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COST OPTIMIZATION OF NET-ZERO ENERGY HOUSE

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ABSTRACT

Environmental and resource limitations provide increased motivation for design of net-zero energy or net-zero CO_2 buildings. The optimum building design will have the lowest lifecycle cost. This paper describes a method of performing and comparing lifecycle costs for standard, CO_2-neutral and net-zero energy buildings. Costs of source energy are calculated based on the cost of photovoltaic systems, tradable renewable certificates, CO_2 credits and conventional energy. Building energy simulation is used to determine building energy use. A case study is conducted on a proposed net-zero energy house. The paper identifies the least-cost net-zero energy house, the least-cost CO_2 neutral house, and the overall least-cost house. The methodology can be generalized to different climates and buildings. The method and results may be of interest to builders, developers, city planners, or organizations managing multiple buildings.

INTRODUCTION

Global climate change, air and water pollution, and deforestation challenge humanity toward creative and rapid solutions. According to a recent report by Sir Nicholas Stern, former vice-president of the World Bank, global climate change could result in a reduction of 20% in the world economy [1]. In attempts to mitigate climate change, 169 countries have mandated reduction of CO_2 emissions by ratifying the Kyoto Protocol as of December 2006 [2]. The American Institute of Architects has proposed a reduction of 10% in building energy use every five years towards carbon neutral buildings by 2030 [3].

The overwhelming cause of global warming is the burning of fossil fuels, which releases stored carbon dioxide into the environment. Present CO_2 levels are about 337 parts per million compared to 300 parts per million before the industrial revolution [4]. Fossil fuels account for over 82% of total world energy consumption [5]. One of the greatest challenges facing humanity is to become CO_2 neutral in our activities. In response to global environmental concerns, the University of Dayton (UD) plans to build a net-zero energy house, called the Eco-house, on campus. A net-zero energy house, such as the Eco-house, would be CO_2 neutral. However, a CO_2 neutral home could purchase tradable renewable certificates, which would guarantee that the energy supplied to the home comes from renewable energy sources. In addition, CO_2 offset credits could be purchased.

If the goal of a project is to become CO_2 neutral, then there is no difference between a net-zero energy house with photovoltaic panels and a house that purchases tradable renewable certificates. With current costs, purchasing tradable renewable certificates is more cost-effective than purchasing a photovoltaic system. However, there are benefits beyond being CO_2 neutral that a net-zero energy house such as the Eco-house would convey. On a college campus, photovoltaic panels would serve as an educational tool for students, faculty, and the surrounding community. If photovoltaic panels were to be used on the UD Eco-house, they would enable the students to design experiments around monitoring the performance of the house and publishing their findings. The panels would also serve as an example of renewable energy technology and visibly demonstrate that the house is CO_2 neutral; a very important tool for the promotion and acceptance of renewable energy technologies in a fossil fuel dominated society.

Design of the Eco-house has been presented in prior papers [6, 7]. The Eco-house was determined to have a lower lifetime cost over 35 years than a baseline house typically constructed by the university [7]. However, the design of the Eco-house has not yet been optimized within net-zero energy or CO_2 constraints. This is the topic of this paper.

In this paper, a method for determining the cost of source energy is presented for photovoltaic panels, tradable renewable certificates, CO_2 credits and conventional energy. Costs of source energy are calculated based on current prices for photovoltaic panels, tradable renewable certificates, CO_2 credits and conventional energy. Next, the building optimization methodology is discussed. Baseline building characteristics and energy use are identified. Key building components such as walls, windows and appliances are selected for optimization. Component options and first costs are identified. Building energy use for component options is determined through building energy simulation. Marginal costs of avoided energy are calculated for energy efficiency measures. Marginal costs for efficiency measures are compared to the cost of source energy supplied by photovoltaic panels, tradable renewable certificates, CO_2 credits and conventional energy. Interactions between building components are not considered in this paper. The method is based on a similar method by Christensen [8]. A case study on a baseline house at the University of Dayton is conducted using the optimization method.

The paper identifies the least-cost net-zero energy house, the least-cost CO_2 neutral house, and the overall least-cost house. The methodology could be used to determine the least-cost design in different locations. The method and results may be of interest to builders, developers, city planners, or organizations managing multiple buildings. The method is important because it compares the economics of net-zero energy, net-zero CO_2 and conventional energy.

OPTIMIZATION CONSTRAINTS

Traditionally, energy efficiency efforts have been implemented when they are least-cost solutions. As discussed above, environmental and resource limitations result in increased motivation to design net-zero energy or net-zero CO_2 buildings with the lowest lifecycle cost. Thus, the least cost optimization is subject to net-zero energy or net-zero CO_2 constraints. This new problem is the subject of this paper.

A net-zero energy home is defined as a home that, over the course of a year, generates the same amount of energy as it consumes. A net-zero energy home could generate energy through photovoltaic panels, a wind turbine, or a biogas generator. The net-zero energy home considered in this paper uses photovoltaic panels (PV) to offset electricity purchased from the grid. For this home, the roof area is large enough to support the required PV panels.

In a CO_2 neutral home, no CO_2 is added to the atmosphere due to the operation of the building. This could be accomplished by purchasing tradable renewable certificates (TRCs) generated by solar, wind, or biogas. It could also be accomplished by purchasing CO_2 credits on a carbon trading market from someone who has CO_2 credits to sell. In addition, the home could generate all of its energy on-site, like a net-zero energy home. Thus, a net-zero energy home is a CO_2 neutral home, but a CO_2 neutral home is not necessarily a net-zero energy home. In this paper, a CO_2 neutral home is assumed to purchase certified renewable energy or CO_2 credits.

