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Renewable Energy Planning: Multiparametric Cost Optimization

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RENEWABLE ENERGY PLANNING: MULTIPARAMETRIC COST OPTIMIZATION

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ABSTRACT

This paper describes a method for determining the combination of renewable energy technologies that minimize life-cycle cost at a facility, often with a specified goal regarding percent of energy use from renewable sources. Technologies include: photovoltaics (PV); wind; solar thermal heat and electric; solar ventilation air preheating; solar water heating; biomass heat and electric (combustion, gasification, pyrolysis, anaerobic digestion); and daylighting. The method rests upon the National Renewable Energy Laboratory's (NREL's) capabilities in characterization of technology cost and performance, geographic information systems (GIS) resource assessment, and life-cycle cost analysis. The paper discusses how to account for the way candidate technologies interact with each other, and the solver routine used to determine the combination that minimizes life-cycle cost. Results include optimal sizes of each technology, initial cost, operating cost, and life-cycle cost, including incentives from utilities or governments. Results inform early planning to identify and prioritize projects at a site for subsequent engineering and economic feasibility study.

1. INTRODUCTION

Several organizations have goals regarding renewable energy use. For example, the federal government has a goal of 7.5% renewable energy for its facilities. Green-building rating systems set percentage goals such as 2.5%, 7.5% and 12.5%. Further, some organizations set the goal of "net zero" utility energy use for a facility (100% renewable). This analysis examines how to meet the goal, whatever it is, while minimizing life-cycle cost. Organizations that operate a lot of real property need a structured, credible, but affordable method of identifying and prioritizing renewable energy projects prior to detailed evaluation. A convenience food manufacturer, a major brewer, a small town in Kansas, a Navy base on an island, and the National Zoo have all asked NREL to help them determine how to meet their renewable energy goals at minimum life-cycle cost.

It is important to acknowledge that energy efficiency measures are prerequisite to renewable energy measures. In this analysis we size renewable energy systems to meet the specified load, assuming that cost effective efficiency measures have already been taken.

The best mix of renewable energy technologies at a site depends on: renewable energy resources; technology characterization (such as installed cost, maintenance costs, efficiency); state, utility and federal incentives; and economic parameters (discount rate, inflation rates). Early in a planning process it is necessary to keep the analysis simple and inexpensive, but each of these effects needs to be represented for the results to be useful. Previous screening efforts have evaluated each renewable energy technology independently, but here we account for the interactions among multiple technologies at a site.

Analysis can be conducted on a facility as a whole, or on each individual building at a facility. Solar water heating, solar ventilation preheating and daylighting are considered only to meet their associated end-use loads on individual buildings. Photovoltaics could be on a building or a central plant. Wind power, solar thermal electric, and the biomass energy alternatives are considered in a central plant arrangement if a facility has multiple buildings.

Analysis is performed by MS Excel spreadsheets (with an add-in called "Premium Solver") using the following data sources: customer-provided energy use and cost and building floor area at each site; GIS databases maintained by NREL; other databases such as utility rates from Platts Inc.; City Cost Adjustment Factors from RS Means and Co.; and incentives from the Database of State Incentives for Renewable Energy maintained by University of North

Carolina. Calculations estimate the installed cost, incentives, energy performance, cost savings, and life-cycle cost. An innovative algorithm based on capacity and capacity factor is used to estimate the effect of simultaneous generation of multiple renewable energy technologies. The solver is used to identify the size of each component (kW of PV, kW of wind, square feet of solar thermal, etc.) that minimizes life-cycle cost. A constraint, such as percentage of energy use supplied by renewable energy, may be specified in the optimization.

The method is intended to use information that is readily available from an organization's real-property management database and utility procurement database, thus minimizing original data collection. At a minimum, the customer would provide: the locations (names of facilities, street addresses) to be considered in the analysis; the square footage of building space; and annual utility use and cost (gas, electric, oil, propane, steam) for the previous year at each facility. A GIS utility is used to convert the street addresses into GIS coordinates for use in the analysis. If the site provides an inventory of waste streams from the facility itself, this is considered in the biomass fuel assessment along with feedstocks from the surrounding area from the GIS data. If more detailed information is available, then any of the many default values in the analysis may be replaced with other information. Examples include a breakdown of types of floor space (office, warehouse, etc.), with different rates of ventilation air and lighting levels for each space, gallons per day of hot water, or other information regarding site energy use that may be available.

