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SIMULATION OF OFF-GRID, OFF-PIPE, SINGLE-FAMILY DETACHED RESIDENCES IN U.S. CLIMATES

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ABSTRACT

This paper discusses current efforts to simulate off-grid, off-pipe houses in five U.S. locations in different climate zones, using an integrated analysis that evaluates the performance of energy and water efficiency and renewable energy measures in each location[1]. The study aims to eliminate the need for non-renewable sources of energy and municipal water in residences by using off-grid, off-pipe design approach. To accomplish this, a simulation model of a 2001 International Energy Conservation Code compliant house in each location was analyzed to determine the base-case energy and water use; then, by simulating energy and water efficiency measures, building energy and water needs were reduced. Finally, the sizing of renewable energy and water collection systems was performed to meet or exceed the reduced needs and achieve complete self-sufficiency in terms of energy and water use.

INTRODUCTION

Energy-efficiency, water-efficiency and renewable energy measures are recognized as potential solutions towards a sustainable future. Currently, there are several approaches to minimize the use of fossil-fuels in buildings, such as net-zero energy (in terms of supply energy, source energy or energy cost), carbon-neutral and net-plus designations. Unfortunately, these approaches utilize grid-connected buildings for the supply and storage of energy. It should be noted that any single approach may not achieve the goals of the other approach (Torcellini et al. 2006). Also, municipal energy used for water supply, sewage treatment and water use for cooling of thermal power plants (i.e., commercial buildings) is usually not considered in the energy balance. On the other hand, an off-grid, off-pipe design approach is aimed at achieving a completely self-sufficient, stand alone, zero energy building. One that is not connected to the grid for energy, water and sewage disposal, and one that uses only on-site renewable energy sources of energy and water for all its needs and treatment of its own waste (Vale and Vale 1975, Rosen 2007). Using this approach, all the above goals can be achieved and non-renewable energy use eliminated for building operation. In addition, the potential exists in some locations for a building that produces more energy than it uses during certain seasons, which would provide electricity for transportation that could payback the carbon debt embodied in the construction materials and construction process – a truly carbon-neutral building.

In addition to the locations with inefficient or no utility-grid services (such as rural areas and remote locations), this design approach has a potential in new suburban development also, where the housing lot can accommodate systems for collection and storage of renewable energy and rainwater, and the treatment and disposal of sewage.

METHODOLOGY

In order to eliminate the need for non-renewable sources of energy and municipal water, energy and water efficiency, and renewable energy measures were analyzed in five different climates of the U.S. The tasks performed for this study included: selection of five locations; simulation of the base-case house; analysis of on-site availability of renewable energy and water, minimization of building energy and water use with energy and water efficiency measures, and the sizing of systems for the collection and storage of renewable energy and water to meet the reduced building needs.

Building energy use analysis was performed using the DOE-2.1e program. Analyses of solar thermal and PV systems were performed using F-Chart (Klein and Beckman 1993) and PV F-Chart (Klein and Beckman 1994), respectively. Analysis of wind power system was performed using wind power curves (AWEA 2007). The sizing of rainwater harvesting systems was performed using methods specified in Gould and

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[1] This paper includes the analyses and results for Minneapolis, MN. The analysis for other climates is being performed in an ongoing study and will be included in the author’s Ph.D. Dissertation.

Nissen-Petersen (1999). TMY2 weather data were used for analyzing the building energy use and sizing the solar systems, respectively. Measured wind and rainfall data for extreme or critical years with minimum availability of these resources were used for sizing the wind power and rainwater harvesting systems.

Selection of locations and simulation of the base-case house

To select locations with distinct base-case energy use characteristics, a DOE-2 simulation model[2] of a 2001 IECC (ICC 1999, 2001) compliant single-family, detached house was run in 17 climate zones classified by the AIA Research Corporation (1978). The size of the house, construction type, HVAC and DHW system types were determined from the housing survey data by the National Association of Home Builders (2003). The characteristics of the building envelope, efficiency of the HVAC and DHW systems, and internal loads were chosen to conform to the 2001 IECC standard design (Chapter 4, 2001 IECC), and the usage profiles were adopted from Hendron (2008). The simulations were performed using TMY2 weather data for a major city in each of the 17 climate zones.