The third possibility is that a house has no energy or CO_2 constraints to meet. In this case, a home is supplied with conventional energy, in the form of purchased electricity and fuel such as natural gas. Currently, these forms of conventional energy are less-costly than most types of renewable energy. However, conventional energy may not be the cheapest way to power a home in the future. Resource constraints are driving the cost of fossil fuel-based energy higher. In addition, a CO_2 tax or reduced subsidies to the coal, natural gas, and oil industries would further increase the cost of conventional energy. And at some point, it is likely that conventional energy will become more expensive than purchasing renewable energy or generating on-site with photovoltaic or other equipment. For example, in Japan, government incentives have made photovoltaic panels cost-effective for homeowners to install on their own homes [8]. In addition, many U.S. states offer incentives to reduce the installed cost of PV panels.

COSTS OF SOURCE ENERGY

In order to compare energy generated from a photovoltaic system, certified renewable energy, CO_2 credits and conventional energy, a common metric must be determined. It is difficult to compare a PV system, certified renewable energy, conventional energy and conventional energy with CO_2 credits. In order to account for the differences between these systems, each alternative will be compared to a PV system over its lifetime. Recurring annual costs, such as those incurred from purchasing conventional energy, are viewed as an escalating series with energy escalation and discount rates. The lifetime present value costs are calculated and averaged to present an average cost of source energy. In this paper, source energy consumption for electricity is 1 mmBtu per 97.7 kWh site energy use [9]. All costs of source energy are calculated as the average present value cost of one kWh and source mmBtu of energy.

Cost of Source Energy from PV

First, the cost of source energy for photovoltaic panels is calculated. The equations relate the cost of source energy to the first cost of photovoltaic panels, the net-present value of lifetime operating costs and the estimated lifetime energy generated. The cost of source energy for a PV system is calculated in Equation 1.

$$CSE_{PV} = (FC + OC) / (LE) \qquad (1)$$

Where:
FC is the first cost of photovoltaic panels
OC is the net-present value of lifetime operating costs
LE is the estimated lifetime energy generated

For example, the photovoltaic system for the UD Eco-house consists of 32 panels with a rating of 165 W per panel, for a total rated output of 5.28 kW. Using SolarSim simulation software, PV system output is estimated to be about 6,577 kWh per year [7]. The estimated lifetime of the PV system is about 15 years and first cost is about $32,000. Assuming negligible maintenance costs, the present value lifetime cost of the photovoltaic system is also $32,000. The lifetime energy generated by the system would be about 101,232 kWh, which is equivalent to 1,036 mmBtu of fuel consumed at a power plant. Thus, the average cost of source energy is about $0.32 per kWh, or $30.9 per mmBtu.

Cost of Source Energy from TRCs

A common metric between costs of source energy for TRCs and PV can be obtained by considering one TRC purchased annually for the lifetime of the PV system. Annual purchasing of TRCs can viewed as an escalating series. The lifetime cost of purchasing one kWh per year of TRCs for some period can be calculated by multiplying the initial cost by the escalating series present worth factor (ESPWF) shown in Equation 1 [10]. The ESPWF is determined by Equation 3 or 4. The average cost of source energy over a given period of time is determined in Equation 5.

LC = IC x ESPWF (2)

$$ESPWF = \frac{n}{(1+e)} \text{ when } i = e \quad (3)$$

$$ESPWF = \frac{1}{(i-e)}\left[1-\left(\frac{1+e}{1+i}\right)^n\right] \text{ when } i \neq e \quad (4)$$

CSE_{TRCs} = LC / n (5)

Where:
LC is the lifetime cost of one unit of energy purchased each year
IC is the current cost of one unit of energy
i is the discount rate
e is the fuel escalation rate
n is the number of years that the series is growing

For example, the UD Eco-house energy escalation rates were bracketed between 1% and 4%, and the discount rate is 5% [7]. In this paper, the energy escalation rate is assumed to be 4% annually. The cost of TRCs is currently about $0.018 per kWh [11]. The cost of purchased electricity is about $0.10 per kWh. Thus, the total cost of electricity from renewable sources is about $0.12 per kWh. Using Equations 2-4, the present value lifetime cost of 1 kWh per year for 15 years is about $1.60. Using Equation 5, the cost of energy is $0.11 per kWh, or $10.45 per mmBtu.

Cost of Conventional Energy

The energy escalation rate is estimated to be 4% annually, and the discount rate is 5% [7]. The current cost of residential conventional energy in Dayton, OH is about $0.10 per kWh [12]. The cost of purchasing one kWh per year of conventional energy can be calculated by multiplying the initial cost by the escalating series present worth factor (ESPWF). Using Equations 2-4, the present value lifetime cost of 1 kWh per year for 15 years is about $1.34. Using equation 5, the cost of energy is $0.09 per kWh, or $8.71 per mmBtu.

Cost of Conventional Energy with CO_2 Credits

The cost of CO_2 credits will fluctuate based on market performance. The total cost of consuming energy and purchasing CO_2 credits is represented in Equation 7. CO_2 credits are sold in tonnes of CO_2. The equivalent source energy consumption will vary based on the makeup of fossil fuels used to produce the energy. The equivalent cost of source energy is represented by Equation 6.

$CSE_{CO2\ Credits}$ = IC / CR (6)

$CSE_{CE\ with\ CO2\ Credits} = CSE_{FossilFuel} + CSE_{CO2\ Credits}$ (7)

Where:
$CSE_{CO2\ Credits}$ is the cost of source energy for CO_2 credits
$CSE_{FossilFuel}$ is the cost of source energy for fossil-fuel energy
$CSE_{CE\ with\ CO2\ Credits}$ is the cost of source energy for fossil-fuel energy with CO_2 credits
IC is the initial cost of CO_2 credits
CR is the ratio of CO_2 emitted into the atmosphere for every unit of fossil-fuel energy consumed