2. GIS DATASETS

NREL's GIS is a computer-based system used to manipulate, manage, analyze, and display renewable energy resource data linked to a spatial reference. NREL datasets used in this analysis include solar radiation (W/m2) on a 40x40 km grid including global on the horizontal and on a tilt equal to local latitude, and beam radiation on tracking east/west axis. Wind power density (W/m2) is on a 200m x1000m grid for most locations, and a 25 km grid in locations where the high-resolution data are not available. Heating degree days and cooling degree days are also included.

GIS data layers can be recombined or manipulated and analyzed with other layers of information. For example, the energy delivery of solar ventilation air preheating is estimated by the integral of solar resource on a vertical south wall and heating degree days at a location.

Illuminance data for daylighting calculations are selected from the closest city for which Typical Meteorological Year weather data is available.

Utility cost data are usually provided by the site under evaluation, but NREL also purchases GIS data sets of residential, commercial, and industrial utility rates from Platts which could be used if data are not available from the site.

The GIS database manages biomass resource information from surrounding areas, reported as tons available within a 50 mile radius. The breakdown of available biomass feedstocks is as follows [all from reference 2]:

- Crop residues (dry tonnes/year) include corn, wheat, soybeans, cotton, sorghum, barley, oats, rice, rye, canola, dry edible beans, dry edible peas, peanuts, potatoes, safflower, sunflower, sugarcane, and flaxseed from Unites States Department of Agriculture (USDA), National Agricultural Statistics Service, 2002 data.
- Orchard and Grape prunings (dry tonnes/year) from USDA, 2002 data.
- Forest residues (dry tonnes/year) from USDA, Forest Service's Timber Product Output database, 2002
- Primary wood mill residues (dry tonnes/year) from USDA, Forest Service's Timber Product Output database, 2002.
- Secondary wood mill residues (dry tonnes/year) from the U.S. Census Bureau, County Business Patterns, 2002 data.
- Urban wood waste (dry tonnes/year) from U.S. Census Bureau, 2000 Population data, BioCycle Journal, State of Garbage in America, January 2004; and County Business Patterns 2002 data.
- Methane emissions from landfills (tonnes/year) from EPA, Landfill Methane Outreach Program, 2003 data.
- Methane emissions from manure management (tonnes/year) including: dairy cows, beef cows, hogs and pigs, sheep, chickens and layers, broilers, and turkey, from USDA, National Agricultural Statistics Service, 2002 data.
- Methane emissions from domestic wastewater treatment (tonnes/year) from the EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003 and U.S. Census Bureau, 2000 Population data.

3. TECHNOLOGY CHARACTERIZATIONS

Initial cost, efficiency, and operation and maintenance cost for each of the renewable energy technologies is characterized according to the cost and performance data reported in edition four of the "Power Technologies Energy Data Book" from NREL [2] and also from "Renewable

Energy Technology Characterizations" from Electric Power Research Institute [3]. Other sources of information are also employed such as the author's project experience.

3.1 Initial Cost

The initial cost of each technology is estimated from the technology characterizations [1,2], staff project experience, and cost estimating manuals [5]. Costs are adjusted for the city cost adjustment factors for each location from RS Means and Co. [5]. The city cost adjustments are for composite project cost including both materials and labor. The initial cost is reduced by any available incentives including the Federal Business Investment Tax Credit (% of cost); state tax credit (% of cost); and/or rebate ($/Watt or % of cost. Even though the Modified Accelerated Cost Recovery Schedule (accelerated depreciation) occurs over five years, we model it here as an equivalent reduction in initial cost (10% as recommended by calculations by Alicen Kandt of NREL). Incentives that may be available at each location from state governments, utilities, or others are as listed in the Database of State Incentives for Renewable Energy maintained by University of North Carolina [6]. Liz Brown of NREL compiled the incentives available for each location into a spreadsheet that can be read by look-up functions.

