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USING EXISTING WHOLE BUILDING ENERGY TOOLS FOR DESIGNING NET-ZERO ENERGY BUILDINGS – CHALLENGES AND WORKAROUNDS

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ABSTRACT

As part of the World Business Council for Sustainable Development's (WBCSD) energy efficiency in building project, the authors have been involved in modelling various technology options for different building market segments to reach net-zero energy goal. This paper describes the modelling of single-family residence in US southeast as a case-in-point to illustrate the most common strategies that are considered during net-zero energy building (NZEB) design stage, ease of modelling these strategies using different tools, and issues of input/output quality control. It will conclude by suggesting critical concepts that need to be added to the simulation tools in general, for them to be useful for design of net-zero energy buildings.

INTRODUCTION

WBCSD's "Energy Efficiency in Buildings" project aims at producing a roadmap for reaching energy self-sufficiency in buildings by 2050, while being economical and socially acceptable. The technical focus of the study is on zero net energy building designs and applying these to the world buildings dataset. The goal is to take a quantitative look at what may be accomplished economically to reduce energy demand and CO_2 emissions in buildings over the next two decades (WBCSD 2008).

Simulation tools are mostly used during the detailed design stage when most of the decisions regarding building massing and system types are already made. The tools in this case allow one to understand the impact of various building and system component efficiencies. To achieve net-zero energy buildings, the simulation analysis should start at the concept stage when building massing and strategies for heating and cooling are also open for discussion. This paper uses one of the WBCSD's sub-market study to illustrate the most common design and system concepts used to achieve net-zero energy design. Although many of the strategies can be simulated with current tools, there are some that have to be approximated, some have to be drastically simplified both for ease of modeling and time reasons. Another important task is the issue of quality control, both for input and output. Input issues regarding internal loads are the most important since they are based on expertise (i.e. the data is not available from the product specifications). The output has to match in terms of expected results and common benchmarks, which are also based on experience.

OVERALL MODELLING APPROACH

The WBCSD EEB model (Figure 1) relies on a submarket approach to evaluate carbon generation and total energy usage in the context of adoption preferences and building system interactions. Submarkets are defined by building end use and location (climate). Project is focused on thorough evaluation of a limited submarket set. Reference building(s) are used to characterize building performance for the submarket. In this paper, we will use the single-family homes submarket for US south east as a case-in-point to illustrate the issues related to net-zero energy building modelling. EQuest was used as the tool of choice for modelling the energy consumption.

Generating reference cases

Residential Energy Consumption Survey (RECS) public use microdata files for 2001, with data specific to east south central division in the U.S., are used to generate the reference cases (RECS 2001) in our study. The survey collects statistical information on the consumption of and expenditures for energy in housing units along with data on energy-related characteristics of the housing units and occupants. This data on energy-related characteristics of the housing units is categorized into reference cases (description of envelope, HVAC, internal loads, etc.) such that the simulated energy consumption times the number of houses depicted by each reference case provides the total energy consumption for the segment and also matches well with the RECS energy consumption data for that submarket. The base assumption for the house is a typical single family residence, two stories, with three bedrooms (occupancy of 4). The size of the house is 2952 ft^2 (weighted median of all the house sizes in the dataset), divided into two HVAC zones, first and second floor. The house is slab on grade with window to wall ratio of 11%. Table 1 gives a description of the five reference cases. The internal loads (lighting, equipment and plug loads, cooking) and water heating are assumed based on Building

America benchmarks (Hrendon 2007). It is assumed that the windows are opened for ventilation and cooling when the temperatures are conducive.

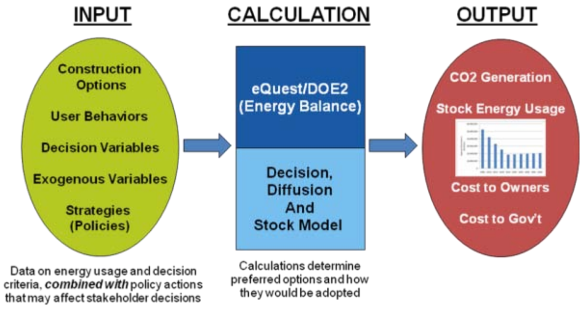

Figure 1 WBCSD EEB model

Net-zero energy building technology options

The technology options that were considered for upgrading the single-family residence to a highly energy efficient and finally net-zero energy residence are as follows:

Envelope system:

1. Improved Wall & Roof Insulation: Two values of insulation are simulated for walls, R-15 $h.ft^2.F/Btu$ (2.6 $m^2.K/W$) and R-25 $h.ft^2.F/Btu$ (4.4 $m^2.K/W$). Similarly for roofs two insulation values, R-20 $h.ft^2.F/Btu$ (3.5 $m^2.K/W$) and R-40 $h.ft^2.F/Btu$ (7.0 $m^2.K/W$), are simulated, resulting in improved air-tightness.
2. Improved Window U-Value: Double low-e clear glass with U-value of 0.35 $Btu/h.f^{t2}.F$ (2.0 $W/^{m2}.K$) and SHGC of 0.73 and triple low-e clear glass with U–value of 0.14 $Btu/h.f^{t2}.F$ (0.8 $W/^{m2}.K$) and SHGC of 0.47 were considered.

