ANALYSIS OF OFF-GRID, OFF-PIPE HOUSING FOR HOT-HUMID AND HOT-ARID CLIMATES

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ABSTRACT

This paper investigates the feasibility of off-grid, off-pipe housing in hot-humid and hot-arid climates in the U.S. 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 2001 International Energy Conservation Code compliant house in Houston, TX and Phoenix, AZ was simulated to determine the base-case energy and water use. Based on the availability of on-site renewable energy and water sources (i.e., solar, wind and biomass and rainfall) in these locations, energy and water-efficiency measures were selected in order to reduce the energy and water use to a level that could be met solely by on-site renewable resources. Finally, the sizing of the renewable energy and rainwater harvesting systems was performed to provide for daily needs as well as cumulative needs during the critical periods, in order to achieve complete self-sufficiency in terms of energy and water use. The analysis was performed by integrating the results of DOE-2.1e, F-Chart and PV F-Chart programs, and cumulative rainwater supply and water demand analysis. The simulation results demonstrate the differences between the priorities for energy-efficiency, water-efficiency and renewable energy measures in hot-humid and hot-arid climates.

INTRODUCTION

Off-grid, off-pipe design approach aims at achieving complete self-sufficiency in terms of electricity, gas, water supply and sewage disposal. By utilizing only on-site renewable resources for all its energy and water needs, and facilitating on-site treatment and disposal of its waste, not only is energy consumption for building operation offset but also, electricity use for municipal water supply, sewage treatment and disposal can be reduced. From this standpoint, such a house can achieve goals beyond net-zero energy and carbon-neutral buildings. In addition to locations with inefficient or no utility grid services (such as rural areas and remote locations), this design approach has potential in new suburban developments where a building lot can accommodate systems for the collection and storage of renewable energy and rainwater, and treatment and disposal of sewage.

Hot-humid and hot-arid regions of the U.S. are characterized by high solar radiation that causes a large cooling load on skin-dominated, detached single-family homes. The resulting high electricity consumption dominates the total building energy use and imposes a large electricity load on the utility grid. Since high cooling loads coincide with high solar radiation, by harnessing solar energy a large portion of the building energy use can easily be offset in these climates. This can help realize the goal of independence from the utility grid. In some cases, when electricity production exceeds the consumption during certain seasons, the excess electricity can be utilized for transportation that could payback the carbon debt embodied in the construction materials and construction process.

Therefore, this study investigates the feasibility of this approach for the two climates and analyzes the differences caused by climatic factors such as diurnal temperature range, humidity and precipitation, which are vastly different in the two climates.

METHODOLOGY

In order to eliminate the need for non-renewable sources of energy and municipal water, energy-efficiency, water-efficiency and renewable energy measures were analyzed in Houston, TX and Phoenix, AZ. The tasks performed for this study included: simulation of the base-case house, analysis of on-site availability of renewable energy and rainwater, minimization of building energy and water use with energy and water-efficiency measures, and sizing of systems for the collection and storage of renewable energy and rainwater to exceed the daily energy and water use, and provide sufficient storage for the cumulative needs during periods when the renewable resources are not available.

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 programs (Klein and Beckman 1994), respectively. The sizing of the rainwater harvesting system was performed using methods specified in Gould and Nissen-Petersen (1999). TMY2 weather data were used for the analysis of building energy use and sizing of solar systems. Measured rainfall data for extreme or critical years with minimum rainfall was used for the sizing of rainwater harvesting system. The integration of results from different programs was performed using the methodology described in Malhotra (2008).

ANALYSIS

The analysis is presented as a comparison between Houston and Phoenix in terms of climate characteristics, availability of renewable resources, building energy use, selection of measures for energy and water efficiency, and sizing of the renewable energy and rainwater harvesting systems.

Analysis of Climate Characteristics

The climate parameters were investigated as determinants of building heating and cooling loads, as well as renewable energy and water resources. Typical conditions were obtained from TMY2 weather data for temperature, humidity and solar radiation. Since TMY2 data does not represent typical rainfall conditions (Marion and Urban 1995), measured hourly data for ten years (1998-2007) were obtained from the National Climatological Data Center (NCDC 2008), and used for determining average rainfall characteristics and identifying critical year within this period with minimum rainfall. Table 1 summarizes the climate characteristics of Houston and Phoenix.