Figure 1 shows the energy use of the base-case house in 17 locations. Based on these results, five locations with distinct energy use characteristics were selected, which fall under five different climate zones classified by the Department of Energy (Briggs et al. 2003). These include: Minneapolis, MN (very-cold), Boulder, CO (cold), Houston, TX (hot-humid), Phoenix, AZ (hot-dry) and Los Angeles, CA (marine climate). Table 1 lists the base-case building characteristics, including climate-specific characteristics for the selected five locations.

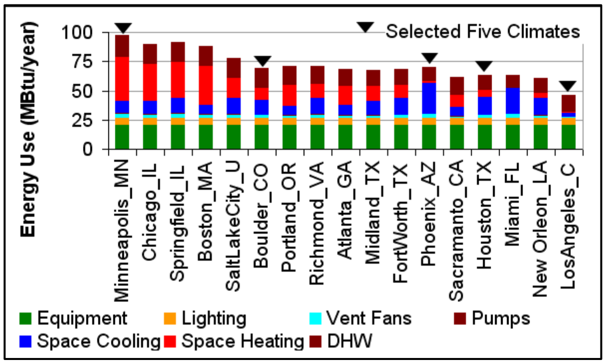

Figure 1: Base-case energy use for 17 locations

Table 1: Base-case building characteristics

General Characteristics	
Building configuration:	2,500 ft^2, four bedroom, square-shape, one-story, single-family detached house
Construction type:	Light-weight wood-frame construction
Exterior walls:	2x4 studs @ 16" on center; fiberglass batt cavity insulation; exterior insulation (if needed); facia brick exterior
Roof/ceiling:	2x10 studs @ 16" on center; cellulose-fill ceiling insulation; gray asphalt-shingle roofing
Windows:	Window area: 18% of conditioned floor area, distributed equally on all four sides; no exterior shading
Underground floor:	Slab-on-grade floor with 4” heavy weight concrete
HVAC systems:	RESYS system with a SEER 13/7.7 HSPF heat pump; ducts in the unconditioned, vented attic
DHW system:	50-gallon electric water heater, 0.86 energy factor
Thermostat set point:	68°F for heating, 78°F for cooling, 5°F set back and set up in winter and summer, respectively

Climate-specific characteristics (2000/2001 IECC)

	Minneapolis, MN	Boulder, CO	Phoenix, AZ	Houston, TX	Los Angeles, CA
Latitude:	44°52	40°1'	33°25'	29°58'	33°55'
HDD65:	7768.4	6011.6	1162.4	1518.8	1328
Ceiling insulation:	R-49	R-49	R-30	R-30	R-30
Wall U-value (Btu/h-sqft-°F):	0.052	0.058	0.085	0.085	0.085
Window U-value (Btu/h-sqft-°F):	0.28	0.30	0.47	0.47	0.47
Window SHGC:	0.68	0.68	0.40	0.40	0.40
Slab perimeter R-value and depth:	R-6, 4 ft.	R-9, 4 ft.	None	None	None
Infiltration (ACH):	0.55	0.50	0.39	0.46	0.38
Supply and return duct insulation:	R-11, R-6	R-8, R-4	R-8, R-4	R-8, R-4	R-8, R-4

Analysis of renewable energy potential

The potential renewable sources for the selected locations were identified using the solar radiation, wind and precipitation maps (NREL 1994, Elliot et al. 1986, USDA 2004). TMY2 weather data were used for a detailed analysis of solar radiation. In addition, since TMY2 data does not represent typical wind or rainfall conditions (Marion and Urban 1995), ten years of hourly measured data for period 1998-2007 for major airport stations in each location was obtained from the National Climatological Data Center (2008), and used for identifying years within this period with minimum availability of wind and rainfall as energy and water resources.

