BRACKETING RESIDENTIAL "NET-ZERONESS" DURING DESIGN STAGE

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ABSTRACT

A net-zero residence is highly dependent on the life-style of the occupants, building construction, equipment operation and maintenance, and the weather conditions. With increasing interest in net-zero energy consumption, it is important to base any claim for the "net-zeroness" of a residence during design-stage on a set of simulation runs instead of just one run for best case scenario (in terms of occupant behavior, equipment maintenance, construction). In the case-study reported herein, these issues were explored while designing a net-zero energy residence. The paper will conclude with identifying influential input parameters and the related output range for the "net-zeroness" of the residence.

INTRODUCTION

Residential energy consumption accounts for more than 20% of U.S. energy consumption (Energy technologies solution). In this regard, there is a move to build as many highly energy efficient, ideally net-zero, residences as possible. The definition of a net-zero building varies depending on the projects's boundary (Torcellini P. *et al.* 2006). For this study, a net-zero energy residence means that it produces at the site, at least as much energy as it consumes over the year.

While the estimation of the sentitivities of the energy efficiency with physical variables like insulation, type and amount of glazing, orientation, etc., are straightforward, the variation with occupant behavior is not. For example, the design occupancy may be known, but what the actual age and number of occupants will be during the first comparison period is not. The situation for a house with solar panels and true net-metering will be quite different if family members are home afternoons, with air conditioning on and drawing electricity from the grid during the peak demand period, vs. the case of working spouses who are at their jobs and who leave the air conditioning on setback with the solar panels generating excess electricity during the peak period.

With the uncertainty inherent during the design stage about the building occupancy, it is important to understand the parameters under which the claim regarding the "net-zeroness" of a residence can be made. One way to do this is to decide on a range of important input parameters to the analysis tool and the resulting energy consumption outputs, instead of just one run for best case scenario (in terms of occupant behavior, equipment maintenance, construction). This paper investigates these issues while designing a net-zero energy residence, a prototype house under development in Hartford, Connecticut. The house is designed using a variety of software tools (eQuest, Trane Trace 700, RetScreen, etc.) to investigate load reduction, system efficiencies, and renewable energy generation options for a net-zero scenario.

BACKGROUND

It is a well known fact that building energy simulation tools are used mostly for comparative purposes – to select various building components for making design decisions. This is because there is inherent uncertainty embedded in the tools – both internal and external. The internal uncertainty is related to how the physics of heat transfer is captured in the simulation tool and the related algorithms for system simulation. The tools vary considerably in their prediction capability, as shown by BESTEST formulation (Judkof, R. and Neymark, J., 1995). For this study, the uncertainty due to tool choice is ignored. EQuest is a popularly used simulation tool and has been tested with BESTEST validation procedure and also compared with real-time monitored data as part of various studies. The external uncertainty, which is the focus of this study, is of three types – 1) the inputs related to the operation of the building (number of people, the type of equipment they use and their requirements for comfort), 2) year-to-year weather variability, and 3) the uncertainty of input (such as occupancy pattern, the opening/ closing of windows, how often and how many appliances are used, infiltration, how the construction was implemented, regularity and thoroughness of equipment maintenance).

Given this uncertainty, using a simulation tool for other than the selection of building components is risky. In order to mitigate the risk one can use the approach that is developed for calibration of simulation tools with measured data (Reddy, A. T. *et al.* 2007). This approach entails using a small set of solutions (as opposed to a single solution) to make predictions about building energy usage. The set of solutions is based on the ranges for the important inputs for the simulation. This approach is demonstrated with an example of providing energy analysis support for a new single-family construction in Hartford.

CASE STUDY

The authors have been involved in the energy analysis of a 1576 ft^2 (146 m^2) two storeyed single family residence in Hartford with unconditioned basement that will be replicated in the neighbourhood. The available roof area is 546 ft^2 (51 m^2) oriented 16^o off south (southwest), with 38^o roof pitch. It has three bedrooms and the occupancy of four people is assumed.