Table 1: Climate Characteristics

	Houston, TX	Phoenix, AZ
Latitude:	29°58'	33°25'
Elevation:	108 ft.	1,112 ft.
HDD65ºF:	1,519	1,162
CDD65ºF:	2,863	4,136
Annual Avg. DBT:	68.1ºF	72.5ºF
Diurnal Temp. Range:	Medium	Large
Relative Humidity:	50-100%	10-50%
Annual Avg. Water Mains Temp.:*	74.2ºF	78.7ºF
Monthly Avg. Daily Solar Radiation:	1,908 Btu/ft^2 (Jun) 790 Btu/ft^2 (Dec)	2,647 Btu/ft^2 (Jun) 938 Btu/ft^2 (Dec)
Rainfall**:	Annual Avg.: 53"	Annual Avg.: 6.5"

 * Monthly average water mains temperatures were determined from Hendron (2007).
** This are based on the ten-year measured hourly data (i.e., 1998-2007) obtained from NCDC (2008).

Typically, Houston can be characterized by cool but short winters, and hot and very humid summers with frequent rains and coastal breeze. The high humidity and clouds prevent the temperature from dropping much at night, resulting in a small diurnal temperature range. Ample sunshine can supply most of the winter heating demands, but increase the cooling loads in summer (Lechner 2001). The annual precipitation averaged 53" during the period 1998-2007, which occurred fairly uniformly throughout the year.

On the other hand, Phoenix, in the Southwest desert region, is characterized by extremely hot and dry summers with large diurnal temperature range and cooler nights, and moderately cold winters. Skies are clear most of the year. Summer cooling load is the main concern (Lechner 2001). The annual precipitation averaged only 6.5" during the period 1998-2007, which occurred mainly from July through September. April through June was the driest period.

Simulation of the Base-case House

The base-case house characteristics for Houston and Phoenix were determined using various resources. 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, internal heat gains, and controls and efficiency of the HVAC and DHW systems were chosen to conform to the 2001 IECC *standard* design (Chapter 4, ICC 1999, 2001).

Table 2 lists the base-case building characteristics including 2001 IECC specified climate-specific building envelope requirements, which are essentially the same for Houston and Phoenix. The DOE-2 simulation model[1] of the 2001 IECC *standard* design of a single-family detached house was run with the base-case characteristics, and then with improved characteristics in Houston and Phoenix. The simulations were performed using TMY2 weather data.

Base-case Energy and Water Use

Figure 1 shows the annual energy use of the base-case house in Houston and Phoenix, which indicates an approximately equal split between the space conditioning and other combined end-uses including lighting, equipment (i.e., kitchen and

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[1] The DOE-2 simulation model SNGFAM2ST.INP v2.50.05, developed by the Energy Systems Laboratory (ESL) 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.

Table 2: Building Characteristics

Building configuration:	2,500 ft.^{2}, four bedroom, square-shape, one-story, single-family detached house oriented N, S, E, W with floor-to-ceiling height of 8 ft.
Construction type:	Light-weight wood-frame construction
Exterior walls	2x4 studs with 25% framing-factor; R-13 fiberglass batt cavity insulation (U = 0.085); fascia brick exterior
Ceiling/Roof:	2x6 studs with 11% framing-factor; R-30 cellulose-fill ceiling insulation; gray asphalt-shingle roofing
Windows:	18% of conditioned floor area, distributed equally on all four sides; U-value = 0.47 Btu/h-sqft-°F, SHGC = 0.4; no exterior shading
Underground floor:	Slab-on-grade floor with 4" heavy-weight concrete; no perimeter insulation
HVAC systems:	RESYS system with a SEER 13/7.7 HSPF heat pump; located in the unconditioned, vented attic
DHW system:	50-gallon electric water heater, 0.86 energy factor, 120°F supply temperature
Thermostat set point:	68°F for heating, 78°F for cooling, 5°F set back and set up in winter and summer, respectively
Ducts:	R-8 supply and R-4 return duct insulation; 5% duct leakage; located in the unconditioned, vented attic
Internal heat gains:	3000 Btu/hr (including heat gains from occupants, lighting and appliances)

laundry appliances) and domestic water heating energy use. The space cooling, space heating, domestic water heating, lighting and equipment energy use were 26%, 14%, 15%, 9% and 32% of the total energy use, in Houston; and 38%, 5%, 13%, 8% and 29% of the total energy use, in Phoenix.

