can help subsidize investment costs (Brent & Rogers, 2010; Deichmann *et al.*, 2010). By way of illustration of the transition from macro-level analysis to micro-level analysis, Figure 2 shows a community level carbon abatement cost curve from a diesel microgrid in a rural village in Nicaragua (Casillas & Kammen, 2010; 2011). The figure shows a suite of interventions, their carbon mitigation potentials, and the costs savings that may result, demonstrated by the negative abatement costs.

Coincidentally, the curve includes a number of interventions that are contained in the macro-level Mexico curve, such as residential lighting, public lighting, biogas and wind generation. All of these costs are vastly different in magnitude from the estimations in the Mexico curve, primarily due to the diesel baseline in the community level curve, and possibly obscured by the aggregate nature of the macro-level estimations in the Mexico curve. In the planning process, micro-level analysis will need to be carried out in order to better understand whether macro-level mitigation strategies are appropriate for the diverse array of potential stakeholders, community by community.

3. USING HOMER RESULTS TO ESTIMATE A COMMUNITY LEVEL CARBON ABATEMENT CURVE

The microgrid simulation and design tool, HOMER, produces system costs and carbon emissions that can be used for constructing a micro-level carbon abatement cost curve. The model allows users to compare costs of various microgrid designs, evaluating the impacts of renewable energy and conservation measures, and has been widely used for the design of rural energy systems.

In order to demonstrate the methodology for analyzing the carbon reduction impacts using HOMER, the following section will explore the integration of more efficient lighting and wind generation into a hypothetical microgrid that has existing diesel generation as its baseline. The two measures, one supply side and the other demand side, were chosen due to the well documented benefits and accessibility of lighting efficiency (Birner & Martinot, 2005; Gadgil & De Martino Jannuzzi, 1991; Kumar *et al.*, 2003) and the numerous examples of wind integration into diesel systems (Baring-Gould *et al.*, 2003; Hunter & Elliot, 1994; Weisser & Garcia, 2005).

3.1 BASELINE

The initial demand profile used in the simulation, based upon field data compiled by the authors, is shown in Figure 3. The average daily load is 312 kWh with a peak demand at hour 19, driven by residential lighting. We assume that there are 150 households in the microgrid, and each household has an average of three 60 W incandescent bulbs, with each light operated for an average of three hours per day.

Table 1: Carbon abatement cost calculation utilizing HOMER simulation runs

	BASELINE Diesel	Lighting + Diesel	Lighting + Wind + Diesel
Annualized cost ($/yr) from HOMER	$53 984	$47 823	$46 769
Annual emissions (tCO2/yr) from HOMER	111 t	94 t	77 t
Relative Cost or Savings ($/yr)	$0	-$6 161	-$1 054
Relative carbon abatement (tCO2/yr)	0 t	17 t	17 t
Relative abatement cost ($/tCO2)	$0	-$358	-$63

Legend: Annualized costs and emissions are from HOMER, and relative costs or savings, relative carbon abatement, and relative abatement costs are calculated from annualized costs and emissions outputs. Relative abatement cost is relative costs or savings divided by relative carbon abatement. The average diesel efficiency for the baseline was 28%, 26% for Lighting + Diesel, and 24% for Lighting + Wind + Diesel.

Thus, 81 kWhper day, equivalent to 26 % of the total load, is consumed for residential lighting. The baseline scenario assumes that generation is based on a 30 kW diesel generator. We assume that the diesel system has a capital cost of $12,000, an operating lifetime of 30,000 hours, a fuel cost of 1.06 $/liter, a project lifetime of fifteen years, and a discount rate of eight percent (see Casillas & Kammen, 2011).

The simulation results show that the diesel system has an operational life of 3.4 years, and mean electrical efficiency of 28%. The fuel costs compose 83% of the lifetime system costs. HOMER calculates a large number of useful metrics that can be used for financial comparisons between different design options, such as lifetime cost of energy, return on investment, and simple or discounted payback.

3.2 EFFICIENT LIGHTING

Using HOMER we examined the impacts of energy efficiency measures. Compact fluorescent light (CFL) bulbs typically deliver the same luminance using 25% of the electricity of incandescent bulbs (Gadgil & De Martino Jannuzzi, 1991). We assume that each of the three 60 W bulbs in the 150 households is replaced with 15W CFLs, resulting in a reduced daily load of 251 kWh, down from 312 kWh, representing a 19% decrease in daily average consumption.