The Architect developed the model in AutoCad. This was then translated into Revit gbxml model to generate the eQuest building model (Figure 1, 2, 3). The main tool of choice was eQuest for analysis of the building loads, comparing component options, and the HVAC system energy consumption, with RetScreen software for the electricity and solar thermal energy production calculations. EQuest allows for very thorough analysis of the envelope, internal loads, and the systems. Trace software was mainly used by the mechanical engineer for equipment sizing. The annual energy consumption results generated by the two software (Trace and eQuest) were within the acceptable range of 5%.

Figure 1: Architects model

Inputs for building model

The inputs for a residence model are related to the site, envelope, internal loads, HVAC systems, and hot-water system. Since the goal is to design a net-zero residence, inputs for electricity and hot water production are also important.

The important variable to consider under site is the weather condition. For simulations used for designing a building, a weather file consisting of typical meteorological year (TMY) data is used. The envelope for this residence is high performance and air-tight. The appliances used are Energy-Star and the lighting is assumed to be all compact fluorescent lamps. The annual lighting and appliance load is assumed from the Building America analysis sheet for a prototype house (Hendron, R. 2007). This allows for a reasonable assumption on the schedules for the lighting and appliances. The number of occupants assumed is four. The heating and cooling is provided by central air system using ground source heat pump technology.

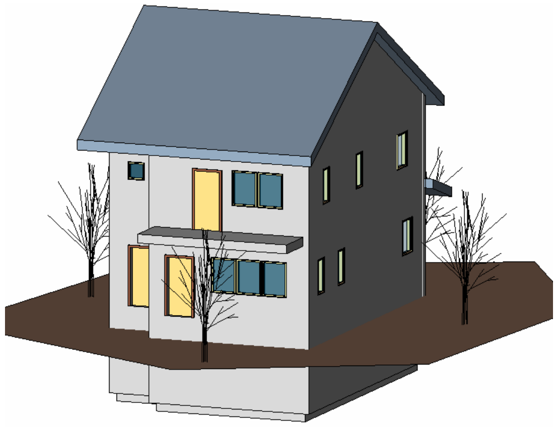

Figure 2: Revit gbxml model

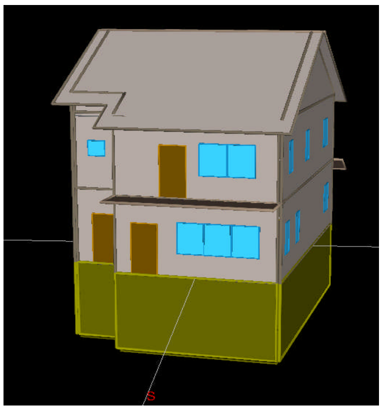

Figure 3: EQuest model

During cooling season, natural ventilation by opening windows is utilized as much as possible. Fresh air is provided using mechanical ventilation.

Hot water is provided by a glazed solar collector system. The solar thermal system covers 80 ft^2 (7.4 m^2) and has 120 gallons (454 L) of storage tank with point of use electric back-up water heaters. It is sized for 85% of the annual water heating load. The PV system consists of mono-Silicone panels with a efficiency of 16.5% and covering 331 ft^2 (31 m^2).

Table 1 gives a list of all the important inputs and their values for the design case. In reality, each parameter would have a range of possible values. The next section discusses the range for some of the important parameters (those that would make a significant diffrence in the prediction of annual energy consumption), and provides the values for the best case and the worst case scenario. The worst case scenario here is for a worst case plausible value and not the ultimate worst case scenario.