For both locations, the base-case indoor water use of 69.3 gallon per capita per day (i.e., 277 gal/day for four occupants, which includes 70 gal/day hot water use) was adopted from an estimate of U.S. average indoor water use (AWWA 1999).

Energy and Water Efficiency Measures

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

To accomplish this, energy-efficiency measures for the building envelope, lighting, appliances, and systems were applied to minimize the base-case energy use. These measures were selected using parametric simulations and sensitivity analysis. The selected measures were applied in a combined simulation to minimize annual as well as critical month thermal and electrical energy use. Table 3 lists measures for achieving maximum energy-efficiency

in both locations. These include: energy-efficient lighting and appliances, high-efficiency HVAC system; HVAC unit and ducts in the conditioned space; a well insulated, air-tight building envelope; high-performance windows; and finally, the most favorable building configuration, window distribution and overhang depth in order to optimize passive solar gain. In addition, demand-actuated or continuous hot water recirculation system or parallel pipe/manifold system (Wendt 2004) were considered to avoid the hot water and energy wastage due to improper water distribution planning (Lutz 2005).

Table 3: Energy Efficiency Measures

	Properties	Base-case characteristics	Measures for max. energy-efficiency
1	Internal heat gain*:	0.19 kW (lighting) 0.69 kW (appliances)	0.05 kW (lighting) 0.46 kW (appliances)
2	Infiltration/ Ventilation:	0.46ACH (Houston) 0.39 ACH (Arizona)	0.35 ACH***
3	Duct location:	Unconditioned, vented attic	Conditioned zone
4	Radiant barrier:	None	Underside the roof deck
5	HVAC system eff.:	SEER 13/7.7 HSPF heat pump	SEER 15/8.5 HSPF heat pump**
6	Ceiling R-value:	R-30	R-55 (equiv. to SIP roof)
7	Wall R-value:	R-13	R-45
8	Wall and Roof Abs.:	0.55 (walls) 0.75 (roof)	0.25 (walls) 0.25 (roof)
9	Window system:	U-value: 0.47 SHGC: 0.4 Aluminum frames	U-value: 0.11 SHGC: 0.25 Fiberglass frames
10	Shading:	None	4' wide roof eaves
11	Window distribution:	Equal window area on all sides	75% on south, 5% on north, 10% on east and west
12	DHW use	70 gal/day	56 gal/day

*Constant internal heat gains were calculated from: (i) annual equipment energy use for conventional vs. energy-efficient kitchen and laundry appliances, and (ii) annual lighting energy use for 0.75 W/sq. ft. (incandescent.) vs. 0.17 W/sq. ft. (fluorescent) installed lighting wattage used with identical lighting schedule.
**Space heating and DHW loads will be met by solar thermal system, with a heat pump (with supplementary electric resistance heater) and a tankless water heater as back-up systems.
*** Minimum ventilation rate required by ASHRAE Standard 62.

For indoor water use reduction, water-efficient fixtures and appliances were considered, which could provide up to 24.1 gallons per capita per day water saving (AWWA 1999, Mayer and DeOreo 1999). For further reduction in water use, if needed, reusing graywater from kitchen, showers and faucets for flushing toilets were considered. This eliminated an additional 9.6 gallons per capita per day of potable water used for toilet flushing. Finally, 20% of the total hot water use, which is usually wasted due to

improper water distribution layout (Lutz 2005), was eliminated using the measures described previously. Thus, for a house with four occupants, 277 gal/day of base-case water use could be reduced to 128 gal/day. This estimate was used for the maximum efficiency option in Houston. For Phoenix, extensive water conservation measures were considered that include recycling and reusing graywater, using low water use or water-less fixtures, composting toilets, faucets with sensors and water break features, and appliances with intelligent sensors and controls. This level of efficiency and conservation would result in significantly reduced water use and reduced sewage disposal needs. However, the required treatment would add to the electricity needs of the house.

