Building-Scale vs. Community-Scale Net-Zero Energy Performance

Srinivas Katipamula, Nick Fernandez, & Michael R. Brambley,
Pacific Northwest National Laboratory[1]
T. Agami Reddy, Arizona State University

ABSTRACT

Many government and industry organizations are focusing building energy-efficiency goals around producing individual net-zero energy buildings (nZEBs), using photovoltaic (PV) technology to provide on-site renewable energy after substantially improving the energy efficiency of the buildings themselves. Seeking net-zero energy (NZE) at the community scale instead introduces the possibility of economically using a wider range of renewable energy technologies, such as solar-thermal electricity generation, solar-assisted heating/cooling systems, and wind energy.

This paper reports results of a study comparing NZE communities to communities consisting of individual nZEBs. Five scenarios are examined: 1) base case – a community of nZEBs with roof-mounted PV systems; 2) NZE communities served by wind turbines on leased land; 3) NZE communities served by wind turbines on owned land; 4) communities served by solar-thermal electric generation; and 5) communities served by photovoltaic farms. All buildings are assumed to be highly efficient, e.g., 70% more efficient than current practice.

The scenarios are analyzed for two climate locations (Chicago and Phoenix), and the levelized costs of electricity for the scenarios is compared. The results show that even for the climate in the U.S. most favorable to PV (Phoenix), more cost-effective approaches are available to achieving NZE than the conventional building-level approach (rooftop PV with aggressive building efficiency improvements). The paper shows that by expanding the measurement boundary for NZE, a community can take advantage of economies-of-scale, achieving improved economics while reaching the same overall energy-performance objective.

Background

Several prominent organizations, including the U.S. Department of Energy (Crawley et al. 2009; U.S. DOE 2008), the State of California (CPUC 2008), and the European Union (European Parliament 2009), have adopted nZEB as strategic targets in their efforts to improve energy efficiency and sustainability. The vision of nZEBs is also being recognized by building design professional societies such as American Society of Heating Ventilation and Air Conditioning Engineers (ASHRAE) (ASHRAE 2008a, b) and American Institute of Architects (AIA) (AIA 2008). Although definitions of nZEB performance vary (Torcellini et al. 2006), the most widely adopted definition is that an nZEB produces at least as much energy onsite from renewable sources as it consumes from off-site, non-renewable sources over the course of a year. This level of energy performance is achieved by sufficiently reducing the energy needs of the building through efficiency improvements that the balance of energy needed can be supplied with onsite renewable energy technologies.

[1] Operated for the U.S. Department of Energy by Battelle Memorial Institute under contract DE-AC05-76RL01830.

Seeking NZE at the community scale opens up the possibility of using a variety of renewable generation technologies, such as solar-thermal electricity generation, solar-assisted heating/cooling systems, onsite battery storage, and wind energy. Furthermore, community-scale energy storage might be used cost-effectively to reduce costs by decreasing the demand for peak electric power. These technologies cannot be easily deployed in a single home or a commercial building. If the focus is shifted from development of single NZE homes or commercial buildings to a NZE community, these and other alternate renewable power sources are technically feasible and potentially practical.

If the push for NZE homes/community is realized, as many organizations hope, it will have significant repercussions on the stability and reliability of the electric grid. It can be expected that the onsite generation technology will introduce additional volatility to the load profile. It is the expected increase in the volatility of a future net-zero load that challenges the transmission and distribution system planning process. Grid operators already expect difficulty integrating intermittent wind energy into the grid because of the unpredictable nature of the resource and the fact that generation is completely decoupled from load. The introduction of large numbers of NZE homes and buildings is likely to exacerbate the problem of renewable integration if there is not careful planning and recognition of the interactions early on.

The paper examines issues concerning whether achieving NZE performance at the community scale provides economic and potentially overall efficiency advantages over strategies focused on individual buildings using a simplified economic analysis. The increased diversity of load, roof and land area available for renewable energy conversion, economies-of-scale, and the variety of renewable energy technologies possible at the community scale suggest that targeting efficiency improvements at this level of aggregation should have distinct practical advantages over pursuing NZE for individual buildings. This study examines these issues considering two locations, Phoenix and Chicago, which experience quite different weather conditions and solar insolation. NZE communities use the same improvements in the efficiency of individual buildings as strategies focused on individual nZEBs. The choice of technology for onsite renewable generation represents the primary difference between these two basic strategies.

Strategy/Approach for Developing the Community

While the exact size and makeup of a community for consideration as a NZE community is somewhat arbitrary, care was taken for this analysis to develop a community that matched well with most peoples' concept of what constitutes a typical community. Qualitatively speaking, the community is intended to constitute residential neighborhoods of the size necessary to completely support one high school and one supermarket, as well as a supporting light commercial infrastructure, likely including things like office buildings, small retail, health care, gas stations, and restaurants. The theoretical community is modeled from an existing community in terms of the square footage and general building footprint. An additional specification is that each of the buildings is designed to be a high-performance (HP) building, which consumes 70% less than a typical building (compared to typical U.S. buildings in the Residential Buildings Energy Consumption Survey [RECS Public Use Microdata Files , 2005] and the Commercial Buildings Energy Consumption Survey [CBECS Public Use Microdata Files, 2003]). The existing community in Columbia, MD (Figure 1) is used for the analysis for the following reasons:

- Columbia is a master-planned city, and the community selected is one of the planned communities within the scope of that development. Thus, the boundaries of the community are well-defined, as opposed to more organic community development, which can be characterized by continuously growing communities with unclear or arbitrary boundaries.
- The website for Howard County, MD (Maps: My Neighborhood, 2009), in which this community is located, contains an interactive Geographic Information Systems (GIS) service that allows a web user to query the owner and obtain top-level construction details of all buildings within each community. This tool was used to estimate the commercial and residential square footage of the community.