Initial cost is represented by the equation:

$$C = (c_{unit,electric}\, P_{rated,electric}) + (c_{unit,boiler}\, P_{rated,\,boiler}) + (c_{unit,storage}\, S_{rated,\,storage}) + (c_{unit,distribution}\, P_{rated,boiler})$$

Where $c_{unit,electric}$ = per-unit cost of installed electrical generating system ($/kW)
$P_{rated,electric}$ = rated power (kW) output of electrical system
$c_{unit,boiler}$ = cost per-kW (or MBH) of solar thermal or biomass boiler
$P_{rated,\,boiler}$ = rated thermal output (kW, or MBH) of solar thermal or biomass boiler
$c_{unit,storage}$ = cost per kWh of thermal storage (e.g. tank)
$S_{rated,\,storage}$= capacity of thermal storage tank (kWh thermal)
$c_{unit,distribution}$ = cost of system to distribute heat from plant to buildings (e.g. $250,000/MBH).

The initial cost is then adjusted for any incentives that may be available as follows:

$$C_{after\ incentives} = (C * CCA - rebate)*(1\text{-federal tax credit})*(1\text{-state tax credit})$$

Where,
C = installed cost of system ($)
CCA = city cost adjustment factor from RS Means and Co. cost estimating manuals

3.2 Annual Fuel and Electricity Savings

At this early planning stage, analysis is conducted using annual average load and resource information. Energy delivery is calculated as a function of renewable energy resources based on annual-average efficiency models (energy delivery=resource*efficiency). For some loads, such as the manufacturing plants and breweries, this introduces little error since the load is essentially constant, but in some cases the error may be substantial. In all cases, this tool is intended only to focus investment in site visits and detailed evaluation using hourly simulation or more sophisticated (and expensive) means of confirming both engineering and economic feasibility.

Energy savings consist of savings in natural gas (or other fuel) and electricity. Natural gas savings are limited to the minimum of: 1) basecase fuel use; or 2) renewable energy heat generating capacity. Electric savings are limited to the facility average electric demand. Renewable energy generation above average demand is sold back to the utility and credited at a lower wholesale rate. Electric savings are limited to: 1) the minimum of generator size (kW) or 2) in the case of solar thermal and biomass heat, limited to generating capacity of the plant multiplied by heat-to-electric cogeneration efficiency. Thermal energy as a by-product of electric generation is added back into the gas savings but multiplied by a heat exchanger effectiveness.

For wind power the energy savings are expressed as:

$$E_{s,\,electric,\,wind} = A_{swept}\, p_{wind}\, \eta_{wind}$$

Where A_{swept} = swept area of wind turbine (m2)
p_{wind} = annual average wind power density (W/m2)
η_{wind} efficiency of wind turbine system.

For the solar photovoltaic and solar thermal options the equations are:

$$E_{s,\,gas} = A_c\, I_{ave}\, \eta_{solar} 365 *(1-\eta_{cogeneration})*e_{hx}/\eta_{boiler}$$

$$E_{s,\,electric} = A_c\, I_{ave}\, \eta_{solar} 365 *\eta_{cogeneration}$$

where
A_c = solar collector area (m2)
η_{solar} = efficiency of solar electric system. For PV this is the efficiency of the PV panels times 0.77 to account for balance-of-system losses.
365 is the days/year
I_{ave} = average solar radiation (kWh/m2/day)
$\eta_{cogeneration}$ is the efficiency of the electric generator (zero for photovoltaics)
e_{hx} is the effectiveness of the heat recovery heat exchanger
η_{boiler} = auxiliary heater efficiency.

Fuel savings delivered by the solar ventilation air preheating system, $E_{s, gas, SVP,}$ is calculated by the equation

$$E_{s, gas, SVP} = A_c\, q_{useful} * (\#days\ per\ week/7) / \eta_{heating}$$

where

$\eta_{heating}$ = heating system efficiency.

Biomass Gas Savings (therms/year) are the minimum of site gas use and thermal energy provided by the biomass boiler minus that converted to electricity, divided by heat recovery steam generator effectiveness.