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 resources were used, their use was specified not to interfere with the normal operation and usage of the house.

The impact of combined application of energy and water-efficiency measures on the annual energy use is shown in Figure 1. It shows up to 45% and 50% energy savings in Houston and Phoenix. Further reduction in energy use could be achieved by sizing the HVAC system for reduced heating and cooling energy use. The reduced energy use includes 62% electricity use and 38% thermal energy use in Houston, and 75% electricity use and 25% thermal energy use in Phoenix.

Sizing of Solar Thermal System

In an off-grid house, the space heating and domestic hot water would be provided by a solar thermal system, with auxiliary components such as pumps and fans consuming photovoltaic system generated electricity. The sizing of the solar thermal system was performed by comparing the monthly solar radiation incident at different tilts with monthly heating energy needs of the house.

Figure 2 shows monthly space heating and domestic water heating energy needs, as well as solar radiation incident on a plane at different tilts. It shows that the thermal energy needs were largest in January (2.3 MBtu/month in Houston and 1.3 MBtu/month in Phoenix[2]). The plots of solar radiation indicate that during peak winter months, the incident radiation is higher at higher tilts. However, increasing the tilt higher than the latitude would

result in a small increase during peak winter months, but a large reduction in annual total incident radiation. Since, the efficiency of a solar collector decreases at lower ambient temperatures due to heat losses from the surface of the collector, the thermal output of a collector across various months may not follow the radiation profile. In other words, the thermal output of a collector would be smaller in winter. Therefore, in order to meet the large heating needs in January and December, the area of solar collectors for this study was determined for a 45° tilt for both locations. However, for a house with an active solar thermal cooling system, a lower collector tilt is desired depending on the heating versus cooling needs of the house.

To determine system-independent inputs required for simulating equivalent space heating loads in F-Chart program, simulation was performed with the DOE-2 system-type SUM and the monthly average hourly space heating energy use were obtained from the DOE-2 SYSTEMS monthly load summary report (SS-A). From the linear curve-fit of these values against monthly average temperatures, the slope and intercept were obtained that represent building's total heat transfer coefficient (building UA) and change-point temperature (T_{bal}), respectively. Figure 4 shows the building UA and T_{bal} for the base-case and the maximum efficiency option for Houston and Phoenix. For the maximum efficiency option, the building heat loss coefficient in Phoenix was 39 Btu/hr- °F, compared to 131 Btu/hr-°F in Houston due to large solar gains in Phoenix.

Finally, using F-Chart inputs for: (i) space heating loads (i.e., building UA and T_{bal}); (ii) domestic water heating loads (i.e., daily hot water usage, supply temperature, water mains temperature, and inputs for tank and pipe losses); and (iii) solar thermal system characteristics (i.e., a test slope of 0.21 and an intercept of 0.42 for the evacuated tube collectors, and 1.85 gallons of hot water storage per sq. ft. of collector area), a 180 sq. ft. area of collector tilted at 45° in Houston and only 64 sq. ft. area of collectors tilted at 45° in Phoenix were found adequate to meet the peak heating needs in winter (Figure 5).

Sizing of Photovoltaic System

An off-grid house would require electricity for operating the cooling system including fans and pumps, additional pumps for the solar thermal system, lighting and appliances, and water pressurization and treatment equipment for the rainwater harvesting system. The sizing of the photovoltaic system was performed by comparing the

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[2] High solar radiation in Phoenix offset the space heating loads in winter.

4

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monthly solar radiation incident at different tilts with monthly electricity needs of the house.