Building energy and water use analysis with energy and water efficiency measures

For each location, energy-efficiency measures for the building envelope, lighting, appliances, and systems were applied to minimize the base-case energy use. In addition, water-efficient appliances and fixtures were considered to reduce domestic water use. Also, measures for minimizing waste due to leaks, misuse, and improper water distribution layout, and water reuse and recycling were considered to reduce the water demand to be met solely by rainwater supply.

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[2] The DOE-2 simulation model SNGFAM2ST.INP v2.30.20, developed by the Energy Systems Laboratory (ESL), Texas A&M University, was used for the analysis. This model uses parameters for various building characteristics, which can easily be assigned different values using an external DOE-2 include file.

While considering these measures, certain performance objectives were defined to ensure maintaining comfort conditions, and to conform to the life style of an average U.S. homeowner. In the case when renewable sources were used, their use was specified not to interfere with the normal operation and usage of the residence.

Space heating and DHW energy use

For the off-grid house, the base-case space heating and DHW systems would be replaced by a solar thermal system. Therefore, the objective of this analysis was to determine system-independent inputs required for simulating equivalent space heating and DHW loads in the F-Chart solar thermal simulation program.

To obtain inputs for space heating loads, one set of simulations analyzing the impact of energy-efficiency measures were performed with the DOE-2 system type SUM. Using the system type SUM provides space heating energy use calculated by DOE-2's LOADS subprogram, which are modified by thermostat settings in the SYSTEMS without simulating a system and its associated efficiencies. These are reported in the DOE-2 SYSTEMS monthly load summary report (SS-A).

After determining an optimized set of energy-efficiency measures for a location, the building's total heat transfer coefficient (building UA) and change-point temperature (T_{bal}) were calculated. Building UA indicates an increase in the space heating loads per unit decrease in ambient temperature, and T_{bal} indicates the temperature at which the heat loss through the envelope is balanced by solar and internal heat gains. These values were calculated from the slope and the intercept, respectively, from the linear curve-fit of the monthly average hourly space heating energy use (calculated from monthly space heating energy use obtained from the DOE-2 SS-A report) and corresponding monthly average temperatures using the ASHRAE Inverse Modeling Toolkit (IMT) (Kissock et al. 2003).

Inputs required for simulating equivalent DHW loads in F-Chart include water mains temperature, supply water temperature and daily water use. An estimation of reduced daily hot water use was made by considering water-efficient appliances and fixtures (Mayer and DeOreo 1999, Vickers 2001) and minimizing energy and water losses at different end-uses (Lutz 2005). These values were first specified for an electric DHW system in the DOE-2 simulation. The DHW monthly energy use was obtained from the DOE-2 Load, Energy and Part Load DHW Tank Operation report (SS-P), and was used to match the DHW energy use calculated by F-Chart. In this fashion, the building UA, T_{bal} and daily hot water use were obtained for F-Chart inputs.

Electricity use for space cooling, lighting, appliances and other:

The off-grid house requires electricity for operating the cooling system including fans and pumps, an additional pump for the solar thermal system, lighting and appliances. To take into account the interaction between the building envelope, systems and equipment, another set of simulations analyzing the combined effect of energy-efficiency measure were performed with the DOE-2 system type RESYS.

After determining an optimized set of energy-efficiency measures for a location, average daily monthly electricity use was calculated by including all end-use, energy use obtained from the DOE-2 Monthly Energy End-use Summary (PS-E) except space heating and DHW energy use. These values were then used for sizing solar PV and wind power systems with battery back-up for days with inadequate solar radiation and wind. The analysis was performed using the TMY2 hourly weather data for building energy use analysis and sizing of solar thermal and PV systems. Measured hourly weather data for a selected year can also be used for the analysis in order to size the systems for heating and cooling loads for extreme or critical years.

Indoor water use

According to American Water Works Association Research Foundation (1999), the mean per capita indoor water use is 69.3 gallons per day. By using water-efficient fixtures and appliances, the indoor water use can be reduced to 45.2 gallons per capita per day. Further reduction in water use can be obtained by recycling and reusing the water, such as reusing grey water from kitchen and showers and faucets for flushing toilets. This can eliminate an additional 9.6 gallons per person per day for toilet flushing. Finally, 20% of the total hot water use can be saved from using measures avoiding water wastage due to improper water distribution planning (Lutz 2005). Thus, for a house with four occupants, 277.2 gallons per day of base-case water use (which includes 70 gallons of hot water use) could be reduced down to 128.4 gallons per day. These estimates were used to determine the water use for the base case and the maximum efficiency option.