Table 1 Input data for single family house design case

CATEGORY	COMPONENT	VALUE
Envelope	Wall	R-40 h.ft^2.F/Btu (7 m^2.K/W)
	Attic floor	R-60 h.ft^2.F/Btu (11 m^2.K/W)
	Basement wall	R-10 h.ft^2.F/Btu (2 m^2.K/W)
	Basement ceiling	R-30 h.ft^2.F/Btu (5 m^2.K/W)
	Window	U-0.31 Btu /h.ft^2.F (1.8 W/m^2.K) SC-0.34
	Infiltration	0.10 ACH
Internal loads	Lighting	0.15 W/ft^2 (1.6 W/m^2)
	Plug loads/ appliances	0.5 W/ft^2 (5.3 W/m^2)
HVAC system	Geothermal water source heat pump with energy recovery ventilator	Cooling COP of 5.6, Heating COP of 4; The well is 300 ft (91 m) deep with 6 in (0.4 m) diameter
	Fresh air	60 cfm (28.32 L/s)
	Natural ventilation	Provides 1/3rd of the required cooling
Domestic hot water system	Solar hot water heater with point of use electric backup heaters	120 gallon (454 L) storage tank with 80 ft^2 (7 m^2) of collector area
Power generation	Photovoltaic system	Sunpower PV, eff. 16.2%, 5 kW peak
Weather data	TMY data for Hartford, CT, USA	

BRACKETING INPUTS

Some of the significant input parameters are 1) internal loads, 2) thermostat schedules, 3) use of natural ventilation for cooling, 4) domestic hot water usage, and 5) solar thermal and PV system efficiencies. All these parameters are highly dependent on the occupant lifestyle. Last, but not least, the effect of weather on the energy consumption is very important. In addition, most of the time, the measured energy consumption is seen to be more that the predicted value due to the control strategies not working as expected. This is mostly the case when new types of HVAC systems or control strategies are used. For this project, the design team is using off-the-shelf HVAC system and control strategy, so the uncertainty due to faulty implementation can be ignored.

The envelope properties are usually very close to the design assumptions if proper care is taken during the construction process. Most of the uncertainty is about how the insulation has been installed and what the air-tightness of the envelope is. Blower door tests have shown that most of the energy efficient houses meet the requirement of very air tight houses.

The biggest uncertainty is in the internal loads energy consumption and the operation of the residence (e.g., the thermostat set point). This is highly dependant on the number and type of occupants. Internal loads are made up of lights, plug loads, and appliances (refrigerator, dishwasher, oven, microwave, washer, dryer) and are anywhere from 50-70% of the total energy consumption. A recent study by Brown (Brown, R., *et al.* 2007) shows that the range of internal loads is from 3100 kWh/yr to 9900 kWh/yr. The bottom line is that a house can be designed to use zero cooling and heating energy, but the appliances, lights, and plug loads will always lead to positive energy consumption. Morever, this energy consumption continues to grow due to the increase in the size of houses as well as increase in the amenities that people need (Brown, R., *et al.* 2007).

The fresh air ventilation value is not varied since it is fixed during the HVAC design stage based on occupancy assumption (four in this case – two in the master bedroom and one for each of the two bedrooms). The ranges for natural ventilation cooling are considered since it requires the occupants to operate the windows during good weather, an activity that is highly dependent on occupant behaviour.

Finally, the uncertainty in the weather affects both the energy production (from PV and solar thermal water heating which are dependent on solar radiation) and the energy consumption (building heating and cooling loads due to conduction, convection, and radiation). The next section describes in detail the ranges used for each of the above mentioned categories and the rationale behind them. Table 2 summarizes the values.

Table 2: Input ranges

Ranges	Best case	Design case	Worst case
Internal load (kWh/yr)	2685	3710	7430
Infiltration (ACH)	0.1	0.1	0.2
Thermostat-heating (^oF) (^oC)	60-68 (16-20)	60-68 (16-20)	70 (21)
Thermostat-cooling (^oF) (^oC)	78-85 (26-29)	78-85 (26-29)	72 (22)
Avg. daily hot water use (gallons/day) (L/day)	45 (170)	56 (212)	67 (254)
Hot Water Consumption (kWh/yr)	2800	3500	4100
Natural ventilation for cooling	1/2 of cooling load	1/3 of cooling load	None
PV system efficiency	80%	75%	70%
Solar thermal system losses	7%	12%	20%

Infiltration

Infiltration makes a difference if the air-change rates are changed sufficiently (for example, when a leaky residence is made airtight). In this case, the difference in annual energy consumption can be as much as 10%. In the case of the Hartford residence, it is assumed that an air-change rate of 0.10 ACH is easily achievable. In certain situations, when the construction is not as air-tight, an air-change rate of 0.2 ACH is assumed.