Lighting:

1. CFL (Compact Fluorescent Lights) Lighting (85 Lm/W)
2. LED (Light Emitting Diode) Lighting (150 Lm/W)

Internal loads:

1. High Efficiency Large Appliances
2. Inductive Heat Cooking

HVAC system:

1. Improved Space Heating (COP 4 for air-to-air heat pump, 95% thermal efficiency for furnace)
2. GSHP Space Heating and cooling (Geothermal Heat Pump)
3. Improved Cooling (SEER 13)
4. High Efficiency Cooling (SEER 18)

Table 1

Five reference cases for the US SE (east south central division)

Reference case	**1**	**2**	**3**	**4**	**5**
Passive Design	Trees	-	Trees	Trees	Trees
Fenestration	Single Pane	Single Pane	Single Pane	Single Pane	Single Pane
Wall Insulation (hr.ft2.F/Btu)	R11 (1.9 $m^2.K/W$)	R11 (1.9 $m^2.K/W$)	R11 (1.9 $m^2.K/W$)	R11 (1.9 $m^2.K/W$)	R-7 (1.2 $m^2.K/W$)
Roof Insulation (hr.ft2.F/Btu)	R15 (2.6 $m^2.K/W$)	R15 (2.6 $m^2.K/W$)	R15 (2.6 $m^2.K/W$)	R15 (2.6 $m^2.K/W$)	R-11 (2.6 $m^2.K/W$)
Space Heating Equipment	Electric Furnace (COP 1)	Electric HP (COP 2.8)	Gas Furnace (Eff 0.78)	Gas Furnace (Eff 0.78)	Gas Furnace (Eff 0.78)
Space Cooling Equipment	Split System DX with Central Air (SEER 9.5)	Split System DX with Central Air (SEER 9.5)	Split System DX with Central Air (SEER 9.5)	Split System DX with Central Air (SEER 9.5)	Split System DX with Central Air (SEER 9.5)
Dedicated Dehumidification	None	None	None	None	None
Lighting	Incandescent	Incandescent	Incandescent	Incandescent	Incandescent
Cooking	Electric Stove	Electric Stove	Electric Stove	Electric Stove	Gas
Water Heating	Electric	Electric	Electric	Natural gas	Electric
Large Plug Loads	Standard Efficiency	Standard Efficiency	Standard Efficiency, 10% less loads	Standard Efficiency	Standard Efficiency, 10% less loads
Small Plug Loads	Standard Efficiency	Standard Efficiency	Standard Efficiency, 10% less loads	Standard Efficiency	Standard Efficiency, 10% less loads

Domestic water heating:

1. High Efficiency Water Heating (90% reduction in standby losses for electric water heaters, 95% efficiency for gas water heaters, reduction in hot water consumption by 20% from reference cases)
2. CO_2 Heat Pump Water Heating

Renewable:

1. Solar Thermal Water heating
2. PV (Photovoltaic)

There are, of course, many more passive design and efficient technology options that help in reducing energy consumption. For WBCSD, the idea was to simulate the most commonly used strategies. Some of the other important options for energy efficiency are as follows:

1. Passive design options:
    a. Building configuration, siting, orientation
    b. Thermal mass
    c. Shading (overhang, portico)
    d. Shading (trees, wall covers)
2. Semi-active strategies
    a. Ceiling fans
    b. Whole house ventilation
    c. Sun-spaces
    d. Building operation
3. Active strategies
    e. Solar space heating
    f. Radiant heating and cooling

Some of these options, like building operation (i.e. how the occupants use the residence), are simulated on some of the cases and its impact is generalized. Since this study was for analyzing the market segment, issues regarding building configuration and orientation had to be kept constant for simplicity.

The above mentioned technology options are simulated individually (except for PV – the rationale being that it does not make much economic sense at current and near future PV prices to install them on an inefficient building[1]) and then in combination with each other, leading to a total of 50-70 runs for each reference case.