HOMER allows for the input of an efficiency multiplier, capital cost, and technology lifetime in order to model efficiency measures. A 19% daily load reduction is equivalent to an 81% efficiency multiplier. Based on field experience, we assume a cost of three dollars for purchase and installation of each bulb, resulting in a total implementation cost of $1350, with a conservative lifetime of two years (see Annex 1 in the Supplementary Material for the details of the lighting calculation and where these can be input into HOMER).

3.3 INTEGRATION OF A COMMUNITY WIND TURBINE

There are numerous successful, village-scale microgrids that utilize intermittent renewable energy technologies, such as wind or solar photovoltaics (PV), used to supplement diesel systems (Baring-Gould *et al.*, 2003; Flavin & Aeck, 2005; Illindala *et al.*, 2007). The diesel generator acts as a load-following generator, increasing or decreasing its output in response to the load. The generator therefore experiences wind or solar production in the grid as equivalent to a load reduction.

Since diesel systems operate most efficiently when running at greater loads (Hunter & Elliot, 1994), wind-diesel systems require a careful technical and economic analysis in order to determine the optimal level of renewable energy integration. Potential fuel savings from renewable energy generation can be mitigated by a decrease in average efficiency of the diesel plant as its load falls. 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 & Elliot, 1994).

The wind resource used for the simulation was a lower class 2 wind regime[1] with an average wind speed of 5.2 m/s, using a 10 kW capacity wind turbine on a 25 meter tower. Capital costs for the turbine, tower, and grid integration components totaled $47 000, with annual maintenance costs of $500. The simulated production resulted in a capacity factor of 25%, producing an average of 59 kWh per day, with a lifetime energy cost of 0.28 $/kWh.

3.4 CONSTRUCTING THE CARBON ABATEMENT COST CURVE

The HOMER simulation results can easily be used to calculate carbon abatement costs. HOMER produces output for every permutation of grid design options. Therefore, a simulation will produce results for the case with diesel only, diesel + efficient lighting, diesel + wind, and diesel + efficient lighting + wind. During the actual planning process, it typically makes financial sense to begin with mitigation options that result in the greatest savings. Installing energy efficient lighting before integrating wind resulted in the greatest cost savings in the simulation.

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[1] The wind regime was based on a Weibull probability distribution, $f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right]$, where v is the wind velocity and the distribution parameters were k = 2.4, c = 6.5 at 25m.

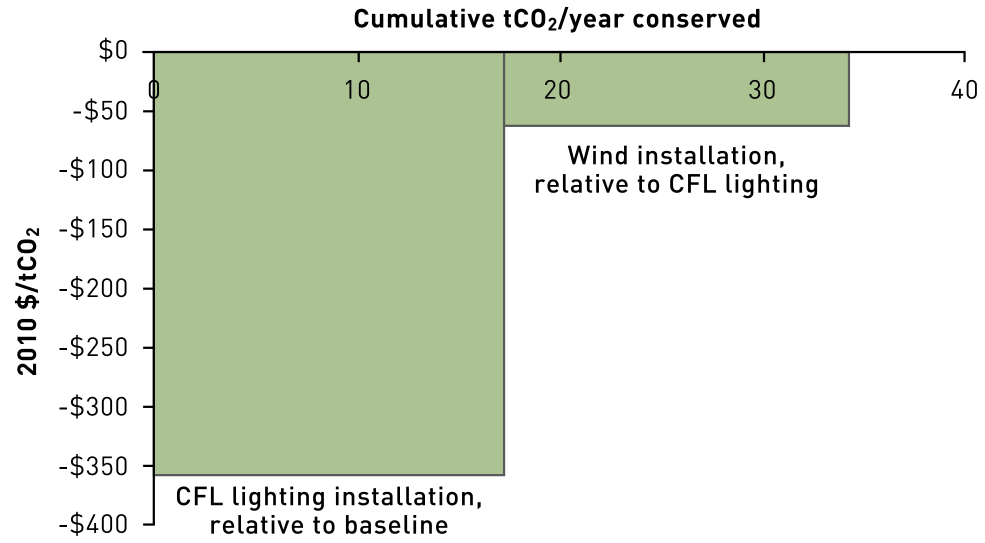

Figure 4: Carbon abatement cost curve derived from HOMER simulation.
Legend: The first box, on the left, shows the cost and total emission abatements relative to the diesel baseline, resulting from the integration of three 15W CFLs in 150 households, replacing 60W incandescent lights. The second box shows the resulting costs and abatements relative to the CFL case, resulting from the integration of a 10 kW wind generator, operating with a capacity factor of 25%. Both installations represent a net savings, shown by the negative costs.