Internal loads range

Building America has internal loads (including lighting, appliances, and plug loads) calculation guidelines for both the benchmark house and a prototype house (Hendron, R., 2007). The prototype house is the house which is being designed and is more energy efficient than the benchmark house. The internal loads for the Building America benchmark house, similar to the square footage and number of bedrooms of the Hartford house, is 7591 kWh/yr (5488 kWh/yr for appliances and plug loads, and 2102 kWh/yr for lighting). For a Building America prototype house with Energy Star appliances and 100% fluorescent lighting, the energy consumption is 3703 kWh/yr (2977 kWh/yr for appliances and plug load, and 796 kWh/yr for lighting). To decide on the value for the best case scenario, a study conducted by Brown et. al. (Brown et. al. 2007) on internal loads in high efficiency houses was used (Table 3). Here, the energy consumption values range from 1.5-8.1 kWh/ft^2/yr (16-87 kWh/yr/m^2). The lower value for the best case scenario was used, resulting in the appliances/plug loads/lighting energy use of approximately 2700 kWh/yr. This value is about 72% of the design case value.

Thermostat schedule

Two types of schedules are assumed. In an aggressive schedule, the assumption is that the home owners of an energy efficient house are engaged in energy conservation issues and would set the thermostat in winter at 68 ^oF (20 ^oC) during occupied hours and set-back to 60 ^oF (15.56 ^oC). In summer, the occupied temperature setting would be 78 ^oF (25.56 ^oC) with a set-back of 85 ^oF (29.4 ^oC). A worst case scenario is that the heating set-point is always set at 70 ^oF (21 ^oC) and the cooling set-point is always set at 72 ^oF (22 ^oC) without any setbacks.

Natural ventilation

An analysis of the hourly dry bulb temperature values for Hartford shows that during the hours when cooling is required, 56% of the time the outdoor condition is conducive to opening windows (the temperature is between 70 ^oF [21 ^oC] and 78 ^oF [25.56 ^oC]). This is assumed to be the best case situation – i.e. the occupants open the windows for cooling whenever the outside temperature is conducive, and thus 50% of the cooling is provided through natural ventilation. For the design case, it is assumed that the natural ventilation is not used to its maximum, thus providing one-third of the cooling. For the worst case, the natural ventilation option is not utilized

Domestic hot water range

The prototype value of average daily hot water usage from Building America is 56 gallons (21 L) /day. This is similar to the calculations done by the architect for the present project. Assuming that it would vary 20% the range is 45-67 gallons (170-254 L). Incidentally the 67 gallons (254 L) value is very close to the Building America benchmark value of 66 gallons (250 L)/day of hot water (Hendron, R., 2007).

Table 3: Internal loads energy usage for high energy efficiency houses

Case	Floor Area ft^2 (m^2)	Other Energy kWh/yr	Other Energy kWh/yr/ft^2 (kWh/yr/m^2)
Civano1	1556 (145)	3100	1.99 (21)
Civano2	2042 (190)	3500	1.71 (18)
Civano3	1566 (145)	7000	4.47 (48)
Civano4	1280 (119)	4100	3.20 (34)
Civano5	1834 (170)	6100	3.33 (36)
Civano6	1834 (170)	5100	2.78 (30)
Civano7	1834 (170)	5000	2.73 (29)
Civano8	1227 (114)	9900	8.07 (87)
Aspen	3453 (321)	5200	1.51 (16)
Tucson	1718 (160)	4900	2.85 (31)

Solar hot water loss estimation

Miscellaneous losses in a solar water heater system occur due to obstruction of the solar collector by snow and/or dirt. The value of this parameter depends on local climatic conditions, on the tilt angle of the collector, and on the presence of personnel on-site to remove the snow or clean the collector. Depending on local conditions and collector type, this value ranges between 2% to 10%. Miscellaneous losses for the balance of systems accounts, for example, for heat losses from the pipes and/or the tank to the surrounding environment. This accounts for an additional 5% to 10% of losses (RetScreen).