Currently in the United States, CO_2 credits are being traded on the Chicago Climate Exchange (CCX). On the CCX, CO_2 credits are trading for about $4.25 per metric tonne of CO_2 as of January 2007 [13]. In the European Union, CO_2 credits are being traded on the European Climate Exchange for about $4.75 per metric tonne of CO_2 as of January 2007 [14]. In this paper, the cost of CO_2 credits will be the cost on the CCX, or $4.25 per metric tonne of CO_2. In Dayton, Ohio, coal is the primary form of source energy used to produce electricity. For coal fired power plants, about 0.051 tonnes of CO_2 are released into the atmosphere for every one mmBtu of source energy consumed [15]. Thus, the current equivalent cost of source energy for CO_2 credits is about $0.22 per mmBtu. In this paper, it is assumed that the real cost of CO_2 credits will increase at a rate of 5% annually. Since the discount rate at the University of Dayton is 5%, the average cost of CO_2 credits for the next 15 years would be $0.22 per mmBtu. However, it is highly unlikely that this will be the case. Many countries have already mandated CO_2 emissions reductions, and as easy measures are taken to reduce CO_2 emissions, the cost of CO_2 credits will likely rise at a faster rate than the discount rate. The cost of CO_2 credits would be added to the cost of consuming energy, or the cost of conventional energy, $8.71 per mmBtu. The total cost of consuming conventional energy and purchasing CO_2 credits would be $8.93 per mmBtu.

Summary of Source Energy Costs

The costs of conventional energy, certified renewable energy, and energy generated on-site by photovoltaic panels are summarized in Table 1. Conventional energy is cheapest, followed by CO_2 credits, certified renewable energy and energy from photovoltaic panels.

TABLE 1. COSTS OF SOURCE ENERGY

	Cost of Source Energy ($/kWh)	Cost of Source Energy ($/mmBtu)
Conventional Energy	$0.089	$8.71
Conventional Energy with CO_2 Credits	$0.091	$8.93
Tradable Renewable Certificates	$0.107	$10.45
Photovoltaic Energy	$0.316	$30.88

OPTIMIZATION METHOD

The optimization methodology presented in this paper is a variation of the methodology presented by Christensen, et al., [9]. Christensen discusses the difficulty in determining a true-optimum zero net energy building. In order to determine a true-optimum building, an exhaustive search must be performed, involving numerous iterations and simulations. An exhaustive search is extremely computer-intensive and often time-prohibitive. Several software packages are briefly described by Christensen that automate the optimization process. These software packages account for interactions between building components. The preferred method described uses a hybrid parallel and sequential search method.

Parallel and sequential search methods are described in a recent paper by Christensen [9]. In these papers, Christensen optimizes the building design for a net-zero energy constraint, but does not address the question of the optimum net-zero CO_2 - house. The approach followed in this paper uses a single-iteration parallel search. While the parallel search method alone does not arrive at the true-optimum design, it arrives at a near-optimum design for net-zero energy, net-zero CO_2 and for no energy or CO_2 constraints.

Baseline Building

The optimization performed in this paper is based on the marginal cost of avoided source energy. In order to calculate marginal costs for building components, a baseline building must be first identified.

Select Components for Optimization

Once a baseline building is identified, building components must be selected for optimization. Building components include walls, windows, roof, orientation, layout, HVAC, lighting, appliances and water heating. Some building components may be fixed and other components selected for optimization. Components may be fixed for various reasons. For example, if a builder wanted to determine the optimum design for an already existing layout, the building layout would be fixed. In addition, if a homeowner wanted to determine the least-cost house to be built on a particular site, building orientation could be fixed.

Energy Efficient Alternatives

Once building components are selected for optimization, energy efficient alternatives must be determined. When identifying energy efficient alternatives, cost and energy ratings must be understood. In the case of appliances, such as a refrigerator, the manufacturer will list an average yearly energy use which can be compared to other refrigerators.

Building energy simulations

If energy efficient alternatives are more complicated than comparing average annual energy use, simulations must be performed. In this paper, ESim building energy simulation software is used [16]. ESim simulates building energy use on an hour-by-hour basis using typical meteorological data [16]. ESim's building load calculations consider heat exchange through the building envelope, solar loads, internal sources of heat and humidity, and air exchange. ESim is appropriate for passive-solar, single-zone and large multi-zone buildings with sophisticated HVAC systems and controls. The computational algorithms are based on fundamental thermodynamic, psychrometric and heat-transfer calculations. Solar radiation on each building surface is computed using the HDKR ansiotropic sky model. Energy-storage effects are considered using transfer-function and finite-difference algorithms.

Marginal Costs of Avoided Energy

Energy efficient alternatives should be compared in terms of the average cost of avoided source energy for their entire lifetime, or $/mmBtu. Building energy use and first costs are determined for all component options. Building energy use and first costs of options are plotted in a chart, such as the chart shown below.

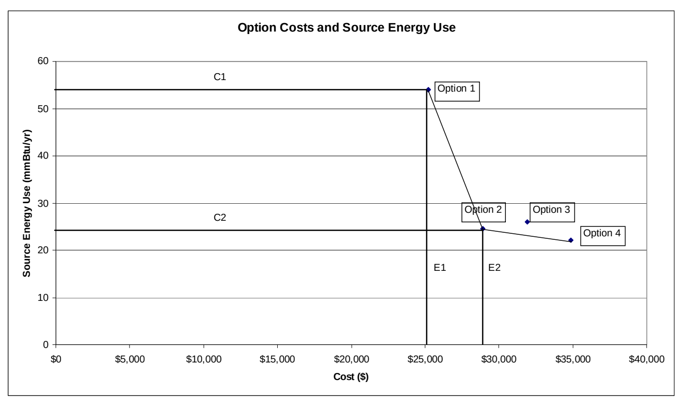

FIGURE 1. OPTION COSTS AND ENERGY USE

The marginal cost of avoided energy (MCE) is calculated as the ratio of the additional cost of the energy efficient alternative (dC) to the energy saved (dE) multiplied by the lifetime of the options (n) in years. The marginal cost of energy is calculated as Equation 8.

$$MCE_{EffMeasure} = \frac{dC}{dE} \times \frac{1}{n} \tag{8}$$

where $dC = C1 - C2$ ($) and $dE = E2 - E1$ (mmBtu/yr)

Determining Optimum Designs

At this point, in the method laid out by Christensen, some options are eliminated based on their location on the graph. Only those options that define the edge of a concave-up region which includes all data points can be part of the optimal building design. This can be accomplished by connecting the points, moving from left to right in the graph, and continuing to increase the slope between points. In the case of the example options presented, Option 3 is determined to be an extraneous point. It could not be part of the optimal building design, and would be eliminated from consideration. Next, Christensen's method requires the comparison of marginal costs of avoided energy for Options 1, 2, and 4. The marginal costs of avoided energy for efficiency measures are compared to constant, horizontal lines, representing the cost of source energy for PV panels, TRCs, carbon credits and conventional energy. The optimum component for each type of energy is determined as the most expensive option which falls below the cost of source energy for PV, TRCs, carbon credits and conventional energy. An example chart is shown below.