Figure 3 shows the monthly electricity needs and solar radiation incident on a plane at different tilts. It indicates that the electricity use was largest in July (811 kWh/month in Houston and 1,120 kWh/month in Phoenix). The plots of radiation indicate that during peak summer months, incident radiation is higher at lower tilts, and maximum for the horizontal plane. A horizontally tilted plane would receive reduced radiation during winter. However, the reduction in the annual total incident radiation would be small. Since, the efficiency of a PV panel decreases with increase in ambient temperature, the electricity output of a PV panel across various months may not follow the radiation profile. In other words, the electricity output of a PV panel would be smaller in summer. The electricity needs in Phoenix are higher in summer because of large cooling loads due to high solar radiation, whereas electricity needs in Houston are relatively flat due to smaller cooling needs in summer. Therefore, the area of PV array was determined for a 15° tilt in Houston to match the winter and summer electricity needs, and 0° tilt in Phoenix to meet the high electricity needs in July.

The analysis was performed with PV F-Chart using 14% array reference efficiency, 113°F cell temperature at NOCT condition, 77°F array reference temperature, and 0.0048 per °F maximum power temperature coefficient, 90% efficiency of maximum power point electronics, and 88% efficiency of power conditioning electronics. With these PV system characteristics, a 550 sq. ft. PV array area tilted at 15° for Houston and a 620 sq. ft PV array area tilted at 0° for Phoenix were found adequate to meet the summer and winter electricity needs (Figure 6).

The battery storage system was sized to store excess electricity generated for use during days when the weather is not favorable for electricity generation. To determine the total electricity use the system must support, the monthly average daily electricity needs combined with the longest overcast period for each month were compared. The largest of these monthly values was used as the required storage size. For instance, considering an overcast period of 7 days in January (15 kWh daily electricity use) and 3 days in July (26 kWh daily electricity use) for Houston, the maximum electricity storage requirement would be 105 kWh. For Phoenix, considering an overcast period of 7 days in January (15 kWh daily electricity use) and 3 days in July (36 kWh daily electricity use), the maximum electricity storage requirement would be 108 kWh. Considering 83% battery efficiency

(during charge/discharge cycle) and 50% maximum depth of discharge, and selecting 8 volt, 820 Amp-hr batteries, 39 batteries would be required. For a 24V battery bank voltage, a series/parallel arrangement with 13 parallel strings of 3 batteries wired in series can be used.

Sizing of Rainwater Harvesting System

The average annual rainfall in Houston in the past 10-year period was 53". However, the year 1999 was critical with only 25.5" annual rainfall which occurred throughout the year. From a 2,500 sq. ft. roof catchment area and 0.9 run-off coefficient, the average daily available water during critical year would be 98 gallons. The water use with efficient fixtures and appliances was estimated as 128 gal/day. This indicates the need to consider strategies for water recycling and reuse (i.e., following the supply-side approach by reducing the needs to match the available supply); or increase catchment area to 3,300 sq. ft. (i.e., following the demand-side approach by increasing the supply to meet the demand). Including the 4 ft. wide roof eaves on all four sides of the house, the total 3,364 sq. ft. roof catchment area could provide the indoor water needs without requiring any further reduction in water use.

On the other hand, the average annual rainfall in Phoenix was only 6.5". However, the year 2002 was critical with only 2.7" rainfall, which would provide only 14 gal/day from the roof. This indicates the need to maximize the catchment area and/or consider extensive water conservation strategies, and provide a large storage for the long dry-periods. For increasing the catchment area, the roof of garage, porch and open-sided barns; ground surfaces including driveway and other paved area; and special-purpose trenches for collecting surface run-off from the building lot can be considered[34]. However, with rainfall as low as 2.7", only about 70 gal/day water can be collected per acre lot in addition to that collected from the roof. Therefore, extensive water conservation approaches, as mentioned previously, were considered in order to reduce the demand.