PV loss estimation

The uncertainties in PV analysis come from module calibration and performance, PV panel maintenance, invertor power measurement, etc. (Ransome, S.). Ransome shows that the difference between the best and worst PV system performance is 75+-5% (this does not include the effect of climate variability from year to year). Note that this is different from the performance of the PV panels (which are 16.5% efficient for this study). The PV system losses consist of wiring loss, invertor loss, and PV panel efficiency loss due to maintenance (RetScreen).

Year-to-year climate variability

One way to capture the year-to-year climate variability is to use the HDD/CDD data for a number of years for the location under consideration and how it deviates from the HDD/CDD used in the simulation (Figure 4). This procedure is similar to the methodology used by energy information administration for the assumptions to the annual residential energy outlook 2007 (EIA - http://www.eia.doe.gov/oiaf/aeo/assumption/residential.html). For understanding the performance of PV and solar hot water, solar radiation is an important parameter to consider. According to the NREL solar data manual, the variability of latitude fixed-tilt radiation is +-11% for years 1961-1990 (Marian, W. and Wilcox, S.). The average daily global horizontal solar radiation (AvgGlo) is within -11% to 4% of TMY file for Hartford compared to weather data from years 1991-2005 (Figure 5), which is within the range seen in the NREL data. For this study, two years are considered when the energy consumption normalized to the HDD and CDD is the highest (2005) and the lowest (1992). For the year 2005, the AvgGlo is same as the TMY file AvgGlo data. For the year 1992, the AvgGlo is -11% of the TMY file AvgGlo data.

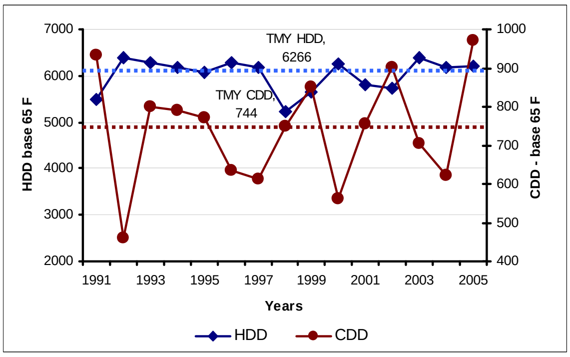

Figure 4: HDD and CDD for Hartford from 1991-2005

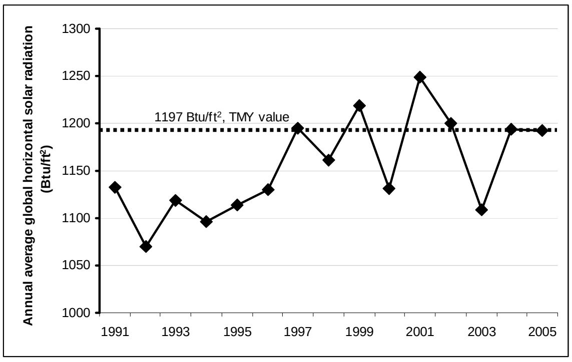

Figure 5: AvgGlo data for Hartford from 1991-2005

RESULTS

The design case annual energy consumption of the house is 8752 kWh/yr, without considering the solar hot water and electricity production. Table 4 shows the breakdown of the annual energy consumption of the house for the design case using the TMY weather file. The highest energy consumption is by the internal loads (lighting and plug loads), followed by domestic hot water (Figure 6).

Table 4: Annual energy consumption for design case, (all electric) kWh/yr

	Base	**With NV**	**With NV & SHW**	**With NV & SHW & PV**
Cooling	311	207	207	207
Heating	1073	1073	1073	1073
Lighting	807	807	807	807
Plug load	2903	2903	2903	2903
Fan/pumps	266	262	262	262
Hot water	3500	3500	500	500
PV production	0	0	0	-5937
Total	8860	8752	5752	-185
% Reduction	-	1%	35%	102%

Table 5 shows the effect of input ranges on the yearly energy consumption for the residence. Table 6 shows the effect of weather data on the yearly energy consumption. The effect of weather data was calculated by considering the years 1991 to 2005. The cooling and heating energy consumption was updated based on the HDD and CDD for the years under consideration. Then the years that had the least (1992) and the maximum (2005) energy used for heating and cooling together were chosen for the mild and max columns data in Table 6. For the year 1992, the AvgGlo is 89% of the solar radiation used in the TMY weather data. For the year 2005, the AvgGlo is same as that of the TMY weather file. Hence the energy production from solar thermal and PV is 11% less than the TMY case for the mild column and same as the TMY case for the max column.