Following is a sample of typical combination of packages:

1. Improved Envelope + Improved Internal Loads (lighting and equipment)
2. Improved Envelope + Improved Internal Loads + High Efficiency Hot Water Heating
3. Improved Envelope + Improved Internal Loads + CO_2 Heat Pump Hot Water Heating
4. Improved Envelope + Improved Internal Loads + Solar Thermal Hot Water Heating
5. Improved Envelope + Improved Internal Loads + High Efficiency Hot Water Heating + Solar Thermal Hot Water Heating
6. Improved Envelope + Improved Internal Loads + CO_2 Heat Pump Hot Water Heating + Solar Thermal Hot Water Heating
7. Improved Envelope + Improved Internal Loads + CO_2 Heat Pump Hot Water Heating + Solar Thermal Hot Water Heating + 4 kW PV

RESULTS AND ANALYSIS

The comparison of energy consumption between the reference cases shows that at the site energy level, all electric homes consume relatively less energy than the homes using gas for heating and/or domestic hot water (Figure 2). This is understandable since the inefficiencies in the gas furnace are considered at the site energy level whereas the inefficiencies in electricity generation are ignored at the site level energy calculations.

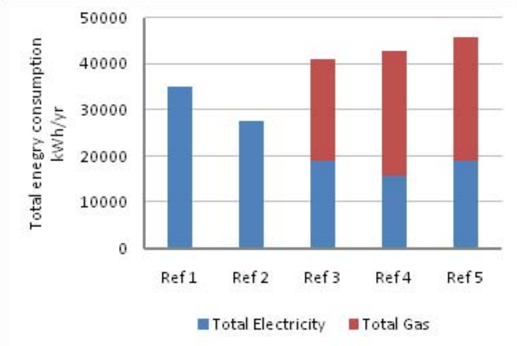

Figure 2: Reference case energy consumption

When high efficiency products are applied to the house, the simulation results show that the energy consumption can be brought down by about 75% in most cases (Figure 3).

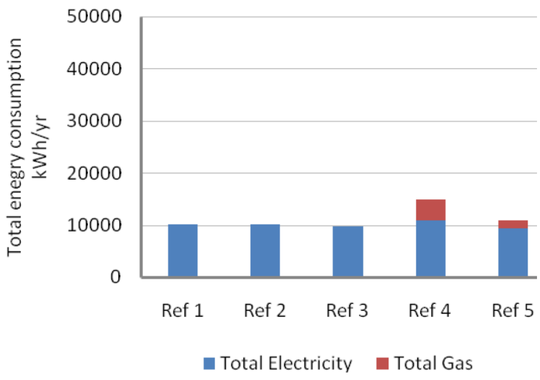

Figure 3: Energy consumption comparison for the high efficiency case

[1] U.S. DOE has set up the target to achieve net zero energy for newly constructed residential buildings by 2020: 70% reduction is from building and system efficiency improvement, and the rest 30% will be compensated by renewable energy generation

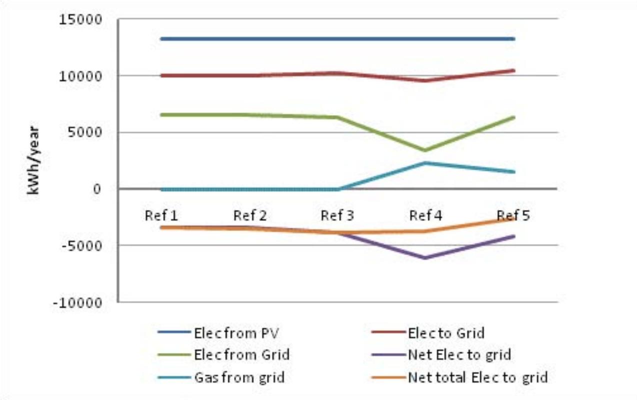

Figure 4: Electricity generation from PV

Once the energy consumption of the house is reduced substantially by using high performance envelope, reduction in internal loads, and efficient conditioning equipment, it is possible to take care of the minimum amount of energy required by using onsite PV and solar thermal systems. Figure 4 shows that with the use of PV and solar thermal, the houses can achieve net-zero energy status and in fact produce more energy than what they consume. One can imagine that such a neighbourhood can be a net-producer of energy and be able to sell credits and generate additional income.

An analysis of occupant behaviour on the energy consumption shows that conservation oriented behaviour can reduce energy consumption by one-third (Figure 5), while in more efficient buildings, by nearly half (Figure 6). The behaviour is considered in terms of both the level of service and the actual day-to-day usage and the level of equipment maintenance (Figure 7).