Annualized costs and annual emissions from the HOMER outputs can then be used to calculate abatement costs. The annual abatement cost, in units of dollars per tonne of carbon dioxide, is calculated relative to the previous state, as:

$$\text{Annual abatement cost } (\$/\text{tCO}_2) = \frac{(\text{Annualized cost of intervention}) - (\text{Annualized cost of reference case})}{(\text{CO}_2 \text{ emissions from reference case}) - (\text{CO}_2 \text{ emissions from intervention})}$$

Negative dollar values indicate savings, while positive values indicate costs. Table 1 shows the values taken from the relevant cases in the HOMER simulation, and the resulting abatement costs.

Carbon abatement is the total emissions from each case subtracted from the emissions of the previous case (i.e. diesel + lighting versus diesel, and diesel + lighting + wind versus diesel + lighting). The integration of efficient lighting and the integration of the wind turbine coincidentally both result in a decrease in annual emissions of 17 tCO_2. The average efficiency of the diesel engine decreases as both lighting efficiency and wind integration reduce the diesel load, from a baseline efficiency of 28%, to 26% with lighting, to 24% with wind integration with lighting. The falling efficiency results in an increase in the average generation cost for the diesel, increasing from 0.47 $/kWh to 0.57 $/kWh (see Supplementary Material). The magnitude of the interaction effects between the diesel generator and any intervention that reduces load may be difficult to predict without a simulation model.

The resulting abatement cost curve is shown in Figure 4.

3.5 FINANCIAL IMPACT OF INTERVENTION MEASURES ON STAKEHOLDERS

It is important to recognize who will bear the costs and benefits of an abatement measure. Economy wide abatement curves typically assume that the abatement costs will be borne by society, without explicitly determining how those costs will be allocated. In the case of a diesel microgrid for a rural area, the costs and benefits of mitigation measures will vary, depending on electricity rate structure, whether or not the intervention is a supply or demand side measure, and whether or not one is analyzing the benefits from the consumer perspective or the perspective of the electricity company. Understanding the various impacts on the beneficiaries is critical for the successful buy-in of an intervention.

By way of example, we will demonstrate the impact of lighting efficiency and wind integration from the perspective of the electricity utility. The revenue stream to the utility can be approximated by incorporating revenue from a simple flat-rate charge (the charge for each additional kWh consumed is fixed) into the costs of the abatement curve. Figure 5 shows the original abatement curve with overlapping blue boxes that represent how the abatement costs would change when the perspective shifts to that of the utility. The utility's revenue stream is taken into account by multiplying an average electricity price of 0.15 $/kWh with the total energy production, the details of which are shown in Annex 4 (see Supplementary Material). Since the marginal diesel generation cost in the simulation is 0.30 $/kWh, each additional kWh results in a net