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[3] Ground surfaces for rainwater catchment have low run-off coefficient due to evaporation and infiltration losses. These losses can be minimized by providing less-permeable, paved and sloping ground surfaces.
[4] Water collected from ground surfaces contains higher levels of chemical and biological contaminants compared to roof surfaces, and requires additional treatment and disinfection. Depending on the quality of water collected from roof or ground, disinfection with chlorine, ultraviolet light or ozone; or membrane filtration such as reverse-osmosis or nano-filtration may be required (TWDB 2005, TCEQ 2007).
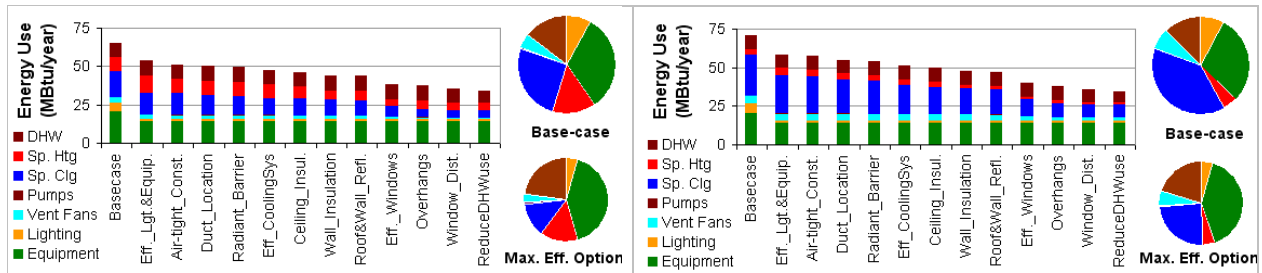
Figure 1.   Annual Energy Use with Different Measures in Houston (Left) and Phoenix (Right)
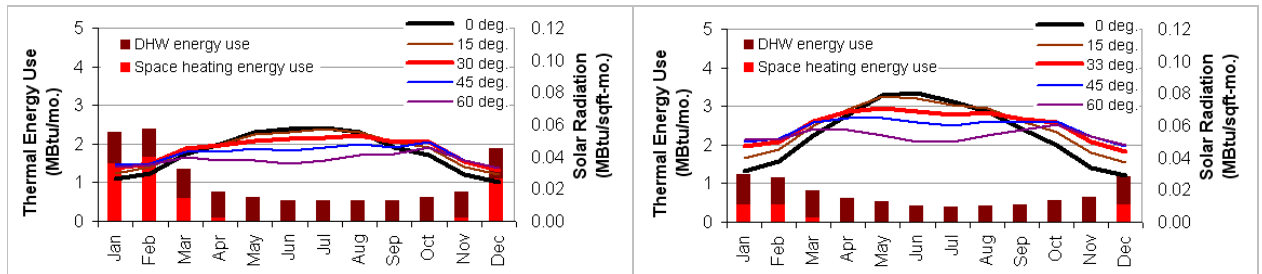

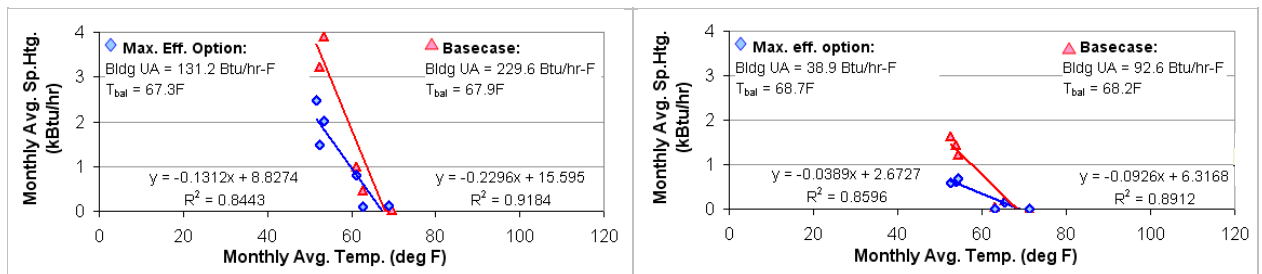Figure 2.   Monthly Thermal Energy Use for Best-case House in Houston (Left) and Phoenix (Right)