Biomass electric delivery (kWh/year) is the minimum of electric energy generation as calculated by cogen capacity times capacity factor or as limited by boiler capacity, boiler efficiency, and boiler capacity factor. For the biomass energy alternatives, annual delivery of heat and electricity are calculated as follows:

$$E_{s, gas, biomass} = P_{boiler} * \eta_{biomass\ boiler} *8760 * CF_{boiler} (1- \eta_{cogeneration} +(1- \eta_{cogeneration})*e_{hx} / \eta_{gas\ boiler}$$

$$E_{s, electric, biomass} = P_{boiler} * \eta_{biomass\ boiler} *8760 * CF_{boiler} *\eta_{cogeneration}$$

where

P_{boiler} = biomass boiler size (M Btu/h), a variable determined by the optimization

$\eta_{biomass\ boiler}$ = efficiency of biomass boiler

CF_{boiler} = capacity factor (% of time operational)

ηcogeneration is the efficiency of the electric generator

ehx is the effectiveness of the heat recovery heat exchanger

ηboiler = auxiliary heater efficiency.

3.3 Annual Utility Cost Savings

Renewable energy delivered less than the site load is credited at full retail value $E_s C_e$. Power delivered in excess of the average load (kW) is credited an "avoided cost" (wholesale rate) $E_s C_{e, avoided}$. Where

C_e = cost of utility energy ($/kWh)

$C_{e, avoided}$ = avoided cost paid by utility for excess power ($/kWh).

3.4 Annual Biomass Fuel Cost

The tons of biomass fuel used is calculated as the boiler heat delivered for both process heat and cogen divided by boiler efficiency and divided by heating value of fuel. The radius to collect fuel (miles) is calculated from the quotient of fuel required (tons) and density (tons/square mile) from the GIS database. The per-ton biomass fuel cost ($/ton) is calculated as a fixed cost ($/ton) plus trucking cost ($/ton/mile). The biomass fuel cost ($/year) is then the fuel used by the biomass energy plant minus fuel available onsite times fuel cost ($/ton).

3.5 Operation and Maintenance Costs

Annual operation and maintenance costs are calculated as an fraction of installed cost or as a multiplier on energy production as reported in Edition 3 of the Power Technologies Energy Data Book [1], or other sources [3] including staff project experience.

3.6 Production Incentives

Production incentives are calculated as the electrical energy delivery from each technology times the per-kWh incentive available for that particular technology. In most cases the production incentives are applied only to power provided to the utility. The cash flows associated with production incentives are not escalated over time.

3.7 Life-Cycle Cost

Life-cycle cost is calculated by adding initial cost to any annual costs discounted to their present value. Annual costs include maintenance, fuel (as in the case of biomass), standby charges from the utility, payments to the utility associated with the difference between retail and delivered power, and any production incentives or other cash flows.

The customer would specify the rate at which future costs are discounted to their present value. For the federal government this rate is specified at 5% in 2007 [4] . A large corporation investing in their own facility may have a 7.5% time-value of money, and the rate may be much higher for third party investors or a small company struggling to make payroll. The effect of higher discount rates is to make the capital-intensive renewables more expensive in terms of life cycle cost.

Fuel escalation rate (according to census region and fuel type), and general inflation rate are also from reference [4] for federal projects, but given considerable uncertainty in these parameters, most customers ask for results over a range of values, from 2% to as high as 15%. It is interesting that some corporations view a 15% fuel escalation rate not only out of academic interest, but they think rates that high are actually possible in coming years.

$$LCC= C_{initial} + (S_{energy} - C_{O\&M} - C_{biomass\ fuel})\, pwf_{25} + (S_{prod\ incentive})\, pwf_{prod\ incentive}$$

Where

LCC= life cycle cost

$C_{initial}$ = initial cost of renewable energy system

S_{energy} = annual savings in electricity and natural gas purchased from utility
$C_{O\&M}$ = annual cost of operating and maintaining renewable energy systems
$C_{biomass\ fuel}$ = annual cost of delivering biomass fuel to the site
pwf_{25} = present worth factor for future savings stream,(e.g. 17.41 years for 25 year lifetime and discount rate specified by NIST for 2005 in reference [3]).
$S_{prod\ incentive}$ =annual revenue from production incentive
$pwf_{prod\ incentive}$ = present worth factor associated with the term of the production incentive.