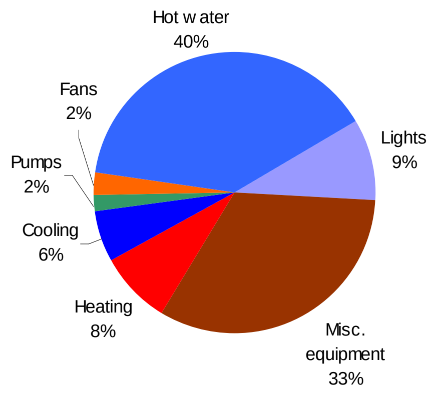

Figure 6: Annual energy consumption (all electric) breakdown by percentages

Table 5: Annual energy consumption (all electric) considering the input ranges, kWh/yr

	Best	**Design**	**Worst**
Cooling	137	207	920
Heating	1169	1073	1172
Lighting	508	807	2032
Plug load	2177	2903	5398
Fan/pumps	264	262	460
Hot water	2800	3500	4100
Total	**7054**	**8752**	**14082**

Table 6: Bracketing results – effect of the weather data

Input range	**Best**			**Design**			**Worst**		
Weather effect	Mild	TMY	Max	Mild	TMY	Max	Mild	TMY	Max
Energy consumption (electric)	7024	7054	7087	8693	8752	8806	13753	14082	14352
Energy production	-11%	0%	0%	-11%	0%	0%	-11%	0%	0%
Solar hot water	2225	2500	2500	2670	3000	3000	2848	3200	3200
PV - electricity	5595	6286	6286	5284	5937	5937	4972	5587	5587
Net energy consumption	-796	-1732	-1700	739	-185	-131	5933	5295	5565

DISCUSSION

The average energy consumption per household for the New England region is 33,695 kWh/yr (RECS, 2001). In comparison, the energy consumption of the design case, considering the TMY weather file, and without considering the renewable energy benefit, is very low – almost one-fourth of the energy consumption of an average New-England house, due to efficient envelope, appliances, and HVAC system. Even the worst case scenario energy consumption is less than half the energy consumption of an average New-England house. The worst case scenario consumes 61% more energy than the design case and the best case scenario consumes 19% less energy than the design case house. Between the design case and the worst case scenario, the internal loads (lighting and plug loads) are the main reason for increase in energy consumption. Due to increased internal loads, the cooling energy consumption also increases.

Figure 7 shows the breakdown of the energy consumption for the average New-England house (RECS, 2001). Here heating energy use is dominant. In energy efficient homes, the plug loads tend to be more dominant. The domestic hot water consumption is about half of that of heating in energy-efficient homes in New-England region (Pettit, 2007). The house considered in this paper has very low heating energy consumption due to the use of GSHP. The same house, when simulated with gas furnace for heating and DX system for cooling shows comparable energy consumption pattern to a energy efficienct home in New-England region. The heating energy consumption in this scenario is about 43% of the total energy consumption followed by hot water heating energy consumption of 22%.

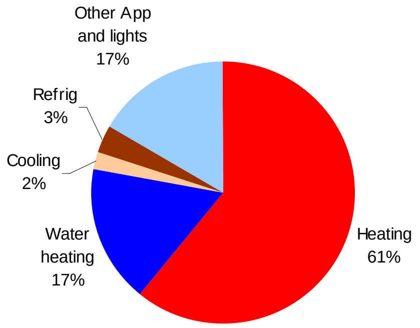

Figure 7: Energy consumption breakdown for average New England house

In this study, only the extreme possibilities and the design case scenario are considered. In reality, there could be any number of combinations of the various input values and the weather conditions. As Table 7 shows, there are 7776 possible combinations for the input ranges and the resulting energy consumption values. Simulating all the combinations would give a much better idea to the designer (and later to the occupant) of which option(s) he/she has to be absolutely meticulous about, in order to reach the net-zero energy goal. Conducting so many simulations manually, especially during the design stage, is not possible in most cases, and also prone to error. A better solution would be for the simulation tool to accept input ranges and automatically generate the output as a matrix.