Figure 3.   Determination of Building UA and T_{bal} in Houston (Left) and Phoenix (Right)
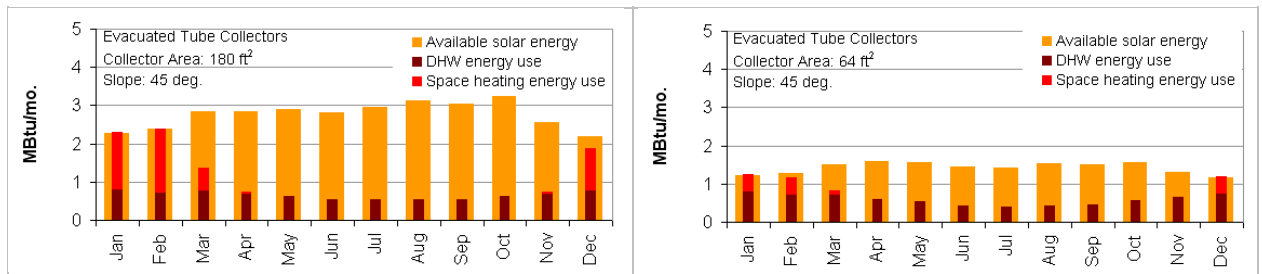

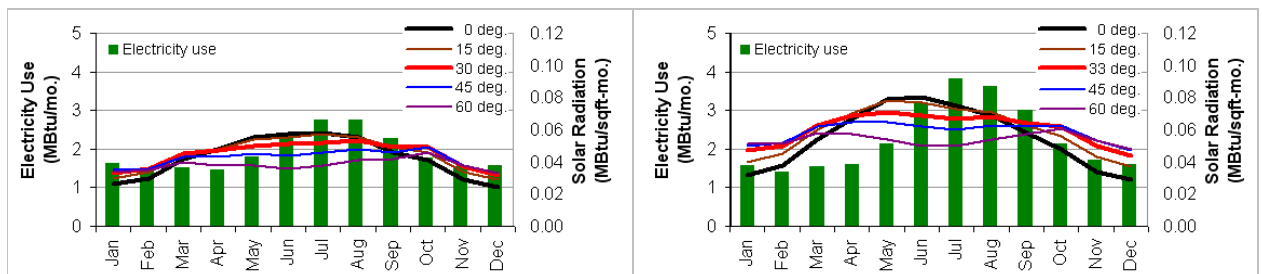Figure 4.   Sizing of Solar Thermal System in Houston (Left) and Phoenix (Right)

Figure 5.   Monthly Electricity Use for Best-case House in Houston (Left) and Phoenix (Right)
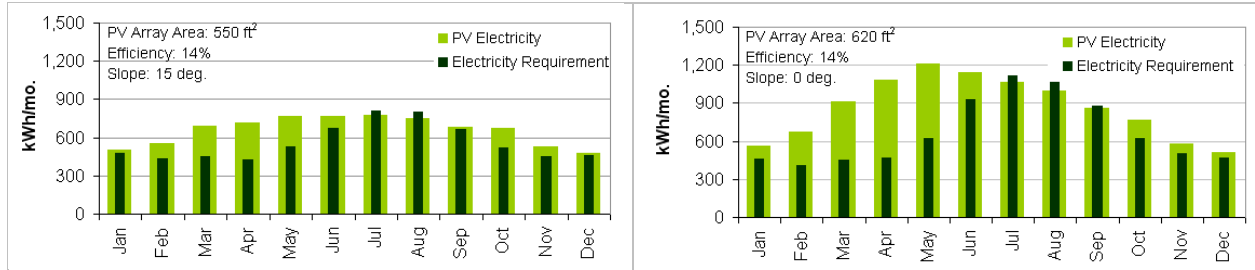
6