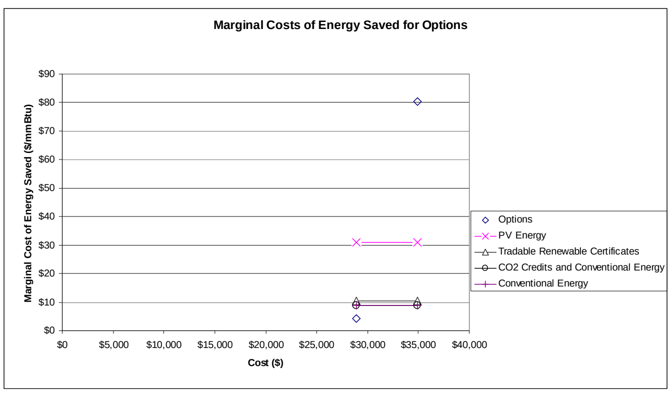

FIGURE 2. MARGINAL COSTS OF AVOIDED ENERGY FOR COMPONENT OPTIONS AND ENERGY CONSTRAINTS

In this case, Option 2 is the optimum component design for energy supplied by PV, TRCs, carbon neutral energy, and conventional energy. It is a bit challenging to conclude that Option 2 is the optimum component design. Perhaps it is more clear to determine the optimum component design by viewing the lifetime owning and operating costs for efficiency measures. Efficiency measures save energy, but still require that some energy is supplied to the home. The remaining energy supplied by PV, TRCs, carbon credits or conventional energy. The optimum design is the design which minimizes the present value lifetime cost of owning and operation for all of these energy sources. A generic lifetime cost of owning and operation is calculated as Equation 9.

$$LC_{Own,Operate} = IC\ (\$) + E_i \times n\ (yrs) \times MCE_{EnergySource} \qquad (9)$$

Where:

IC is the initial cost of the option

E_i (mmBtu/yr) is the annual energy use for a given option

n is the lifetime of the component option

$MCE_{EnergySource}$ ($/mmBtu) is the cost of energy for a given energy source i.e. PV, TRCs, carbon credits, or conventional energy

For all options presented in Figure 2, above, the lifetime costs of owning and operation are shown in Figure 3, below.

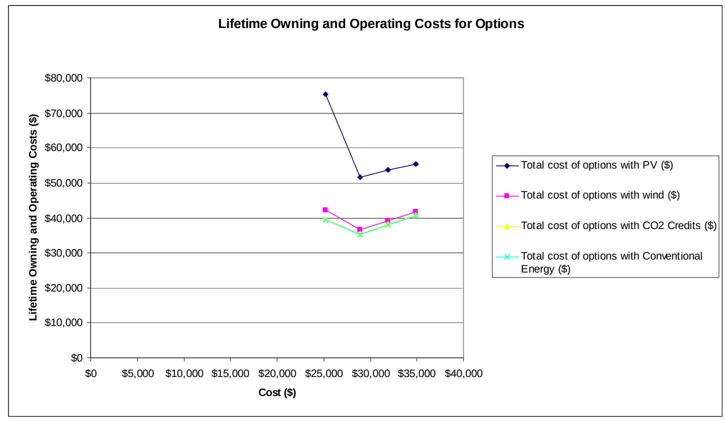

FIGURE 3. LIFETIME OWNING AND OPERATING COSTS FOR OPTIONS WITH ENERGY CONSTRAINTS

In Figure 3, the overall least-cost option for lifetime owning and operating costs can be seen for PV, TRCs, carbon neutral energy, and conventional energy. According to Figure 3, Option 2 is the optimum design because it results in the least lifetime cost for a building with PV energy, TRCs, carbon neutral energy and conventional energy. This graph is our preferred method of determining optimum component designs, and will be presented in the remainder of the paper.

Summary of Optimization Method

In summary, the steps of determining an optimum building design are:

1. Determine baseline house characteristics
2. Select building components for optimization
3. Identify options for selected building components
4. Perform building energy simulations
5. Calculate marginal costs of avoided energy for efficiency measures
6. Determine optimum design for energy or CO_2 constraints

CASE STUDY: UNIVERSITY OF DAYTON STUDENT HOUSING

Baseline House Characteristics

The University of Dayton has decided that most new student housing will be 5-person houses located in the student neighborhood. UD has already constructed five new houses with conventional building techniques. These techniques define the baseline house. The walls have an R-value of 13 hr-ft2-F/Btu, ceilings have an R-value of 16 hr-ft2-F/Btu, and the windows have an R-value of about 2 hr-ft2-oF/ Btu. The rate of infiltration is constant at about 0.62 air changes per hour. The houses use 80% efficient natural gas furnaces and natural gas hot water heaters with an average efficiency of about 55%. The air conditioners have a SEER of 10 (Btu/Wh). The north and south sides of the house measures 23 feet and the east and west sides measure 30 feet. A summary of baseline house characteristics is found in Table 2 [7].