Figure 1. Google Maps Satellite Image of the Wilde Late Community

Residential Building Characteristics and Energy Use

To determine the average square footage for each building type within the residential sector, 20 different buildings from each building type (single-family detached homes, townhouses, and apartment units) were queried at random using the GIS tool on the Howard County, MD website (Maps: My Neighborhood, 2009). The average square footage from those samples is assumed to be the typical square footage for each household of that type in this community (Table 1).

Table 1: Makeup of the Residential Sector of Wilde Lake

Home Type	Floor Area (square feet)	# in Community	Total Square Footage
Single-Family Detached	2030	684	1,388,520
Townhouse	1535	440	675,400
Apartment	1223	1494	1,827,162
Total		2618	3,891,082

To estimate the residential building sector's energy consumption, the RECS database (RECS Public Use Microdata Files, 2005) was queried for 'all-electric' buildings matching a certain building type and climate zone. For Phoenix, the 'Southwest' climate zone is used, and for Chicago, the North-Central climate zone is used. Table 2 shows the energy use intensities (EUIs) for buildings of each residential building type in the climate zone containing each city. The number of building samples available in the RECS database is shown in parentheses next to each figure. In the column to the right of the RECS data is the EUI for a corresponding HP building. The HP building is arbitrarily assumed to consume 70% less than a typical building.

Table 2: Residential Building Energy Use Intensities (EUIs, kWh/sf/year)

	Chicago		Phoenix	
Building Type	**RECS**	**HP building**	**RECS**	**HP building**
Detached Home	5.72(95)	1.72	6.78(83)	2.03
Townhouse	7.60(5)	2.28	9.67(3)	2.90
Apartment	11.01(32)	3.30	13.15(49)	3.95

A limitation of this approach is that for some building types in some climate locations, the sample size can be very small for the purpose of determining an accurate value for building energy consumption. In the analysis performed in this study, however, the economics of the NZE community plans are relatively insensitive to individual building energy consumption. The EUIs for the HP buildings in Table 2 are multiplied by the community total building square footages from Table 1 to calculate the total electricity consumption of the residential sector in Table 3.

Table 3: Residential Sector Energy Demands (kWh electricity/year)

	Chicago	**Phoenix**
Detached homes	2,383,284	2,823,819
Townhouses	1,539,327	1,960,017
Apartments	6,034,035	7,210,166
Total	9,956,647	11,994,002

Commercial Building Characteristics and Energy Use

The community is assumed to have the following commercial buildings:

- 4 medium office buildings (30,000-90,000 square feet)
- 7 small office buildings (< 30,000 square feet)
- 1 shopping center containing 14 strip-mall-sized stores and restaurants, a bank, a gas station, and a community center
- 1 convenience store
- 1 high school, 1 middle school, and 2 elementary schools
- 1 interfaith worship center
- 3 neighborhood centers, with day-care nursing facilities for young children.

Each building listed above was assigned a building type, according to the building types categorized in CBECS. EUIs for each building type in each climate for all-electric buildings were obtained in the same way as for the residential sector. They are presented in Table 4 along with the corresponding EUIs for HP buildings. The sample size for each building type in each climate zone is provided in parentheses next to each EUI figure from CBECS.

The HP building EUIs from Table 4 are multiplied by the building square footages, queried from the Howard County GIS tool to calculate the annual energy consumption of the commercial sector (details of square footage and other classification please refer to Fernandez et al. 2010), for Phoenix and Chicago, in Table 5.

Table 4: Commercial Building EUIs (kWh/sf/year)

	Chicago		Phoenix	
Building Type	**CBECS**	**HP building**	**CBECS**	**HP building**
Food Sales	37.99(6)	11.40	61.30(10)	18.39
Food Service	47.33(4)	14.20	27.59(4)	8.28
Public Assembly	14.19(6)	4.26	21.73(10)	6.52
Education	12.36(11)	3.71	13.95(34)	4.18
Retail	20.98(9)	6.29	20.78(42)	6.23
Office	26.55(22)	7.97	20.75(58)	6.23
Religious Worship	6.48(7)	1.94	15.26(10)	4.58

Table 5: Commercial Sector Energy Demands (kWh electricity/year)

	Chicago	**Phoenix**
Food Sales	148,145	239,087
Food Service	251,331	146,521
Office	2,641,513	2,064,368
School	1,742,934	1,966,775
Retail	293,491	312,933
Religious Worship	58,344	137,362
Public Assembly	221,344	339,036
Total	5,357,102	5,206,083

Renewable Technology Scenarios Considered

Five different renewable technology scenarios were considered for the analysis.