The energy and water efficiency strategies were selected to reduce the energy and water use to the extent that they could be met by available renewable resources. In other words, the investigation of available renewable energy potential guided the selection of energy and water efficiency measures, as well as the ranking of the priorities in terms of selection and sizing of renewable energy and water systems.

Renewable energy analysis

The sizing of renewable energy and water collection systems was performed using F-Chart, PV F-Chart[3], wind power curves and calculations for rainwater harvesting. TMY2 weather data were used for sizing the solar systems. Measured wind data and rainfall data for years with minimum availability of these resources within past ten years (1998-2007) were used for sizing wind power and rainwater harvesting systems.

Solar thermal system

For solar thermal system, the system parameters and weather data in F-Chart and DOE-2 were cross-checked to confirm that they match. This included the building UA, T_{bal}, water mains temperatures, supply hot water temperature and daily hot water use. Using parametric runs, the area and tilt of the solar collectors were then determined to provide at least 80% of the winter space heating and DHW energy requirements. The analysis then assumes the remaining 20% of the heating energy requirement would be met by an auxiliary biomass heating system.

Solar PV and wind power system

For power generation systems, solar PV and wind systems were considered based on the availability of solar and wind as renewable sources for electricity. After determining the potential system type (wind, PV or hybrid), the capacity of electricity generating and storage systems were determined to meet/exceed the electricity use for days with inadequate solar radiation and wind.

For locations with the potential of solar power generation, monthly building electrical energy use obtained from the DOE-2 PS-E report was converted into monthly average hourly electrical loads required by the PV F-Chart program (Klein and Beckman 1994).

For locations where wind was found as a potential source of energy, the capacity of wind turbine was determined by comparing monthly total electric output from the wind turbine against monthly total electricity requirement of the house. For this, a wind turbine was selected and a wind power curve was obtained from the manufacturer. Using an appropriate curve-fit between the wind speed and the power output for the turbine, electricity generation at different hourly wind speeds was obtained. The analysis was performed using the hourly wind data of a year with minimum availability of wind in order to determine the electricity output in the most unfavorable condition.

For hybrid systems combining wind and PV systems, a wind turbine was selected to meet the base electricity loads of the winter months. Then, sizing of the PV system was determined to meet/exceed the remaining loads that would mainly include summer cooling electricity use.

The battery storage system was sized to store excess electricity generated for use during days when the weather is not favorable for electricity generation. The parameters used for sizing the battery system include: total electricity requirement for a period the system must support (specific to the location), battery efficiency due to charge/discharge cycle, allowable depth of discharge, performance of battery as affected by the extreme winter conditions, battery voltage and system voltage. In addition, charge controllers and inverters were sized according to the PV panel/wind turbine output and the building’s electrical loads.

Rainwater harvesting system

A rainwater harvesting system for domestic water use consists of a catchment area, a conveyance system, storage and delivery system, with optional components such as filtering and treatment systems. Storage can either be underground or surface type depending on the type of catchment, space availability, support structure, ease of water extraction, and maintenance. The sizing of rainwater harvesting system is determined from the rainfall amount and pattern, catchment area, runoff coefficient, water demand and system cost (TWDB 2005). By combining water-efficiency and conservation measures, the need for a large storage can be offset.