TABLE 2. BASELINE HOUSE CHARACTERISTICS

Baseline House Characteristics	
Awalls (ft^2)	2,002
Awindows (ft^2)	78
Aceiling (ft^2)	662
Number occupants	5
Floor area (ft^2)	662
Perimeter length (ft)	104
Rwalls (hr-ft^2-F/Btu)	13
Rwindows (hr-ft^2-F/Btu)	2
SHGC	0.531
Rperimeter_insulation (hr-ft^2-F/Btu)	10
Rceiling_roof (hr-ft^2-F/Btu)	16
Infiltration (ACH)	0.62
Internal Loads (kWh/mo)	949
Temperature Setbacks (10pm - 8am)	None
Winter (F)	72
Summer (F)	72
Furnace Efficiency	0.8
SEER of Air Conditioner	10

<u>Building Component Selection</u>

Building components can be divided into general categories; appliances and lighting, building shell, and heating, ventilation and air conditioning (HVAC). Within the building shell category, overall layout, orientation, walls and window components could be optimized. Within HVAC category, heating systems, cooling systems and ventilation systems could be optimized. Within lighting and appliances category, lighting, refrigerator, dishwasher, clothes washer, clothes dryer, and water heating components could be optimized. In the case of the UD Eco-house, certain baseline features will not be modified. These include building orientation, building layout, lighting and clothes dryer. An exhaustive list of building components are shown in Table 3, along with components which have been selected for optimization.

TABLE 3. SELECTION OF BUILDING COMPONENTS FOR OPTIMIZATION

Building Components	Selected for Optimization
Appliances and Lighting	
Clothes Dryer	No
Clothes Washer	Yes
Dish Washer	Yes
Lighting	No
Refrigerator	Yes
Water Heating	Yes
Building Shell	
Building Layout	No
Building Orientation	No
Walls and Roof	Yes
Windows	Yes
HVAC	
Heating, Cooling and Ventilation System	Yes

The seven building components selected for optimization must be compared to baseline building components. The baseline building components are displayed in Table 4.

TABLE 4. BASELINE BUILDING COMPONENT DESCRIPTIONS

	Model Number	Description
Water Heating	GCV-50	55% efficient, Low Efficiency Water Heater
Walls and Roof	None	2x6 Construction, R13 Walls
Refrigerator	FRT18G4A	Energy Star, 479 kWh/yr
Dishwasher	FDB750RC	Energy Star, 328 kWh/yr
Clothes Washer	FWS833AS	Energy Star, 436 kWh/yr
Windows	None	Double Pane Windows, SHGC 0.531, R of 2 hr-ft2-F/Btu
Heating/Cooling	None	80% efficient heating, 10 COP

<u>Building Component Options</u>

Next, component options were gathered from a variety of sources. Appliance options were determined from a review of manufacturer's websites. Walls and roof options were determined by speaking with a Structurally Insulated Panel (SIP) installer. SIPs were chosen due to their high insulation values and tight construction which reduces infiltration. Double and triple-pane windows were considered with argon gas and low-e coatings. Window options were determined by speaking with a local window salesperson. An energy efficient furnace and air conditioner were considered along with an energy efficient heat pump. Option costs were obtained from speaking with local retailers and local building contractors if possible. Component options are displayed in the following table. Relevant information, including a model number, description, and energy use ratings are shown in Table 5.

TABLE 5. ENERGY EFFICIENT OPTIONS FOR BUILDING COMPONENTS

Building Component Options	Model Number	Description
Water Heating		
Baseline Water Heater	GCV-50	55% efficient, Low efficiency water heater, 28 mmBtu/yr
Energy Efficient Water Heater	XGV-50	60% efficient, High efficiency water heater, 23.6 mmBtu/yr
Solar Water Heater	200153C80EX	7.48 square meters, FrTa = 0.74, FrUl = 1.527, 80% effective heat exchanger, 120 gallons of storage
Walls and Roof		
Baseline Walls and Roof	None	2x6 Construction, R13 Walls, R? Roof
Low End SIPs	None	6" SIP walls, 8" SIP Roof, 75 cfm ERV, 52% effective
Medium Range SIPs	None	8" SIP walls, 10" SIP Roof, 75 cfm ERV, 52% effective
High End SIPs	None	10" SIP walls, 12" SIP Roof, 75 cfm ERV, 52% effective
Refrigerator		
Baseline Refrigerator	FRT18G4A	Low efficiency, no Energy Star label, 479 kWh/yr
Energy Efficient Refrigerator	ET8WTEXM	Energy efficient, Energy Star label, 411 kWh/yr
Super Energy Efficient Refrigerator	MTB1895A	Super efficient, Energy Star label, 409 kWh/yr
Heating and Air Conditioning		
Baseline Furnace and Air Conditioning	None	AFUE 0.94, SEER 10.2
Energy Efficient Heat Pump	None	Heating COP 9.4, Cooling SEER 14.5
Energy Efficient Furnace and Air Conditioning	None	AFUE 0.966, SEER 16
Dish Washer		
Baseline Dishwasher	FDB750RC	Low Efficiency, no Energy Star label, 328 kWh/yr
Medium Energy Efficient Dishwasher	FDR252RB	Medium efficiency, Energy Star label, 315 kWh/yr
High Energy Efficient Dishwasher	D3212	High efficiency, Energy Star label, 278 kWh/yr
Super-energy efficient Dishwasher	D3432	Super-high efficiency, Energy Star label, 231 kWh/yr
Clothes Washer		
Baseline Clothes Washer	FWS833AS	Low efficiency, no Energy Star label, 436 kWh/yr
Energy Efficient Clothes Washer	GLTF2940E	High efficiency, Energy Star label, 215 kWh/yr
Windows		
Baseline Windows	None	R 2, SHGC 0.79
B Windows	None	R 2.78, SHGC 0.74
C Windows	None	R 4, SHGC 0.67
D Windows	None	R 5, SHGC 0.29

Building Energy Simulations

For some building components, such as clothes washer, dish washer, and refrigerator, no simulation is performed. Manufacturers estimate the yearly energy consumption for each model, based on a standard operating schedule. Appliances are compared based on first costs and rated annual energy use. However, for walls and roof, windows and heating and air conditioning, energy simulation is necessary to estimate annual energy use. For walls and roof, windows and heating and air conditioning, the ESim building energy simulation software is used [16]. Solar water heating was modeled with SolarSim software [17]. Simulation results are described in a previous paper [7]. Energy use and first costs for component options are summarized in Table 6.