Base Scenario – A Community of NZEBs

The base scenario is meant to embody what a whole community of nZEBs would look like. The buildings themselves are HP buildings that achieve 70% reduction in energy consumption over the current national average for that building type, and use electricity for all building energy consumption. The only generation technology available onsite to each building in the community is roof-mounted PV. For some building types, rooftop PV will not satisfy all of the building electricity requirements, even for these HP buildings. In this analysis, these buildings simply fail to meet NZE status. This does not have any effect on the economic analysis, however, because it is done on a $/kWh (generated) basis. Community costs unique to this scenario include the full installation cost of the PV panels and inverters, plus maintenance/cleaning costs required to keep electricity production at expected levels.

Community-Scale NZE using Wind Turbines (Scenario A)

In this scenario, the buildings are the same as in the base scenario, except without rooftop PV. Wind turbines are used to achieve NZE status for the community as a whole. Land for the entire wind farm is purchased at rates typical of the median rate for the outer suburbs of the city being analyzed (because this is where development is likely). Community costs unique to this scenario include the full installed cost of the wind turbines, operations and maintenance (O&M) costs for the wind farm, land purchase costs, and net metering credits (because a discrete number of wind turbines must be purchased, the community ends up producing slightly more than it consumes, so the difference is sold back to the grid at the mean 2008 wholesale electricity price for its region).

Community-Scale NZE using Wind Turbines (Scenario B)

In this scenario, land required for the site of each turbine base is leased from local farms or private landowners, as is typical in situations where all land in the vicinity of a proposed wind site is pre-owned or prices for land ownership are prohibitively expensive. The details of the leasing arrangement are set according to the arrangement described in Area Farmer Doesn't Mind Wind Turbines on His Land (2009), and the rental costs set according to the relative land value between the site described in the article and the proposed sites in Phoenix and Chicago. Community costs unique to this scenario include the full installed cost of the wind turbines, O&M costs for the wind farm, land rental costs, and net metering credits. Costs associated with the dismantling of the wind farm at the termination of the lease and credits associated with its recycling thereafter are ignored. The wind farm is assumed to be within the boundaries of the community, thus the grid connection costs are assumed to be negligible.

Community-Scale NZE using a Solar-Thermal Electric Plant

In this scenario, a parabolic trough, concentrating solar-thermal plant is designed and scaled to achieve NZE status for the community. The troughs are on a single-axis tracking system, aligned N-S. The plant is built on additional land purchased and used solely by the plant. Community costs unique to this scenario include the full installed cost of the solar-thermal plant, O&M costs for the plant, and land purchase costs. A parabolic trough plant was selected for this analysis because it is the most mature utility-scale solar-thermal technology, with the most available cost data.

Community-Scale NZE using a Solar PV Farm

In this scenario, a solar farm is designed and scaled to achieve NZE status for the community. The panels are designed as fixed structures, set at a 35° angle with respect to the ground[2]. The plant is built on additional land purchased and used solely by the farm. Community costs unique to this scenario include the full installed cost of the PV farm, O&M costs for the farm, and land purchase costs.

Analysis Methodology

The goal in this study is to compare the relative costs of the NZE building concept to the NZE community concept. The analytical methodology used to compare various NZE community and NZE building scenarios started with the specification of a community of high-performance residential and commercial buildings (see pervious section). It is also assumed that the baseline community specification also includes standard electricity distribution infrastructure. Thus, in the cost analysis, it is not necessary to analyze all of the costs that are borne during the construction and operation of the community, only the cost components that are not shared by each scenario. Thus, components such as the construction of the buildings themselves, and the electricity distribution network are left out because these costs are identical from one scenario to the next. It is assumed that in either the NZE community or the NZE building case, the generation will be located within the community, such that there is no need for extra transmission infrastructure. By comparing generating costs between the two options, the net cost to the community at large of choosing one NZE approach over another can be analyzed.

Generating costs are presented in this paper in terms of $/kWh, combining annualized capital costs and recurring O&M costs into a single levelized cost of electricity generation (LCOE). Capital and O&M costs for electrical generating infrastructure, including renewable energy, are functions of the installed capacity of the generator, and in some cases, the total electric energy produced. The methodology to size the installed capacity of generation involves creating an hourly model of each type of renewable energy generation (each functions of the wind and solar resource as well as other factors like temperature), and solving for the installed capacity size (in kW or MW), for which the annual electric energy generation (the sum of kWh generation from each hour of the year) from all of the renewable energy generators is equal to the annual sum of the electric loads from each of the community's buildings. Because the community is only required to be net-zero energy on an annual basis, and because it is assumed the grid costs are the same for buying as well as selling, an hourly model for community loads is not necessary in this analysis framework. Annual electric energy consumption is estimated from the RECS and CBECS databases of existing buildings, with each building in the envisioned high-performance building community being 70% more energy efficient (by floor area) than buildings of corresponding type within the two databases. The methods for analyzing each of these factors are described in detail in Fernandez et al. (2009) and are summarized here.

Models of Renewable Energy Generation

For each of the renewable energy technologies analyzed, a simple hourly model was created to estimate hourly electricity production, which was then summed over the course of a year, and matched with the annual community electricity load to size the system to net-zero energy.

[2] Typically, the rule-of-thumb is to use the latitude angle for the optimum angle of elevation for fixed PV. However, in the case of Chicago and Phoenix, our modeling using TMY data showed optimum angles for both cities close to 35°. This angle was used for both cities for simplicity.