For this analysis, two methods for sizing the storage system were used: a) supply-side approach, i.e., sizing for maximum supply from a given catchment (this may require reducing water demand if supply is not enough), and b) demand size approach, i.e., sizing for meeting a required demand (since all rainwater need not be collected in locations having abundant rainfall) (TWDB 2005). The sizing of storage was based on the measured rainfall data for the year with minimum annual rainfall and longest dry season over the ten-year period. First, the supply (amount of maximum collectible rainwater) and water demand (annual water use, considering water efficient fixtures and appliances) were estimated. For locations with less rainfall, the potential of increasing the catchment area (including roof and ground) to meet the demand was also investigated. Then, by comparing supply and demand, one of the two methods was selected for the analysis. For the supply-side approach, the water use was further

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[3] The MS Windows versions of F-Chart and PV F-Chart (Klein and Beckman 1993, 1994) use TMY2 monthly average weather data. In addition, ground temperatures were used for water mains temperatures in F-Chart program, which was modified using the procedures of Hendron (2008).

reduced to match the supply by applying strategies for water conservation, recycling and reuse. Finally, the storage tank was sized to meet the cumulative water needs for the longest dry season.

ANALYSIS AND RESULTS

To demonstrate the analysis method, Minneapolis, MN, a location with the highest annual energy use, was selected. The analysis is based on TMY2 weather data for building energy use and sizing of solar thermal and PV systems, measured wind data for 1998 for sizing wind power system, and measured rainfall data for 2003 for sizing rainwater harvesting system. The measured data for these years were selected for sizing the systems for the extreme or critical years.

Table 2 lists measures for achieving maximum energy-efficiency in Minneapolis. These include: energy-efficient lighting, appliances in order to reduce electricity use as well as internal gain; high-efficiency HVAC system and ducts in the conditioned space; a well insulated, air-tight building envelope; high-performance windows with night insulation; and finally, most favorable window distribution, overhang depth and building configuration in order to utilize passive solar gain. The impact of combined application of these measures on the heating energy use and electricity use is shown in Figures 2 and 4. Further reduction in energy use could be achieved by sizing the HVAC system for reduced heating and cooling energy use. Figure 3 through Figure 9 show the results of energy-efficiency and renewable energy analysis, using the methods described in the previous section.

Table 2: Energy efficiency measures

	Properties	Base-case characteristics	Measures for maximum energy-efficiency
1	Internal heat gain*:	0.19 kW from lighting, 0.69 kW from appliances	0.05 kW from lighting, 0.46 kW from appliances
2	HVAC system efficiency:	SEER 13/7.7 HSPF heat pump	SEER 15/8.5 HSPF heat pump**
3	Duct location:	Unconditioned attic	Conditioned zone
4	Infiltration:	0.55 ACH	0.35 ACH
5	Slab perimeter insulation:	R-6, 4 ft.	R-10, 4 ft.
6	Ceiling R-value:	R-49	R-55
7	Wall R-value:	R-15 cavity + R-5 exterior insulation	R-15 cavity + R-30 cont. insulation (equiv. to SIP wall)
8	Window system:	U-value: 0.28, SHGC: 0.68, Aluminum frames	U-value: 0.14, SHGC: 0.48, Fiberglass frames
9	Night insulation:	Not considered	50% reduction in glass conductance
10	Overhang:	None	2’ wide roof eaves
11	Window distribution:	Equal window area on all sides	85% on south, 5% on north, and 7.5% on east and west
12	Building layout:	Square shape, one-story	Square shape, two-story

*Constant internal gains were obtained from annual equipment and lighting energy use, using conventional vs. energy-efficient appliances, 0.75 W/sq.ft. (incand.) vs. 0.17 W/sq.ft. (fluor.) installed lighting wattage and identical usage profiles for the base-case and maximum efficiency option (Appendix B, Malhotra 2005).

**Space heating and DHW loads will be met by solar thermal system, with heat pump and tankless water heater as back-up systems

Analysis of heating energy use and solar thermal system

Figure 2 shows the annual space heating energy use (from the DOE-2 SS-A report) as reduced by incremental application of energy-efficiency measures for the building envelope, lighting and appliances; and annual DHW energy use (from the DOE-2 SS-P report). These values were obtained by simulating each scenario with system type SUM. Therefore, the impact of measures for system efficiency improvements in the heating energy use is not seen. It shows that up to 64% space heating energy use could be reduced by using measures for maximizing winter-time solar gains and minimizing heat losses in cold climates. The reduction in hot water use resulted in an equivalent DHW energy savings.