TABLE 6. FIRST COST AND ANNUAL ENERGY USE FOR COMPONENT OPTIONS

Component Option	Lifetime	First Cost ($)	Annual Electricity Use (kWh/yr)	Annual Gas Use (mmBtu/yr)
Water Heating				
Baseline Water Heater	15	$480	0	28
Energy Efficient Water Heater	15	$580	0	23.56
Solar Water Heater	15	$3,735	112	0
Walls and Roof				
Baseline Walls and Roof	30	$25,200	2,036	33.2
Low End SIPs	30	$28,881	2,025	3.8
Medium Range SIPs	30	$31,881	2,020	2.8
High End SIPs	30	$34,881	2,016	1.4
Refrigerator				
Baseline Refrigerator	13	$449	479	0
Energy Efficient Refrigerator	13	$579	412	0
Super Energy Efficient Refrigerator	13	$679	409	0
Heating and Air Conditioning				
Baseline Furnace and Air Conditioning	15	$2,628	2,036	33.2
Energy Efficient Heat Pump	15	$2,775	5,313	0
Energy Efficient Furnace and Air Conditioning	15	$4,250	1,272	32.4
Dish Washer				
Baseline Dishwasher	13	$279	328	0
Medium Energy Efficient Dishwasher	13	$419	315	0
High Energy Efficient Dishwasher	13	$780	278	0
Super-energy efficient Dishwasher	13	$1,100	231	0
Clothes Washer				
Baseline Clothes Washer	13	$279	436	0
Energy Efficient Clothes Washer	13	$749	215	0
Windows				
Baseline Windows	20	$2,340	2,218	35.1
B Windows	20	$2,457	2,187	33.8
C Windows	20	$2,600	2,141	33
D Windows	20	$2,821	1,875	35.6

Marginal Costs of Avoided Source Energy

Marginal costs of avoided source energy are calculated for each option within each building component. Those options which are extraneous points have been thrown out. The marginal costs of avoided source energy for energy efficiency alternatives are compared to the costs of source energy for PV, TRCs, carbon neutral energy and conventional energy. The resulting marginal costs of avoided energy can be seen in Table 7. If an option has a lower marginal cost of avoided energy than PV, TRCs, carbon neutral energy or conventional energy, then it is more cost-effective to purchase the energy efficient option than to purchase energy.

TABLE 7. COMPARISON OF ENERGY EFFICIENCY OPTIONS TO VARIOUS ENERGY SOURCES

Component Option	Marginal Cost of Avoided Energy ($/mmBtu)	Cost of PV ($/mmBtu)	Cost of Wind ($/mmBtu)	Cost of CO2 Credits and Conventional Energy ($/mmBtu)	Cost of Conventional Energy ($/mmBtu)
Water Heating					
Energy Efficient Water Heater	$1.50	$30.88	$10.45	$8.93	$8.71
Solar Water Heater	$9.38	$30.88	$10.45	$8.93	$8.71
Walls and Roof					
Low End SIPs	$4.16	$30.88	$10.45	$8.93	$8.71
Medium Range SIPs	$95.13	$30.88	$10.45	$8.93	$8.71
High End SIPs	$69.40	$30.88	$10.45	$8.93	$8.71
Refrigerator					
Energy Efficient Refrigerator	$14.58	$30.88	$10.45	$8.93	$8.71
Super Energy Efficient Refrigerator	$250.51	$30.88	$10.45	$8.93	$8.71
Heating and Air Conditioning					
Energy Efficient Heat Pump	-$28.70	$30.88	$10.45	$8.93	$8.71
Energy Efficient Furnace and Air Conditioning	$10.97	$30.88	$10.45	$8.93	$8.71
				$8.93	
Dish Washer					
Medium Energy Efficient Dishwasher	$80.93	$30.88	$10.45	$8.93	$8.71
High Energy Efficient Dishwasher	$73.33	$30.88	$10.45	$8.93	$8.71
Super-energy efficient Dishwasher	$51.17	$30.88	$10.45	$8.93	$8.71
Clothes Washer					
Energy Efficient Clothes Washer	$15.98	$30.88	$10.45	$8.93	$8.71
Windows					
B Windows	$3.62	$30.88	$10.45	$8.93	$8.71
C Windows	$10.23	$30.88	$10.45	$8.93	$8.71
D Windows	$196.13	$30.88	$10.45	$8.93	$8.71

Component Optimization

In the graph of lifetime owning and operating costs, the options are evaluated based on their first cost and annual building energy requirements. The cost of energy required by the house is varied for PV, TRCs, carbon neutral energy and conventional energy, resulting in four corresponding curves with as many points as options which are presented. The optimum component design will be the design which minimizes lifetime owning and operating costs.

Wall and Roof Optimization

In Figure 4, which shows lifetime owning and operating costs for wall and roof options, Option 2 has a lower lifetime owning and operating cost for PV, TRCs, carbon neutral energy and conventional energy. Option 2 is the optimum design for a house supplied with each form of energy.

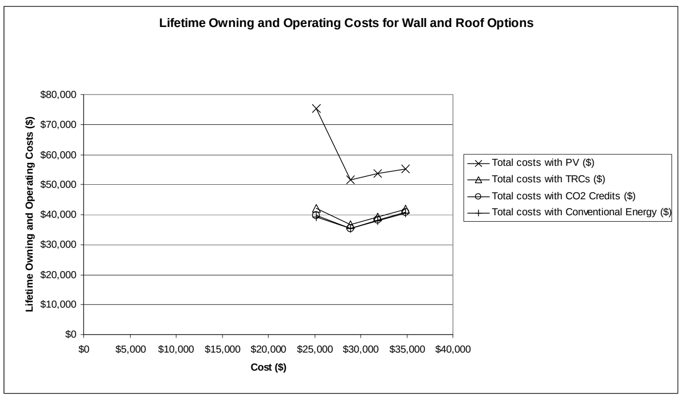

FIGURE 4. LIFETIME OWNING AND OPERATING COSTS FOR WALL OPTIONS

Water Heating Optimization

In Figure 5, which shows lifetime owning and operating costs for water heater options, the lowest lifetime owning and operating cost for the building for PV and TRCs is with Option 3. The lowest lifetime owning and operating cost for the building for carbon neutral and conventional energy is with Option 2.