Solar Photovoltaics (PV)

To model solar PV electricity production, a two-step approach was used. First, EnergyPlus was used to model solar insolation on two types of surfaces: a flat surface characteristic of commercial building roofs, and a 35° inclined surface, assumed to be characteristic of residential buildings, aligned facing due south (which may be possible for an intentionally designed community of net-zero energy buildings). This 35°, south facing surface was also assumed to be characteristic of a solar PV farm, used in one of the net-zero community scenarios. The next step was to take these hourly solar insolation values from EnergyPlus and estimate actual net electricity production. This, in turn was a two-step process that involved 1) the calculation of an hourly direct current (DC) conversion efficiency, and 2) the application of various derate factors that affect the actual net alternating current (AC) electric output from the panel. Thus, hourly net electric production is given by Equation 1:

$$P_{AC,net} = P_{insolation} \cdot \eta \cdot DerateFactor \qquad (1)$$

The hourly DC conversion efficiency, η, is assumed to be a function of the nominal efficiency, η_0, of the panel at a specific rated test condition, and the actual surface temperature of the panel, T_s. This relationship is based on an established linear relationship of the effect of panel temperature on efficiency, as shown in Equation 2.

$$\eta = \eta_o \cdot [1 - 0.005(T_s - 25)] \qquad (2)$$

The specific panel used in this modeling was a BP Solar SX3190B panel, selling in 2009 for $3.10/watt (Beyond Oil Solar 2009), with a nominal efficiency of 15.0%, and a temperature coefficient of power of -0.5%/°C. Panel surface temperature was modeled by applying an energy balance between the incoming solar radiation and the outgoing convective and radiative transfer from the top surface of the panel. Derate factors include losses in the conversion process from DC to AC, losses in the wiring and diodes/connections, as well as factors to account for degradation of production with panel age and degradation of production caused by normal soiling of the panel surface. The overall derate factor used is 0.729.

Wind Power

Wind power generation is modeled in a two-step process that first involves the conversion of wind speeds from the height of the recording station (typically at a height of 10 meters) to the hub height of the turbine, using the seventh root relationship in Equation 3:

$$\left(\frac{v_2}{v_1}\right) = \left(\frac{h_2}{h_1}\right)^{1/7} \qquad (3)$$

Second, hourly average velocity measurements at the hub height are used to estimate the power production from the wind turbine, using power curves developed by wind turbine manufacturers. A parameterized curve was developed for several wind turbines, whose power curves were available from manufacturers' websites. These curves allowed estimation of hourly wind power production as a function of the wind speed at the hub height. GE's 1.5 MW '1.5XLE' wind turbine model was selected as the model of choice for estimating generation from the community wind farm.

Solar Thermal Electric Power

A simple model for hourly production of solar-thermal electric power from a parabolic trough plant was made by combining some basic assumptions about a Rankine-cycle power plant. The first assumption is that the solar array outlet's steam temperature is directly proportional to the direct component of the solar insolation collected at the array, with the ambient temperature as a moving baseline (i.e., if there is no solar insolation, the outlet temperature from the solar array is the ambient temperature). The second assumption is that the plant's solar conversion efficiency is a constant fraction of the Carnot efficiency (Equation 4). Third, the maximum steam temperature at 25°C ambient temperature is 400°C, occurring at a direct solar insolation level of 950 W/m^2. Finally, the annual weighted average solar conversion efficiency is 12%, for a plant located in the Nevada desert. The latter two assumptions are based on typical values reported in Tester, et al. The 12% conversion efficiency constraint effectively defines what constant fraction of Carnot efficiency such a plant achieves (calculated as 26%).

$$\eta_{carnot} = 1 - \frac{T_{ambient}}{T_{steam}} \tag{4}$$

For the collectors themselves, a N-S axis of orientation was selected for a 1-axis tracking system, for which Equation 5 was adopted from Duffie and Beckman (1980) to calculate the angle of incidence of the sunlight, θ with respect to the collectors at each hour of the day.

$$\cos(\theta) = [(\sin\phi \cdot \sin\delta + \cos\phi \cdot \cos\omega \cdot \cos\delta)^2 + \cos^2\delta \sin^2\omega]^{1/2} \tag{5}$$

In this equation, ω is the solar azimuth angle, ϕ is the latitude, and δ is the solar declination.

Land Requirements

Each of the three net-zero energy community scenarios requires additional land for the generating stations. In the case of a wind farm, two sub-scenarios were analyzed. In Scenario B, the wind farm leases ½ acre of land per turbine. In Scenario A, the community is required to purchase the land from the farm on suburban land with 3 rotor-diameter spacing between turbines within a row, and 10 rotor-diameter spacing between rows, as specified by the New York State Energy Research and Development Authority. No credit is taken for other land use that might occur on the purchased land. This would likely be an unnecessarily expensive scenario for the NZE community, but is included nevertheless as an upper-bound scenario, to illustrate the idea that to be economic, community wind farms, especially in suburban areas need to work out leasing or other land use deals in order to mitigate excessive land costs. For the solar thermal plant, it is assumed that rows between the collectors are equal to 3/2 the width of the collectors themselves (increasing the required land by a factor of 5/2 over what is taken up by the collectors alone). This was estimated based on a satellite image of the Nevada One parabolic trough solar-thermal electric plant. Solar PV farms are likewise assumed to have the same spacing between rows.