4. DISPATCH ALGORITHM

Special consideration is required to represent the way the electrical systems (PV, wind, solar thermal electric, biomass electric, daylighting) interact with each other. In particular, it is not possible to save the same kWh twice, and it is necessary to determine how much renewable energy is generated in excess of the load and supplied back to the serving utility under a net metering policy or as wholesale electric power. Similarly, it is necessary to calculate how much of the load is served directly by the renewable energy systems and how much is purchased from the utility. These effects are often represented by hourly simulation, but in this case we need a means to do it with only annual averages. Using the term "integrate" as it is used in calculus (area under a curve), the method employed here "integrates" power delivery from renewable energy installations with respect to time. The "integral" is illustrated as the area of the colored boxes in the following figure. The grey rectangle represents the load being served by a combination of renewable energy and conventional utility power.

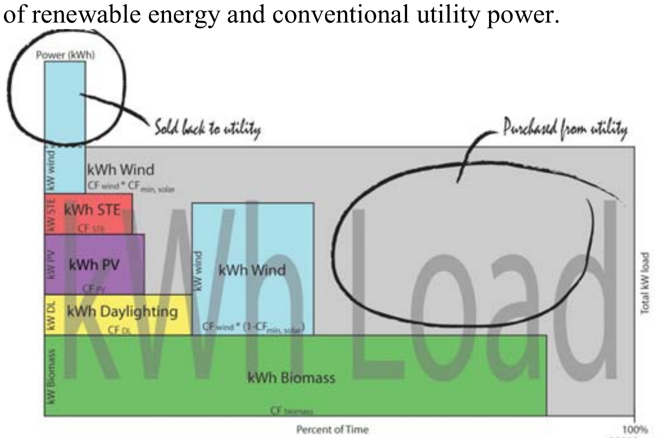

Figure 1. Annual energy quantities are represented as rectangles with height proportional to rated power and width proportional to operating hours in order to account for simultaneous actions of multiple energy sources.

Referring to Figure 1, the energy delivery of each technology is represented as its capacity times it operating hours. The sum of the capacities (kW) of all the renewable energy systems operating concurrently is multiplied by the hours that those technologies are operating concurrently. Operating hours are calculated according to the energy delivery of each system and the temporal relationships indicated in Figure 1. Regardless of how the energy delivery (kWh/year) of each system was estimated, it is now represented as rated capacity times hours of operation. Hours of operation are calculated according to the capacity factor as described in Section 3 of this paper except that in the case of daylighting, hours are stipulated at 2500 hours/year. It is important to note that the relations of Figure 1 do not "describe" how these technologies interact at a site but rather "prescribes" the assumed interaction that will be used in order to calculate the energy quantities.

For example, the sum of electrical capacities (kW) of wind, solar thermal electric, photovoltaics, daylighting and biomass are multiplied by the hours that those five devices are operating simultaneously. Then the sum of capacities of solar thermal electric, photovoltaics, daylighting and biomass are multiplied by the hours that those four devices are operating simultaneously. In this way it is possible to calculate the energy sold back to the utility and the energy purchased from the utility to serve a load with a combination of different renewable energy technologies.

5. OPTIMIZATION TECHNIQUE

The objective of the optimization problem is to minimize life-cycle cost. An MS Excel spreadsheet was prepared to estimate the cost and savings associated with each renewable energy measure and the life cycle cost for energy use at each facility. A computer program named "Premium Solver" from Frontline Systems Inc was then used to adjust each of the 15 variables to minimize life-cycle cost: 1) kW of PV; 2) kW of wind power; 3) square feet of solar ventilation air preheating; 4) square feet of solar water heating; 5) square feet of solar thermal (parabolic troughs); 6) kW of solar thermal electric; BTU/hour of biomass boiler capacity for 7) combustion, 8) gasification, 9) pyrolysis, 10) anaerobic digestion; kW of biomass electric for for 11) combustion, 12) gasification, 13) pyrolysis, 14) anaerobic digestion; and 15) square feet of daylighting aperture for each type of space.