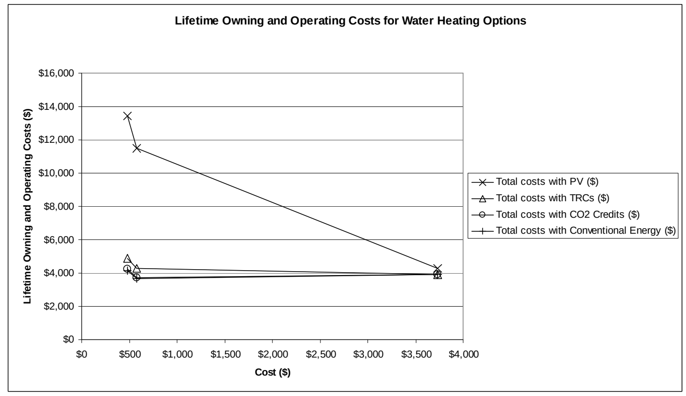

FIGURE 5. LIFETIME OWNING AND OPERATING COSTS FOR WATER HEATING OPTIONS

HVAC Optimization

In Figure 6, which shows lifetime owning and operating costs, the lowest lifetime owning and operating cost for the building for PV energy is with Option 3. The lowest lifetime owning and operating cost for the building for TRCs, carbon neutral and conventional energy is with Option 1.

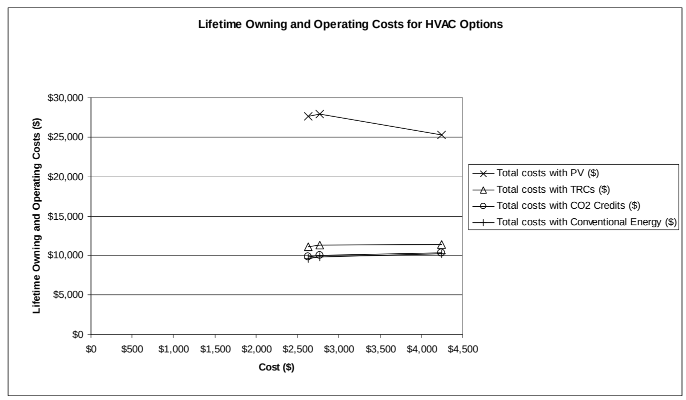

FIGURE 6. LIFETIME OWNING AND OPERATING COSTS FOR HVAC OPTIONS

Refrigerator Optimization

In Figure 7, which shows lifetime owning and operating costs for refrigerator options, the lowest lifetime owning and operating cost for the building for PV energy is with Option 2. The lowest lifetime owning and operating cost for the building for TRCs, carbon neutral and conventional energy is with Option 1.

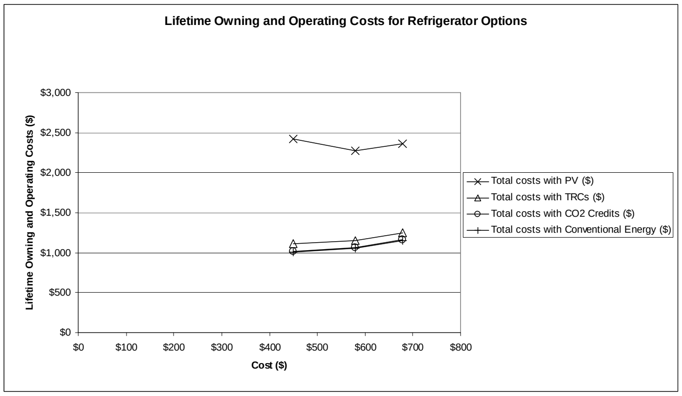

FIGURE 7. LIFETIME OWNING AND OPERATING COSTS FOR REFRIGERATOR OPTIONS

Clothes Washer Optimization

In Figure 8, which shows lifetime owning and operating costs for clothes washer options, the lowest lifetime owning and operating cost for the building for PV energy is with Option 2. The lowest lifetime owning and operating cost for the building for TRCs, carbon neutral and conventional energy is with Option 1.

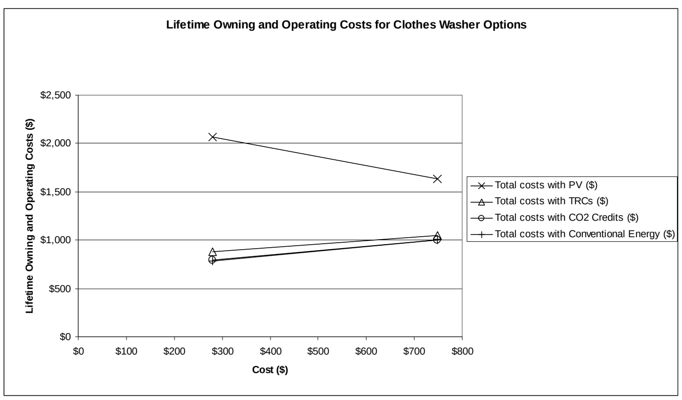

FIGURE 8. LIFETIME OWNING AND OPERATING COSTS FOR CLOTHES WASHER OPTIONS

Dish Washer Optimization

In Figure 9, which shows lifetime owning and operating costs for dish washer options, the lowest lifetime owning and operating cost for the building for PV, TRCs, carbon neutral and conventional energy is with Option 1.