Costs

Based on curve fitting from a database of almost 25,000 PV installations in California from the California Electricity Commission, Equation 6 was developed to estimate PV costs as a function of installed capacity size for each installation. Based on limited PV farm project installation cost data, this equation appears to be very accurate at predicting installation costs at the utility scale as well. For wind power installed costs, based on data from Wiser and Bolinger (2009), while economies of scale do exist between different turbine sizes, no economies of scale appear to exist in the U.S. market for wind farms having more or less turbines. Thus, a constant $1900/kW installed wind capacity was assumed to be valid for farms using 1.5-kW turbines (Wiser reports $1900/kW as the mean price in 2008, and 1.5 kW is very close to the average size of U.S. installed turbines). Equation 7 shows the equation for installed cost of a solar-thermal electric power plant without storage, derived from available cost data from existing plants, and a report from Price (2002) describing the economies of scale for parabolic trough plants.

$$Installed\ Cost_{PV\ (\$US,2009/W)} = \$8.65 \cdot \left(\frac{Capacity_{PV}}{1.5kW} \right)^{-0.049} \quad (6)$$

$$Installed\ Cost_{STE\ (\$2009/kW)} = \$5015 \cdot 4.255 \cdot \ln(Capacity_{STE,MW})^{-1.035} \quad (7)$$

O&M costs for PV systems were taken as the default values from National Renewable Energy Laboratory’s (NREL’s) Solar Advisor Model (SAM) and are $74/kW/year for residential, $17.69/kW/year for commercial, and $6/kW/year for utility-scale systems. O&M costs for wind turbines were derived from Wiser and Bolinger (2009) and represented as a function of wind farm installed capacity, and annual kWh output, as shown in Equation 8. O&M costs for parabolic trough plants were estimated from Stoddard et al. (2006) and adjusted to scale with installed capacity in the same way as installed costs for parabolic trough plants. The result is shown in Equation 9

$$O\&M\ \ wind(\$/kWh) = \$0.0207 \cdot Farm\ Size_{(MW)}^{-0.167} \quad (8)$$

$$Annual\ O\&M\ Costs_{STE\ (\$2009/kW/year)} = \$85.86 \cdot 4.255 \cdot \ln(Capacity_{STE})^{-1.035} \quad (9)$$

Land costs were taken as median suburban land costs in the Phoenix and Chicago areas for parcels of land larger than 10 acres available in late 2009 at www.landwatch.com.

Financial Assumptions

The financial analysis combines all costs into a $/kWh (generated) levelized cost of electricity (LCOE). The analysis is performed in constant 2009 dollars, with a real discount rate of 3.0%/year. This is roughly the historic average of real interest rates from 1870-2000 documented by Girola (2005). Costs for each technology are annualized over the number of years representing the expected lifetime (20 years for wind turbines, 28 years for PV, 30 years for parabolic trough plants). The lifetimes used for each technology are the median values found from researchers performing life-cycle assessments and technology reviews.

Results

The results of analyzing the two NZE community options with various renewable energy scenarios are described below.

Baseline Scenario - a Community of NZE Buildings

The two unique cost components of the baseline community are the capital cost of the PV panels to be installed on the individual building roofs and the maintenance costs required to keep the panels clean and in working order. Capital costs are borne by each building owner and O&M costs are a function of the system size and the type of installation. Aggregated total community costs for capital and O&M, and the corresponding levelized cost of electricity generation (LCOE) are presented in Table 6.

The combined levelized cost of electricity generation from the PV systems of $0.431/kWh for Chicago and $0.331/kWh for Phoenix provide the baseline to which each of the alternative NZE community LCOEs are compared. Phoenix receives 56% more sunlight over the course of the year than Chicago. The net electric generation from the PV panels in Phoenix, however, is only 32% higher than in Chicago, because of the higher temperatures in Phoenix, which reduce the PV cell efficiency. Thus, the cost of rooftop PV electricity generation in Phoenix is about 75% of Chicago's.

Community-Scale NZE using Wind Turbines

A summary of the details of electricity generation and costs is presented in Community-Scale NZE using a PV Farm

A summary of the details of electricity generation and costs is presented in Table 9 for the NZE community scenarios, using a PV farm.

Capital costs for the PV farm are almost 30% lower than the capital costs in the NZE building PV scenario. O&M costs are dramatically lower for the PV farm. This scenario provides a very concrete example of how cost savings can be achieved through economies of scale. Instead of planning, installing, and grid-wiring thousands of individual PV systems, the same energy can be generated through one large installation. Instead of maintenance taking place at thousands of different facilities, each requiring roof access for maintenance personnel and their cleaning equipment, cleaning can be handled en masse, and possibly even automated. The only tradeoff is that new land is required for the PV farm, as opposed to the already-developed roof area in the NZE building scenario.

Table 7 for both NZE community scenarios involving wind turbines. In Scenario A, the land required for the wind farm is bought outright and devoted entirely to the wind farm. In Scenario B, land for the wind turbines is leased from nearby farmers or other large private land owners.

To generate the community's 14 million kWh in Chicago using wind power at the calculated capacity factor of 0.360 requires 4.44 MW of installed capacity. Because this capacity comes in discrete, 1.5-MW increments, the community must purchase three 1.5-MW turbines at a levelized capital cost of 4.09 cents/kWh. The sale of the electricity from the extra 60 kW of rated capacity represents a negligible contribution to the LCOE. In Chicago, the levelized O&M costs of the wind farm are about 40% of the magnitude of the capital costs. Using leased land for the turbines, the total cost of generated electricity comes out to only about 7 cents/kWh. If instead, all the land is bought outright (in the relatively expensive suburbs of Chicago), the levelized cost of electricity generation would be 5.4 cents/kWh higher (12.4 cents/kWh compared to 7 cents/kWh).