The solver routine calculates the change in life-cycle cost associated with a change in the size of each of the renewable energy technologies, and then moves in the direction of decreasing life-cycle cost by an amount determined by a quadratic approximation. The solver routine involved the following parameters—precision: value of energy use 0.0 +/- 0.0001; convergence: change in life-cycle cost less than

$0.0001 for five iterations; quadratic extrapolation to obtain initial estimates of the variables in one-dimensional search; central derivatives used to estimate partial derivatives of the objective and constraint functions; and Newtonian Search Algorithm used at each iteration to determine the direction to search

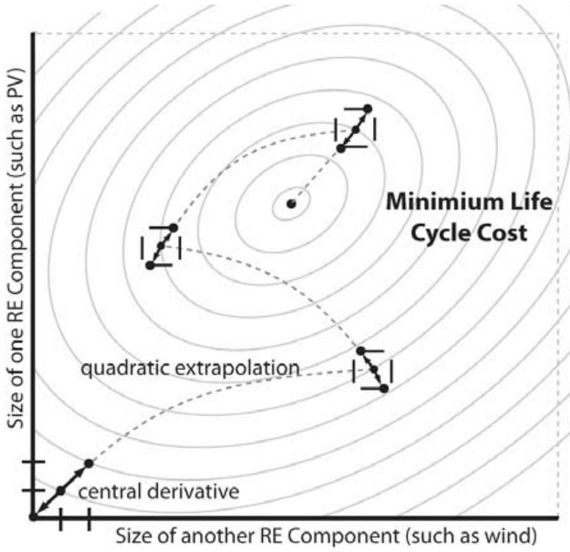

Figure 2. The solver routine finds the minimum Life Cycle Cost in 16 variables, but only two variables can be illustrated in this two-dimensional figure. An increase and decrease in the size of each renewable energy component is used to indicate direction of reducing life cycle cost.

6. <u>EXAMPLE: ZERO ENERGY PLANNING FOR NATIONAL ZOO</u>

This method was used to determine the combination of renewable energy technologies that would provide 100% of a Smithsonian Institution (SI) National Zoological Park energy on an annual basis at the minimum life-cycle cost. The facilities considered in the study include the National Zoological Park in Washington D.C. and the associated 4,600 acre Conservation Research Center in Front Royal VA. Results indicate that renewable energy measures could be integrated directly into buildings at both sites (PV, solar water heating, solar ventilation air preheating) but that central plant use of renewables (wind and biomass) would be needed to meet the zero energy goal. Table 1 lists the sizes of each component that minimize life cycle-cost in this example.

Life-cycle costs are summarized in Table 2. The base case of continuing to purchase electricity, gas and propane has zero initial cost but high annual cost and a life-cycle cost of $52 million. The net zero case has high initial cost of $46 million but low annual cost and a life-cycle cost of $74 million. Over a 25 year analysis period, the life cycle cost of the zero energy case is higher than the basecase, but the life cycle-cost analysis does not include a dollar value for emissions, educational value, or other benefits associated with the zoo's zero energy goal. Figure 3 illustrates how the use of electricity, gas, and propane would be replaced by renewable energy sources in a Net Zero Facility. The method may now be used to evaluate alternatives, such as biodiesel instead of wood chips, in response to issues that emerge during the process of implementation.

Table 1. OPTIMAL SIZES OF EACH TECHNOLOGY IN ZOO EXAMPLE

	National. Zoological Park, D.C.	Conservation. Research Center, VA	Total
Photovoltaics Size (kW)	638	224	862
Wind Capacity (kW)	0	14,500	14,500
Solar Vent Preheat Area (ft2)	10,655	8,075	18,730
Solar Water Heating Area (ft2)	7,535	2,180	9,715
Biomass Gasifier Size (M Btu/h)	10,996	0.000	10,996
Biomass Cogeneration Size (kW)	1,168	0	1,168
Anaerobic Digester Size (FT3)	3,723	459	4,182
Anaerobic Digester Cogeneration Size (kW)	12	0	12
Daylight Aperture (Skylight) Area (ft2)	21,221	6,476	27,697