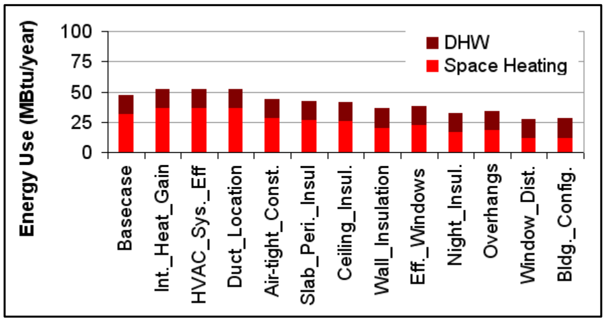

Figure 2: Space heating and DHW energy use (from SS-A and SS-P reports, with system type SUM)

Figure 3 shows the plot of monthly average hourly space heating energy use for the base case and maximum efficiency scenarios vs. monthly average temperature. From the plot, the building UA and T_{bal} were obtained. The reduction in the building UA (92.0 Btu/hr-°F vs. 260.3 Btu/hr-°F) confirms that the building envelope measures would reduce space heating energy use by 64%. The building UA and T_{bal} estimated for the maximum efficiency option were then directly inserted into F-Chart.

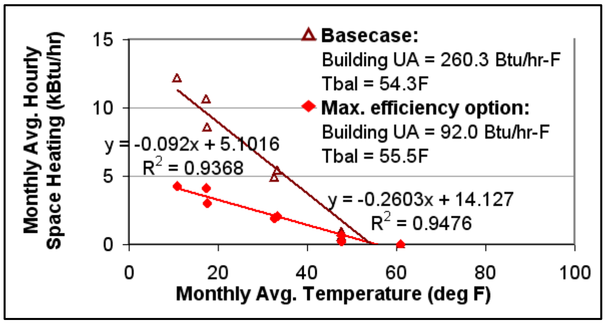

Figure 3: Determination of building UA and T_{bal}

Table 3 lists the input values for F-Chart. A collector area of 192 square feet tilted at 60° was simulated to meet most of the high heating energy requirements in winter months. Figure 5 shows the F-Chart results, and indicates that for December up to 20% of the heating energy use (0.87 MBtu) would be required from auxiliary sources such as biomass. Considering 5,000 Btu/lbm energy content of biomass, 174 lbm of biomass will be required to provide auxiliary heating needs.

Table 3: F-Chart collector input parameters

Number of collector panels:	6
Collector panel area:	32 sq. ft.
Collector slope:	60 deg.
Collector azimuth (South=0):	0 deg.
Collector type:	Evacuated tube
Collector flow rate/area:	11 lb/hr-sq. ft.
Water set temperature:	120 deg. F
Daily hot water usage:	70 gallon
FR*UL (Test slope):	0.188 Btu/hr-ft^2-F
FR*TAU*ALPHA (Test intercept):	0.78
Building UA:	149 Btu/hr-F
Balance point temperature:	56.7 deg. F

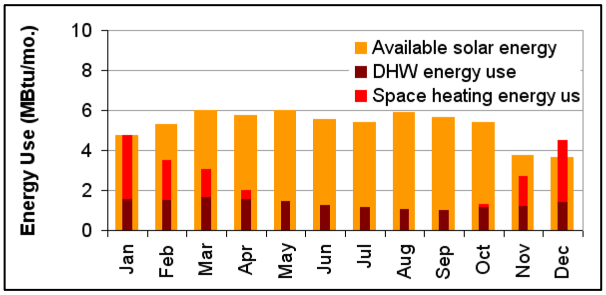

Figure 4: F-Chart results

Analysis of electricity use and hybrid system with solar PV panels and a wind turbine

Figure 5 shows the electricity use (from the DOE-2 PS-E report) as reduced by the incremental application of energy-efficiency measures for the building envelope, lighting, appliances and systems. These values were obtained by simulating each scenario with the DOE-2 system type RESYS and specifying an air-conditioner with a heat-pump/electric resistance heating system. The figure shows that in a cold climate up to 47% electricity use could be reduced by combining all the energy-efficiency measures analyzed. Measures for efficient lighting and appliances contributed the highest electricity use reduction of 30%. Surprisingly, building envelope measures that resulted in large heating energy savings increased the cooling electricity use by 16%. The electricity requirement for the maximum efficient scenario was considered for sizing the renewable energy electricity production systems.