Table 6: Comparison of LCOE for Chicago and Phoenix

	Chicago	Phoenix
Energy Demand (kWh/year)	13,996,908	17,674,273
Roof Area Available (sf)	2,207,405	2,207,405
Aggregate Roof Area Required to meet NZE (sf)[3]	841,953	780,528
Fraction of Demand Met (%)	92.10	97.40
Net-Zero PV Capacity (kW)	12044	12075
Installed Cost ($/Watt)	7.81	7.89
Installed Cost ($2009)	94,025,758	95,211,159
O&M Cost ($2009)	649,367	690,852
LCOE Capital ($/kWh)	0.3847	0.2920
LCOE O&M ($/kWh)	0.0464	0.0391
LCOE total ($/kWh)	0.4311	0.3310

For Phoenix, the wind turbine scenarios suffer from a very low capacity factor, brought about simply by a lack of consistent wind. Thus, for Phoenix, the capacity factor is three times lower than Chicago's (0.120), and the levelized capital cost is three times higher because there is no economy of scale cost benefit for building the larger number of turbines required. Despite having four times as many turbines, the levelized O&M cost in Phoenix is calculated as being lower than in Chicago. This is mainly for one reason: wind turbine O&M costs are typically reported per MWh of generation, as in Wiser and Bolinger (2009), rather than per MW of installed capacity; yet the economy of scale curve for O&M is based on MW of installed capacity. Thus, Phoenix benefits (from an O&M standpoint, relative to Chicago), from having a large field of less productive turbines. There is a good argument for why O&M costs should be a function of generated energy rather than being a per-turbine rate (which would be the case if they were reported as per MW of installed capacity). Turbines subject to lower wind speeds would be expected to have lower component failure rates because of lower mechanical stresses and lower electric loads on the power equipment. With four times the land area required for both land acquisition scenarios and comparable land prices for Phoenix and Chicago, the cost of the total required land ends up being about four times higher for the community in Phoenix. Using leased land, the LCOE of electric generation for Phoenix is 18.3 cents/kWh, but using purchased land, the cost doubles to 36.6 cents/kWh.

Community-Scale NZE using a Solar-Thermal Electric Parabolic Trough Plant

A summary of the details of electricity generation and costs is presented in Table 8 for the NZE community scenarios, using a solar-thermal parabolic trough plant.

The solar-thermal electric parabolic trough plant is most economical in Phoenix, which receives ample direct sunlight. There, the plant operates at a capacity factor of around 25%. Chicago, on the other hand, receives less than half of the direct sunlight that Phoenix does, and its capacity factor is just over 10%. The plant in Chicago is further hindered by frequent part-

[3] There is enough roof area on an aggregate basis for the community as a whole to meet NZE status, but because each building is designed to meet NZE using only its own roof area, the community of NZE buildings in effect comes up short, due to the presence of energy intensive buildings with relatively small roofs.

load operation at lower turbine inlet steam temperatures, which reduces the plant's efficiency. The Schott Company recommends a plant size of 150 to 200 MW to fully take advantage of the economy of scale for solar-thermal power plants (Schott 2004). The required plant size for the community studied here is over an order of magnitude smaller, and for both locations, solar-thermal suffers from a high capital cost. For the case of Phoenix, with a very small 8.1-MW plant, the estimated capital cost is $7750/kW installed. For Phoenix, the capital cost represents just over 75% of the levelized cost of electricity generated, with O&M representing about 20%, and land representing the remaining 5%. To make solar-thermal electricity the most economic solution, however, the size of the community must be scaled up. If the size of community were scaled 5 times the size of the community used for this analysis, it would be the least cost option in Phoenix. In Chicago, even if the size of the community were increased, it is never more cost effective compared to the other generation options considered with exception to building PV.

Community-Scale NZE using a PV Farm

A summary of the details of electricity generation and costs is presented in Table 9 for the NZE community scenarios, using a PV farm.

Capital costs for the PV farm are almost 30% lower than the capital costs in the NZE building PV scenario. O&M costs are dramatically lower for the PV farm. This scenario provides a very concrete example of how cost savings can be achieved through economies of scale. Instead of planning, installing, and grid-wiring thousands of individual PV systems, the same energy can be generated through one large installation. Instead of maintenance taking place at thousands of different facilities, each requiring roof access for maintenance personnel and their cleaning equipment, cleaning can be handled en masse, and possibly even automated. The only tradeoff is that new land is required for the PV farm, as opposed to the already-developed roof area in the NZE building scenario.