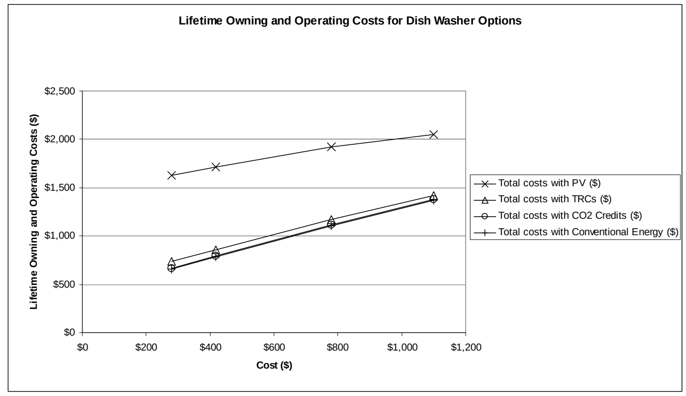

FIGURE 9. LIFETIME OWNING AND OPERATING COSTS FOR DISH WASHER OPTIONS

Windows Optimization

In Figure 10, which shows lifetime owning and operating costs for window options, the lowest lifetime owning and operating cost for the building for PV, TRCs, carbon neutral and conventional energy is with Option 3.

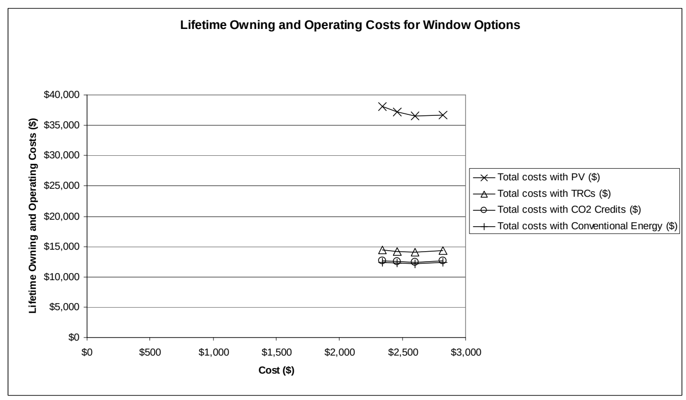

FIGURE 10. LIFETIME OWNING AND OPERATING COSTS FOR WINDOWS OPTIONS

Least Cost Building Design

So far, the least-cost optimization for building components has been presented. The option which minimizes life-cycle costs for each building component can be combined to indicate a whole-house near-optimum design. The optimization yields a near-optimum design rather than a true-optimum design because it fails to consider interactions between components and fails to perform an exhaustive search. The near-optimum designs for a net-zero energy house with PV panels, a net-zero CO_2 house with TRCs, a net-zero CO_2 house with CO_2 credits and a house with no CO_2 or energy constraints are summarized in Table 8.

TABLE 8. NEAR-OPTIMUM BUILDING DESIGNS FOR ENERGY CONSTRAINTS

Building Component	Net-zero Energy with PV Panels	Net-zero CO2: Tradable Renewable Certificates	Net-zero CO2: Conventional Energy with CO2 Credits	No energy or CO2 constraints: Conventional Energy
Water Heating	Solar Water Heating	Solar Water Heating	High Efficiency Water Heating	High Efficiency Water Heating
Walls and Roof	6-inch SIP Construction with HRV	6-inch SIP Construction with HRV	6-inch SIP Construction with HRV	6-inch SIP Construction with HRV
Refrigerator	Energy Efficient Refrigerator	Baseline Refrigerator	Baseline Refrigerator	Baseline Refrigerator
Heating and Air Conditioning	Energy Efficient, AFUE = 0.966, SEER = 16	Energy Efficient, AFUE = 0.966, SEER = 16	Baseline HVAC	Baseline HVAC
Dish Washer	Baseline Dish Washer	Baseline Dish Washer	Baseline Dish Washer	Baseline Dish Washer
Clothes Washer	Energy Efficient Clothes Washer	Baseline Clothes Washer	Baseline Clothes Washer	Baseline Clothes Washer
Windows	Double-pane, low-e, argon filled, R = 4, SHGC = 0.67	Double-pane, low-e, argon filled, R = 4, SHGC = 0.67	Double-pane, low-e, argon filled, R = 4, SHGC = 0.67	Double-pane, low-e, argon filled, R = 4, SHGC = 0.67

SUMMARY AND CONCLUSIONS

This paper presents a method for determining near-optimum building designs with a net-zero energy constraint, a net-zero CO_2 constraint, and with no energy or CO_2 constraints. The method is easily generalized for different buildings and climates.

The method is demonstrated for a proposed net-zero energy house in Dayton, Ohio. The results show that certain energy efficiency options are cost effective even in traditional buildings which purchase conventional energy. For example, the results show that all new houses built by the University of Dayton should include energy efficient water heaters, 6-inch thick SIPs with a Heat Recovery Ventilator, and double-pane, low-e, argon-filled, windows. Solar water heating and efficient HVAC equipment (AFUE = 0.966, SEER = 16) are cost-effective for a net-zero energy house and net-zero CO_2 house with TRCs, but not for a house that is purchasing conventional energy or conventional energy and CO_2 credits. Six-inch thick SIP walls with a Heat Recovery Ventilator and double-pane, low-e, argon-filled windows are cost effective for all energy and CO_2 constraints. Energy efficient refrigerators and clothes washers are cost-effective for a net-zero energy house, but not for a house with TRCs, carbon credits or conventional energy. Standard dish washers are the most cost effective option for each energy or CO_2 constraint.

The method and results may be of interest to builders, architects, developers, city planners, or organizations managing multiple buildings. For example, the method may be especially useful for the AIA initiative to make all new buildings CO_2 neutral by 2030. Also, builders seeking to provide the least-cost net-zero energy or net-zero CO_2 house to their customers may benefit from the method described here. In future work, optimum building designs will be determined for several typical climates across the United States, highlighting differences in optimum component designs across climates. By reducing CO_2 emissions cost-effectively, the results of this work can have a positive effect on both the environment and economy.

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