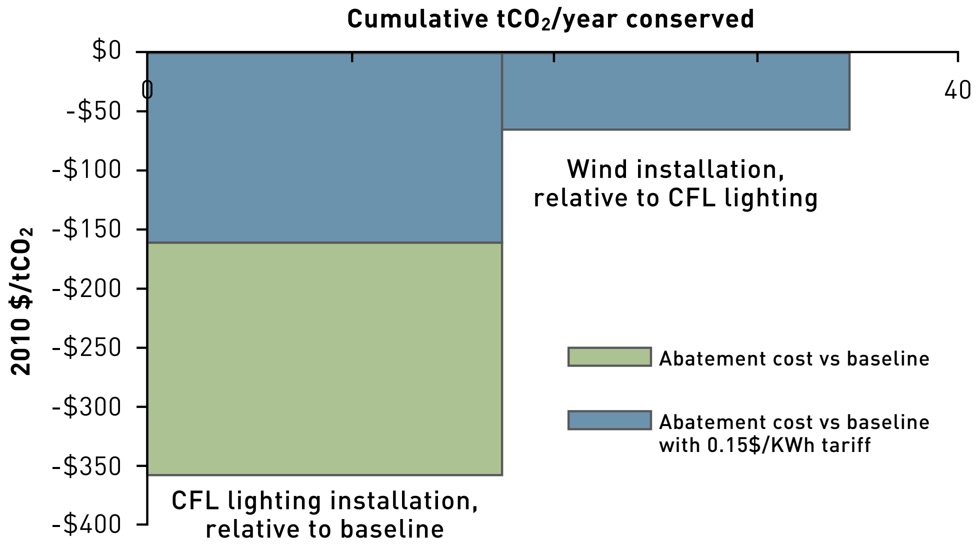

Figure 5: Abatement costs curve from HOMER simulation with 0.15 \$/kWh electricity rate.
Legend: The grey rectangles show the relative abatement costs to society, the same as shown in Table 1. The blue rectangles show the costs from the utility perspective with an electricity rate of 0.15 \$/kWh included in the calculation (i.e. a profit calculation). Negative values for the blue boxes are income or savings to the utility.

loss to the utility. This is not an unusual situation for a rural electrification scheme where the government is subsidizing the generation costs. From the utility's perspective, a reduction in demand results in a marginal savings of 0.15 \$/kWh (marginal generation cost minus revenue loss). The customers also receive a savings of 0.15 \$/kWh for each kWh that is conserved. This demand side reduction represents financial savings to both the utility and the consumers.

Abatement costs for the supply side measure, wind integration, don't result in a reduction of consumer demand, so the revenue to the utility doesn't change. The abatement costs remain the same whether or not revenue is taken into account. Thus, the abatement costs from the utility perspective are identical to the social perspective, resulting in identical sized overlapping boxes in the figure.

Figure 6 is similar to Figure 5, except that it shows what the resulting curve would look like if the electricity charge was 0.40 \$/kWh, which is greater than the marginal generation cost, signifying that the utility accrues positive revenue from each marginal unit of electricity produced by the diesel system. Therefore, any reduction in units of electricity sold to consumers would result in a net loss of revenue. This would result in the abatement cost for the introduction of lighting efficiency becoming a net cost to the utility, while the savings to customers would increase.

Table 2: Carbon abatement cost calculation for lighting intervention, from the perspective of society, utility, and customers, with electricity rates of 0.15 \$/kWh and 0.40 \$/kWh

	Society	Utility	Customers
tariff (\$/kWh)	n/a	\$0.15	\$0.15
CO$_2$ abated (tCO$_2$/yr)	17	17	17
Relative costs (\$/yr)	-\$6 166	-\$2 750	-\$3 416
Abatement cost (\$/tCO$_2$)	-\$358	-\$160	-\$199
tariff (\$/kWh)	n/a	\$0.40	\$0.40
CO$_2$ abated (tCO$_2$/yr)	17	17	17
Relative costs (\$/yr)	-\$6 166	\$2 944	-\$9 110
Abatement cost (\$/tCO$_2$)	-\$358	\$171	-\$530

Legend: Relative costs are the difference between the diesel microgrid with efficient residential lighting and the diesel baseline. The Abatement cost is the relative costs divided by the total CO$_2$ abated. Details are shown in Annex 4 (see Supplementary Material).

The resultant curve, composed of blue boxes in Figure 6, shows that when incorporating the profits into the calculation, with an electricity charge of 0.40 \$/kWh, wind integration now becomes the most attractive first option, from the point of view of the utility. The interventions would need to be reordered to create a positive sloped supply curve. However, from the point of view of the consumers, conservation measures allow them to attain the same energy service with decreased consumption, always representing a cost saving, as can be seen in Table 2.