Considering the effect of the weather on the production of electricity and hot water, one can see that that there are certain situations when the house will not be net-zero. For the worst case scenario, it is understandable. For the design case, when the weather is mild, the heating and cooling energy consumption is less. At the same time, the solar radiation is less, leading to less production of hot water and electricity. Still, for the worst case scenario with mild weather, the net energy consumption is 5933 kWh/yr, less than 20% of the average New-England house.

Table 7: Number of possible parametric runs

Ranges	Number of input options
Internal load	3
Infiltration	2
Thermostat-heating	2
Thermostat-cooling	2
Avg daily hot water use	2
Hot Water Consumption	3
Natural ventilation for cooling	3
PV system efficiency	3
Solar thermal system losses	3
Weather	2
Number of combinations	7776

CONCLUSION

This paper has described a way of capturing the range of probable energy consumption values for a single-family residence being designed with net-zero energy consumption as a goal. Such a range is useful for the occupants – it gives them an idea of what to expect in terms of energy consumption and how their life-style and weather will effect the outcome. This methodology is also useful for certain types of studies (demand reduction, providing rebates or credits for energy efficiency, policy decisions) that rely on occupant behaviour. Having said that, it is a time cosuming task to consider the effect of various ranges and conducting an exhaustive search, which can make the number of simulations run in thousands. One way to address this issue is by having an option of incorporating ranges into the simulation tool instead of single values as input, and having the results as ranges. Also, obtaining a reasonable input range depends on the expertise of the designer/analyst. A common repository of submeterd data for residential energy consumption would go a long way towards establishing reliable usage assumptions.

ACKNOWLEDGMENT

The authors acknowledge the helpful coments provided for the paper by Charles Veley, Director of Real Estate Development, United Technologies Corporation. They would also like to acknowledge the collaborative discussions with SAND, Crosskey Archtects, and Accorn Consulting engineers Inc.

NOMENCLATURE

ACH – Air-change rate

CDD – Cooling degree days

COP – Coefficient of performance

GSHP – Ground source heat pump

HDD – Heating degree days

HVAC – Heating, Ventilation, and Air-conditioning

NV – Natural ventilation

R – Resistance

SC – Shading coefficient

SHW – Solar hot water

TMY – Typical meteorological year

U – Conductance

REFERENCES

Brown, R., Rittleman, W., Parker, D., and Homan, G.; 2007; Environmental Energy Technologies Division, LBNL, California 94720; LBNL-62440;

Energy technologies solution: public – private partnerships transfering industry, 2007, www.eere.energy.gov/industry;

EQuest software; www.doe2.com;

Hendron, R., 2007; Building America Research Benchmark Definition; Technical report NREL/TP-550-40968;

Judkoff, R., and Neymark, J., 1995; International Energy agency Building Energy simulation Test (BESTEST) and Diagnostic Method; NREL;

Marian, W., and Wilcox, S.; Solar Radiation Data Manual for flat-plate and concentrating collectors; (http://rredc.nrel.gov/solar/pubs/redbook/PDFs/CT.PDF);

Pettit, Betsy 2007; Toward Zero Impact Homes Ten Case Studies; www.buildingscience.com;

Ransome, S.; How well do PV modelling algorithms really predict performance?; BP Solar UK; http://www.bp.com/liveassets/bp_internet/solar/bp_solar_spain/STAGING/local_assets/downloads_pdfs/0_999/4EP_1_1.pdf;

Reddy, A, T., Maor, I., and Panjapornpon, C., 2007; Calibrating detailed building energy simulation programs with measured data; HVAC&R Research Volume 13, Number 2;

RetScreen software; www.retscreen.net;

Torcellini, P., Pless, S., Deru, M., Crawley, D.; 2006 ; NREL/CP-550-39833.