Table 7: Generation and Cost Details for a NZE Community using Wind Power

	Chicago	Phoenix
Community Electric Demand (kWh/yr)	13,996,908	17,674,273
Capacity Factor	0.3600	0.1195
Required Capacity (MW)	4.44	16.88
1.5 MW Turbines Required	3	12
Capital Cost - Turbines	$8,617,500	$34,470,000
O&M Cost Turbines ($/yr)	$229,191	$241,458
Acres Required (Scenario A)	141.2	564.7
Land Cost (Scenario A)	$14,117,647	$60,345,398
Acres Required (Scenario B)	1.5	6
Land Rental Cost (Scenario B), $/yr	$120,000	$769,404
Extra Generation (kWh/yr)	195,534	1,172,854
Sale of Extra Electricity ($/yr)	$11,537	$76,236
LCOE (Capital)	$0.0409	$0.1297
LCOE (O&M)	$0.0164	$0.0137
LCOE (Land, Scenario A)	$0.0671	$0.2270
LCOE (Land, Scenario B)	$0.0129	$0.0435
LCOE (Sale of Extra Electricity)	-$0.0008	-$0.0043
LCOE Total, Scenario A	$0.1236	$0.3661
LCOE Total, Scenario B	$0.0694	$0.1826

Cost Comparison

The LCOE for each NZE approach for both cities is summarized in Figure 2. The relative costs from the base case of the community of NZE buildings to each of the NZE communities are labeled above the bars for each NZE community scenario. In Chicago, the community-scale NZE scenario using wind turbines is the least expensive, with a levelized cost of electricity generation that is between 71% and 84% less than the nZEB scenario, the precise difference depending on how the land is acquired. For Phoenix, despite its poor capacity factor, wind power is still the least expensive option at this scale, when the required land is leased, rather than purchased. Otherwise, building a solar-photovoltaic farm is the most economical choice for the community.

Discussion and Conclusions

In Phoenix, achieving NZE on the building scale using rooftop PV would most likely be the most expensive way to achieve NZE status. In Chicago, the costs of the NZE community with rooftop PV are exceeded only by the NZE community using solar thermal electric power on the scale of community studied. However, the LCOE for rooftop PV is about equal to the LCOE for solar-thermal electricity for a community of 16,000 people in Chicago. This is an interesting result, because according to conventional thinking, while not optimally suited for Chicago, rooftop PV would still be a viable technology for those building owners looking to 'go green'. That same conventional thinking, however, would dictate that a solar-thermal plant is a ridiculous idea in a place like Chicago. In reality, however, the costs can be nearly equivalent for powering a NZE community in Chicago for these two technologies. Similarly for Phoenix, in the Arizona desert, it would seem almost criminal to suggest wind power over solar power. Yet, at the default community size, the case of the wind farm on leased land, as inefficient as the wind generation may be, is still more cost-effective than either solar-thermal electric generation or a PV farm at the default community size (let alone rooftop PV, which is more expensive still).

Thus, one could argue that conventional thinking may have a bias towards the idea of a nZEB and/or a lack of appreciation for economies-of-scale. Furthermore, there may be an automatic assumption that having one more favorable renewable resource endowment means that the most cost-effective solution must utilize that resource. The bias towards nZEBs may have something to do with the idea of liberating the building from external sources of generation, but in a technical sense, this is not true, because NZE buildings are still very much dependent on the grid.

Phoenix was chosen for this study because it has such abundant solar resources, and poor wind resources, making it one of the most attractive places for NZE buildings using PV. Thus, what has been shown in this study is that even for the best case in the U.S. for NZE buildings, there are more cost-effective approaches to achieving NZE than the conventional suite of technologies (rooftop PV, with aggressive energy-efficiency measures) used at the building level. By expanding the conceptual boundary for net-zero, a community can take better advantage of economies-of-scale, as well as having other generation options at its disposal.

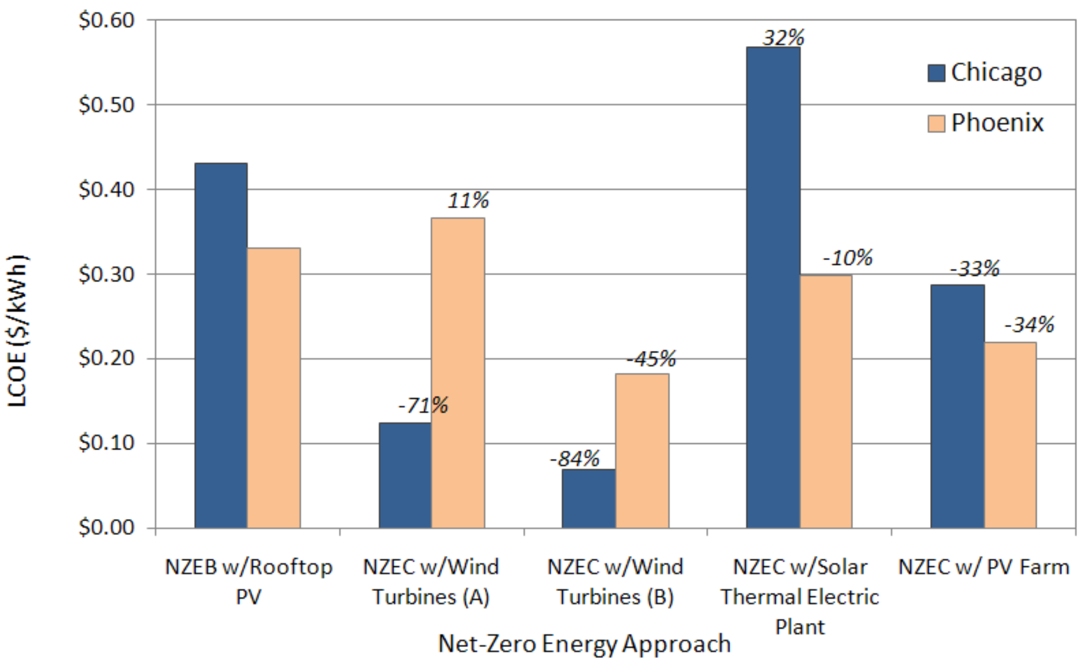
Table 8: Generation and Cost details for a NZE Community using a Solar Thermal Electric Plant