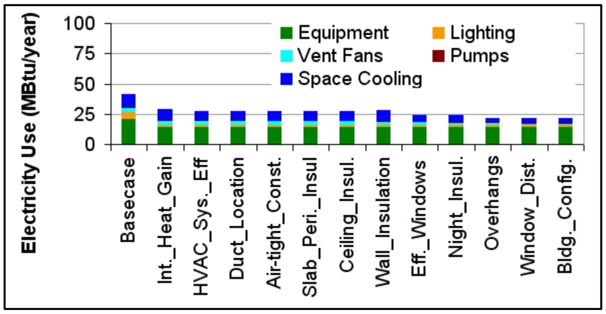

Figure 5: Electricity requirement (from PS-E report, with system type RESYS)

Since wind and solar, both, are potential electricity sources in Minneapolis, a hybrid system comprised of a wind turbine, PV panels and battery storage was considered for this location. For sizing of the wind turbine and determining the power output, a year with minimum wind resource was identified using a histogram of measured hourly wind data for the period 1998-2007. Comparing the plots, 1998 was identified as a year with maximum numbers of hours in low wind speed bins (i.e. below 10 miles per hour) at which a very small power output was obtained.

First, two small wind turbines of 2.5 kW and 6 kW capacities intended for residential application were selected for initial analysis, and the wind power curves were obtained from the manufacturer. Using an appropriate curve-fit between the wind speed and the power output for each turbine, the total electricity generation at different wind speeds was obtained.

Figure 6 shows the histogram of hourly wind speed using measured wind speed data for 1998 and electricity output at different wind speeds from the two wind turbines, which was used to calculate the monthly and annual wind power generation. Using hourly measured data of 1998, the two turbines would generate a minimum of 1,822 kWh and 4820 kWh electricity per year in the worst scenario. These are 28.5% and 75.4% of the annual electricity use in a typical year.

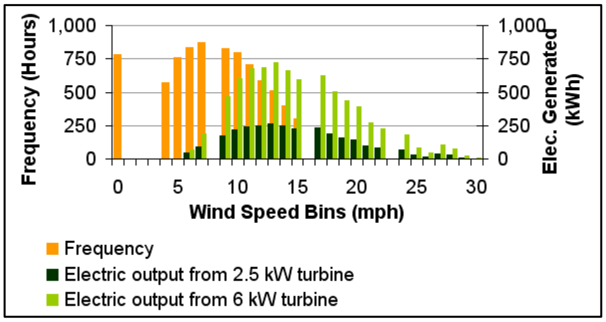

Figure 6: Electricity generation from 2.5 kW and 6 kW wind turbines

For the remaining electricity requirement, a solar PV system was considered. A comparison of available wind electricity and electricity required by the house indicated that additional electricity was required for the period from July through September. Therefore, the PV panel area and tilt were optimized for this period. With this objective, a 188 square feet PV panel array installed at 30° tilt from horizontal was considered. The monthly PV electricity and wind electricity output (kWh/month) were integrated and shown in Figure 7, which indicates that by using battery storage system, the extra electricity stored before June could handle the excess loads still not met by the system.

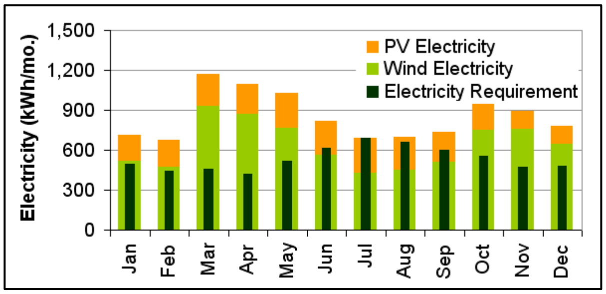

Figure 7: Monthly wind and PV electricity output vs. electricity requirement

The battery bank was sized for 10 days with no solar and wind electricity generation. Considering maximum daily electrical load of 28 kWh, 83% battery efficiency (during charge/discharge cycle), 24V battery bank voltage, 50% maximum depth of discharge, and selecting 2 volt, 1799 Amp-hr batteries, the battery bank required would consist of 12 batteries in series, and a total of 24 batteries.