Figure 6.   Sizing of Photovoltaic System in Houston (Left) and Phoenix (Right)
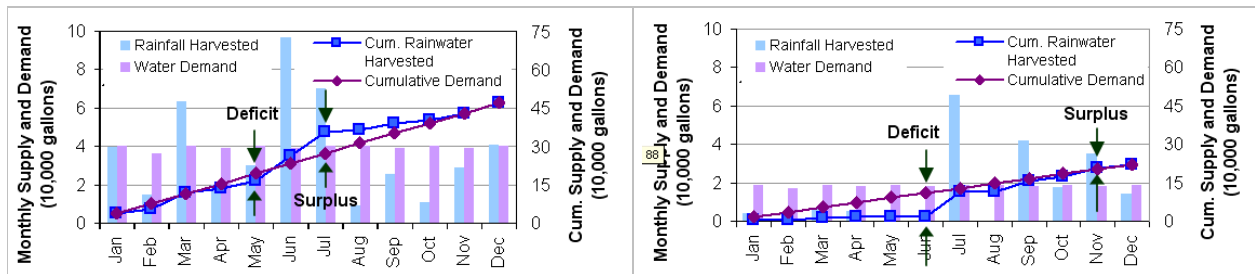

Figure 7.   Sizing of Rainwater Harvesting System in Houston (Left) and Phoenix (Right)

Figure 7 shows the analysis using the measured rainfall data of the critical years in Houston and Phoenix. The sizing of the storage tank was determined by comparing the cumulative demand and rainwater supply. The analysis is based on: (a) a 3,364 sq. ft. roof catchment area in Houston; and (b) water conservation measures and increased catchment area in Phoenix, as described above. The monthly bars indicate that for the most part of the year, the monthly water use was higher than the harvestable rainwater. The cumulative rainwater supply and demand plots show that cumulative water demand exceeded rainwater harvested until the middle of summer.

In Houston, the maximum deficiency of 2,800 gallons of water in May, combined with the maximum surplus water of 8,300 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 and water stored at the end of the year was sufficient for the beginning of the next year. However, with further reduction in water use, a proportionately smaller storage tank could provide the annual water needs. In the same manner, in Phoenix, the maximum deficit of 9,500 gallons of water in July, combined with maximum surplus water of 500 gallons in November would require a 10,000-gallon rainwater storage tank, initially full, in order to provide the reduced annual water needs.

CONCLUSIONS

The analysis showed that with an identical base-case and same measures for energy-efficiency, the

space heating and cooling needs were different in Houston and Phoenix. However, up to 50% annual energy savings could be achieved in both climates.

The relatively large heating needs in Houston required 180 sq. ft. area of solar collectors tilted at 45° in contrast with only 64 sq. ft. area of solar collectors tilted at 45° in Phoenix. The high summer cooling loads in Phoenix required 620 sq. ft. area of horizontally-placed PV panels. The relatively flat profile of monthly electricity needs in Houston required 550 sq. ft. area of PV array tilted at 15° to meet for electricity needs in throughout the year. Based on the stated assumptions about the overcast days in winter and summer, the required size of the battery storage for the two climates was similar. The excess electricity generated in February through June, October and November, after providing the daily needs and charging the battery bank, can be utilized for transportation.

The most distinct feature of the off-grid house in both climates would be the rainwater harvesting system. Because of the insufficient rainfall in Phoenix, self-sufficiency for rainwater would be difficult to achieve in houses on a small building lot or without utilizing a large building lot for rainwater catchment. In addition, rigorous water-conservation measures would be required to reduce the demand.

Design of off-grid, off-pipe houses would also require a consideration for occasions when the operation of a system is hindered during a failure or repair of its components. Designing systems with modular components in a parallel arrangement and

providing standby/multiple storage would minimize the likelihood of any hindrance in the operation of the entire system. However, for critical periods, biomass-based systems for heating and power, and purchased water can be considered as back-up.

For achieving self-sufficiency without compromising the comfort and functionality, high-efficiency building envelop and systems are essential in order to minimize the energy and water needs. In addition, septic system for on-site treatment of sewage and wireless system for communication would be required. It is recognized that the measured analyzed in this study do not represent current building practices, and the building cost with these measures would be significantly high. However, without these measures, a small increase in the daily needs would add up to large cumulative needs, requiring much larger storage systems. In addition, higher peak loads and accordingly sized renewable systems would result in reduced utilization of renewable systems making them less cost-effective. A discussion of these issues together with the cost-analysis will be included in an ongoing study (Malhotra 2009).

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