The table shows the abatement costs from the perspective of society, the utility, and the customers, for the efficient lighting intervention. The society perspective includes the investment costs, without accounting for financial flows passing to the

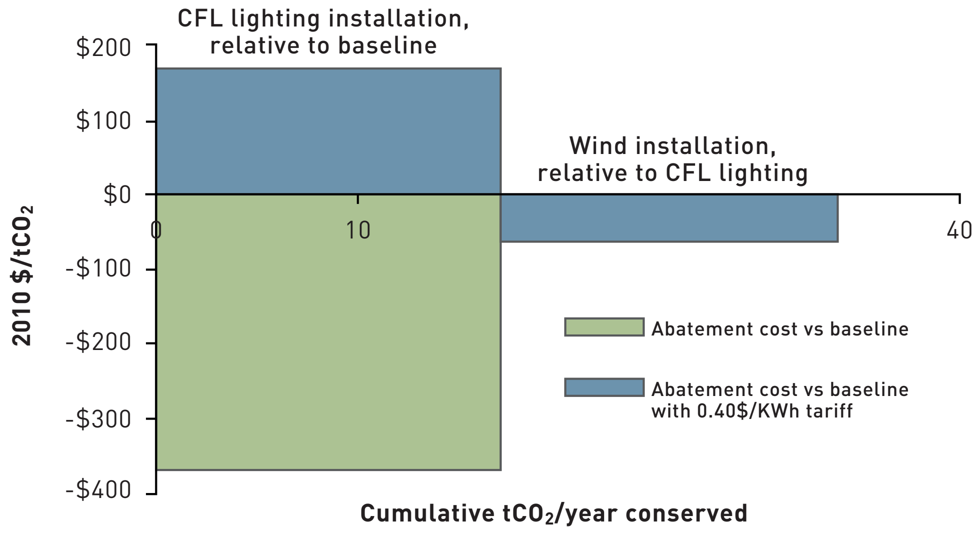

Figure 6: Abatement costs curve from HOMER simulation with 0.40 $/kWh electricity rate.
Legend: The grey rectangles show the abatement costs from Table 1. The blue rectangles show the costs from the utility perspective with an electricity rate of 0.40 $/kWh included in the calculation (i.e, a profit calculation). Negative values for the blue boxes are income or savings to the utility, and positive values are costs.

various stakeholders (customers and the utility). In general, the abatement costs to society could include externalities, such as environmental damages. The abatement costs seen by the utility include the society costs (in this particular case, but certainly not cases when negative externalities are included), plus the revenue that comes from customers paying for electricity consumption. The abatement costs seen by the customers are estimated as the negative of the electricity charge revenue accrued by the utility. In this particular case, it is assumed that the utility pays for the installation of the efficient lights. As the electricity rates increase above the marginal generation cost, efficiency measures represent greater loss to the utility and greater savings to the customers.

4. CONCLUSIONS

Based on the growing role that diesel microgrids may play in the provision of rural electrification, as well as the potential that carbon financing offers, it is useful to be able to construct reasonable estimations of the impact that mitigation strategies may have, especially when they result in cost savings. With the recent popularity of macro-level abatement cost curves, planning and implementation will necessarily require tools for micro-level assessments.

We explore several nuances regarding the estimation of carbon reduction and abatement costs in a diesel microgrid. Most carbon mitigation measures decrease the load on the diesel generator, and thus its efficiency. Therefore, it is important to understand the impact of both demand and supply side measures on plant efficiency, to ensure a net reduction in emissions. For example, installing efficient lighting will result in a decrease in demand, but the load reduction causes a poorer average efficiency of the diesel generator and therefore greater average emissions per unit of electricity. The free microgrid optimization model, HOMER, is useful for exploring the costs and emissions resulting from both conservation and supply measures. Its output can be used to easily construct micro-level carbon abatement cost curves, which are necessary complements to macro-level carbon abatement cost curves that have become popular in policy circles.

Careful modeling in conjunction with validating data from case studies can be used by policy makers to determine economic choices for mitigating carbon emissions. Casillas and Kammen (2011) provide an example of carbon abatement calculations based on actual decreases in demand resulting from the installation of conventional meters and installation of efficient lighting in houses from a rural village. The data from the case study can be used to validate assumptions in other carbon abatement curves for diesel microgrids that have similar defining parameters.

It is also important to understand how revenue streams may be impacted by certain mitigation efforts. It is well known that demand-side conservation measures are not attractive to utilities unless adequate regulation or financial incentives are provided (Kushler *et al.*, 2006). The electricity rate structure may need to be altered in order to compensate profit-making utilities, and encourage investment in conservation. In the case of a subsidized electric system, where the utility is *losing* money on each unit of energy generated, energy conservation results in savings to both the utility and the consumer.

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