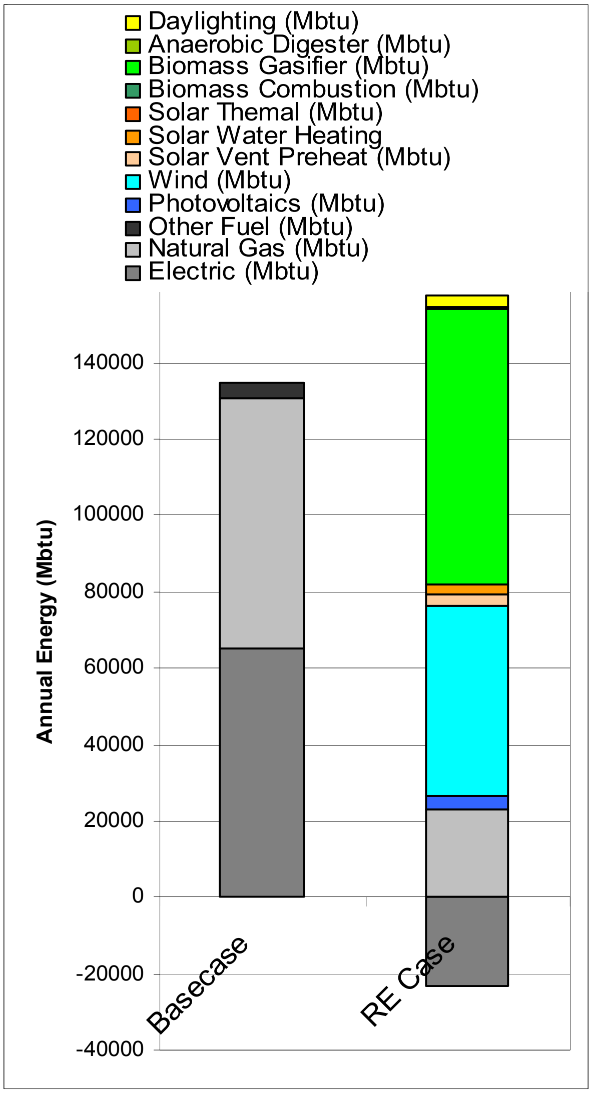

Figure 3. Annual energy associated with each technology for basecase and zero energy case. Extra electric generation at the farm in VA (below the zero axis) is to offset remaining natural gas use at Zoo in D.C.

Table 2. LIFE-CYCLE COST OF BASECASE AND ZERO ENERGY CASE IN ZOO EXAMPLE

Name	Basecase Life Cycle Cost ($)	RE Case Life Cycle Cost ($)
Initial Cost	$0	$45,858,421
O&M Cost	$0	$13,135,266
Biomass Fuel Cost	$0	$5,762,545
Gas Cost	$17,323,188	$5,713,053
Electric Cost	$34,914,085	$7,196,488
Production Incentives	$0	-$2,887,806
Total	**$52,237,272**	**$74,777,968**

7. CONCLUSIONS

The approach described in this paper offers a means of providing actionable information very early in the process of planning renewable energy at a facility. Most large organizations can point to renewable energy projects that they have completed or are planning. But often these projects are selected anecdotally, and may not represent the best investment. This method offers a structured approach to identify and prioritize measures for further evaluation. The method represents the effects that are most important including local resources, utility rates, and incentives. The method requires only summary information regarding the facility making it affordable to conduct this analysis without an expensive data collection effort. The method has proven to be effective in early planning to meet renewable energy goals in industrial and government applications.

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This paper describes a method for determining the combination of renewable energy technologies that minimize life-cycle cost at a facility, often with a specified goal regarding percent of energy use from renewable sources. Technologies include: photovoltaics (PV); wind; solar thermal heat and electric; solar ventilation air preheating; solar water heating; biomass heat and electric (combustion, gasification, pyrolysis, anaerobic digestion); and daylighting. The method rests upon the National Renewable Energy Laboratory's (NREL's) capabilities in characterization of technology cost and performance, geographic information systems (GIS) resource assessment, and life-cycle cost analysis. The paper discusses how to account for the way candidate technologies interact with each other, and the solver routine used to determine the combination that minimizes life-cycle cost. Results include optimal sizes of each technology, initial cost, operating cost, and life-cycle cost, including incentives from utilities or governments. Results inform early planning to identify and prioritize projects at a site for subsequent engineering and economic feasibility study.

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