	Chicago	Phoenix
Community Electric Demand (kWh/yr)	13,996,908	17,674,273
Capacity Factor	0.106	0.248
Overall Plant Efficiency	0.0989	0.1164
Required Capacity (MW)	15.04	8.12
Capital Cost - Solar Thermal Plant	$102,826,484	$63,734,729
O&M Costs ($/year)	$1,494,547	$806,896
Acres Required	78.6	42.5
Land Cost	7,859,746	4,537,592
LCOE (capital)	$0.4183	$0.2336
LCOE (O&M)	$0.1203	$0.0514
LCOE (land)	$0.0284	$0.0130
LCOE(total)	$0.5670	$0.2980

Table 9: Generation and Cost Details for a NZE Community using a PV Farm

	Chicago	Phoenix
Community Electric Demand (kWh/yr)	13,996,908	17,674,273
Capacity Factor	0.1273	0.1679
Overall AC Efficiency	0.104	0.093
Required Capacity (MW)	12.55	12.01
Capital Costs - Solar PV farm	$69,757,146	$66,909,100
O&M Costs ($/year)	$78,956	$75,569
Acres Required	50.8	48.6
LCOE (capital)	$0.2631	$0.1998
LCOE (O&M)	$0.0056	$0.0043
LCOE (land)	$0.0191	$0.0155
LCOE(total)	$0.2879	$0.2196

Figure 2: LCOE for Each NZE Approach



References

AIA. 2008. "AIA 2030 Challenge." www.aia.org/about/initiatives/AIAB079458.

Area Farmer Doesn't Mind Wind Turbines on His Land. (2009, February 20). *Globe Gazette* . Mason City, IA.

ASHRAE. 2008a. *ASHRAE Strategic Plan*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, Georgia.

ASHRAE. 2008b. *ASHRAE Vision 2020: Producing Net Zero Energy Buildings*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, Georgia.

Beyond Oil Solar. (2009). Retrieved July 10, 2009, from http://www.beyondoilsolar.com/solarpanels.htm

CBECS Public Use Microdata Files. 2003. Retrieved September 2, 2009, from Commercial Buidling Energy Consumption Survey: http://www.eia.doe.gov/emeu/cbecs/cbecs2003/public_use_2003/cbecs_pudata2003.html

CPUC (California Public Utilities Commission). 2008. California Long Term Energy Efficiency Strategic Plan. CPUC, San Francisco, California.

Crawley, D., S. Pless, and P. Torecellini. 2009. "Getting to Net Zero." ASHRAE Journal, Vol. 51, No. 9, pg. 18-25.

Duffie, J., and Beckman, W. 1980. Direction of Beam Radiation. In *Solar Engineering of Thermal Processees* (p. 15). New York, NY: John Wiley and Sons.

European Parliament. 2009. "All buildings to be zero energy by 2019." Press release by the European Parliament, Committee on Industry, Research and Energy. Accessed on the web at http://www.europarl.europa.eu/sides/getDoc.do?type=IM-PRESS&reference=20090330IPR52892 &language =EN on December 2, 2009.

Fernandez, N., S. Katipamula, M.R. Brambley and T.A. Reddy. 2010. Economic Investigation of Community Scale Versus Building Scale Net-Zero Energy. Pacific Northwest National Laboratory Report # PNNL-19095, Richland, Washington.

Girola, J. 2005. *The Long Term Real Interest Rate for Social Security*. U.S. Department of Treasury. Research Paper No. 2005-02.

Maps: My Neighborhood. 2009. Retrieved September 2, 2009, from Howard County, Maryland: http://gis.howardcountymd.gov/PublicGISOnline/MyNeighbor.aspx

RECS Public Use Microdata Files . 2005. Retrieved September 2, 2009, from Residential Buiding Energy Consumption Survey: http://www.eia.doe.gov/emeu/recs/recspubuse05/pubuse05.html

Price, H. 2002. Concentrating Solar Power Systems Analysis and Implications. *Systems-Driven Approach to Solar Workshop*. Linthicum, Maryland: U.S. Department of Energy - Energy Efficiency and Renewable Energy, Solar Energy Technologies Program, Washington D.C.

Stoddard, L., J. Abiecunas, and R. O'Connell. 2006. *Economic, Energy, and Environmental BEnefits of Concentrating Solar Power in California*. NREL/SR-550-39291, prepared for NREL by Black and Veatch, Golden, Colarado.

Torcellini, P., S. Pless, M. Deru, and D. Crawley. 2006. "Zero Energy Buildings: A Critical Look at the Definition." *Proceedings, 2006 ACEEE Summer Study on Energy Efficiency in Buildings*, American Council for an Energy Efficient Economy, Washington, DC.

Wiser, R., and M. Bolinger. 2009. *2008 Wind Technologies Market Report*. United States Department of Energy, Report # DOE/GO-102009-2868.