Rainwater harvesting system

In Minneapolis, the annual total rainfall in 2003 was 21.67 inches which includes the period of May through September with abundant rainfall, and January through March with least rainfall and the longest dry period of 25 days. Considering roof catchment area of 2,500 square feet and run-off coefficient of 0.9, the average daily available water is 83 gallons. The daily water use with efficient fixtures and appliances was estimated to be 128.4 gallons per day. This indicates the need to consider strategies for water recycling and reuse, and use supply-side approach; or to increase catchment area to 4,000 square feet, and use demand-side approach. Figures 8 and 9 show the analysis based on the supply-side approach, which considers further reduction in water use by conservation and reuse to match the supply (i.e., 83 gallons per day). Figure 8 indicates that for most part of the year, the monthly water use is higher than the available rainwater. Figure 9 plots cumulative rainfall harvested and cumulative water use, and shows that cumulative water demand exceeded rainwater harvested until May. The maximum deficiency of 5,200 gallons of water in March, combined with maximum surplus water of 5,900 gallons in July would require an 11,000-gallon rainwater storage tank, initially full. This would ensure that the water demand until May was met, leaving an empty tank in the beginning of May and providing enough water storage for the beginning of the next year.

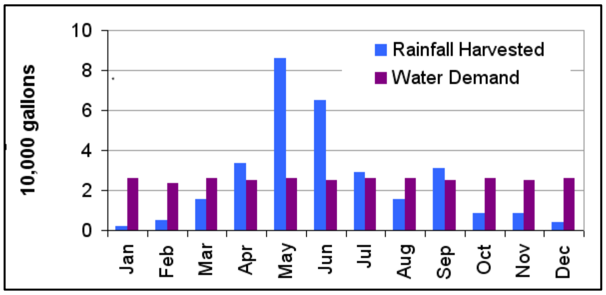

Figure 8: Rainwater supply and reduced water demand

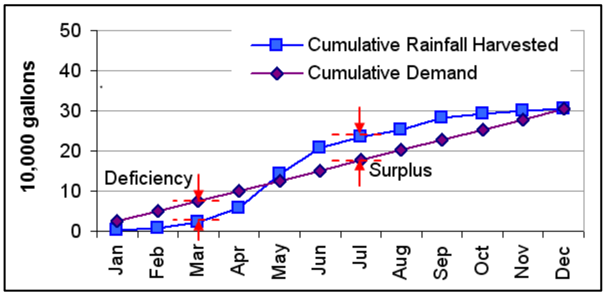

Figure 9: Cumulative supply and reduced demand

CONCLUSION

The results demonstrate that a methodological approach, which considers efficiency, conservation and use of renewable sources, can deliver an off-grid, off-pipe residence in a very cold climate for a house with traditional HVAC and DHW systems. For Minneapolis, MN, energy-efficiency measures reduced the electricity use by 47% and heating energy use by 64%. Water-efficiency measures can reduce the water use and associated hot water energy use by more than 50%. However, in periods of severe drought, the occupants would need to further conserve or recycle water. Most of the reduced energy requirement was met by the installation of a 192 square feet of thermal collectors tilted at 60°, a 188 square feet of PV panels tilted at 30° and a 6 kW wind turbine along with battery storage. In addition, a 174 lbm of biomass would also be needed to carry the home through a severe winter. An 11,000-gallon rainwater storage tank, initially full, provided year round water supply and initial storage for the beginning of the next year.

A similar analysis in other climates would yield different results mainly due to the difference in heating and cooling energy needs, and availability of solar radiation, wind and rainwater[4].

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[4] The analysis for other climates is being performed in an ongoing study and will be included in the author’s Ph.D. Dissertation.