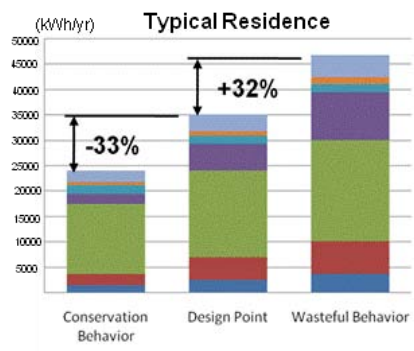

Figure 5: Behaviour impact on typical residence

CHALLENGES & WORKAROUNDS

The main challenges for simulation of a net-zero energy building can be categorized broadly into a) modelling of technology options, b) availability of input data, and c) output quality assurance. Ease of use is a big challenge, but we believe that, in most cases, it is a function of the above-mentioned categories. Some of these challenges are tool specific (for e.g. ability to simulate a particular technology) and some are applicable to almost all simulation tools (for e.g. issues of quality control). We have outlined these challenges with respect to three commonly used whole building energy analysis tools – eQuest (www.doe2.com), EnergyPlus (www.energyplus.gov), and TRNSYS (tess-inc.com).

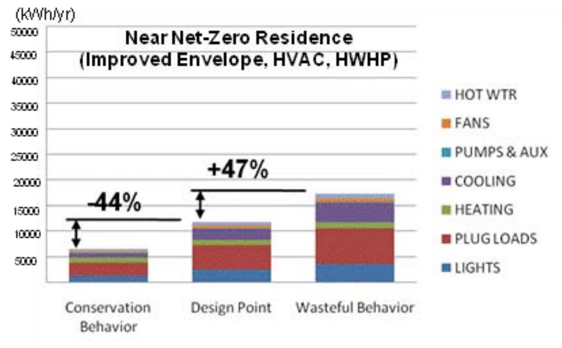

Figure 6: Behaviour impact on high efficiency residence

Category	Variable	Conservative	Designed	Wasteful
Level of service and usage	Plug and lighting levels	-47%	-	+47%
	Amount of water (gallons/day)	-20%	-	+20%
	Hot water set-point (F)	-10	-	+10
	Thermostat set-point – cooling (F)	+8/+8[1]	-/-[1]	-4 (24 hr)
	Thermostat set-point – heating (F)	-4/-4[1]	-/-[1]	+4 (24 hr)
	Window open when natural cooling possible	All the time	½ the time	Never
Maintenance	Cooling efficiency	Current	Current – 10%	Current – 20%
	Heating efficiency	Current	Current – 10%	Current – 20%
	Boiler efficiency	Current	Current – 10%	Current – 20%
	Solar thermal system efficiency[2]	-2%	-5%	-8%
	PV panel efficiency[2]	0%, 0%	-2%, -12.5%	-4%, -25%

Figure 7: Range of behaviour values

Design and technology options

Building massing and shading:

Although the three tools, in some ways, can model building massing (building's three-dimensional form) and shading, in some tools it is easier/quicker than others. EQuest has predefined shapes that one can choose from that makes it easier for a modeller to study the impact of building shapes on energy consumption very quickly.

Trees for shading:

None of the tools allow for direct simulation of trees (based on type, foliage, etc.). There impact is simulated by treating them as external shade with a percentage of transparency that can be varied according to season.

Natural ventilation:

Depending on climate and building types, natural ventilation can be used as an alternative to mechanical cooling systems, saving 10%-30% of cooling energy consumption due to free cooling. Both EnergyPlus and TRNSYS can handle the modelling of natural ventilation system by the adoption or integration with COMIS. TRNSYS can also combine with other external software like CONTAM to model natural ventilation. EQuest allows natural ventilation in conjunction with mechanical ventilation for some of the system types. It is the easiest to use, but requires the user to input an air-change rate. There is no clear guidance on what are typical rates air-change rates in houses when cross-ventilation is allowed. Broniek (Broniek 2008) mentions that the typical natural ventilation rates in a Fort Wayne house is 1.05 ACH to 2.37 Ach with an average value of 1.87 ACH. For the WBCSD study, the authors used the economizer approach to simulate natural ventilation. Another approach is to post-process the hourly cooling and fan energy consumption with respect to outdoor temperature and humidity. The assumption is that windows are opened when outside conditions are conducive. This assumption, in conjunction with probability of window being opened, gives a reasonable indication of savings due to window opening.

Ceiling fans:

From authors' knowledge, there are no tools that can model the system with ceiling fans accurately, since the majority simulation tools assume well-mixed air inside a given zone, and do not include air velocity as a parameter in the simulation. In general, any technology relying on air movement is best modelled by using Computational Fluid Dynamic (CFD), but in case of whole building energy analysis, especially in the concept design stage, it might not be possible due to time constraints. An indirect way to simulate would be allow for increase in the temperature setpoint such that the thermal comfort is the same as in the case without ceiling fan but lower temperatures.

PCM (Phase Change Materials):

The application of PCM in building envelope constructions can add thermal mass to the building, therefore enhancing building energy storage capability. Both EnergyPlus and TRNSYS have special modules to handle PCM. All the three tools can simulate thermal mass.

Lighting options:

Using daylight is a big energy saver for reducing lighting energy consumption. For the building with daylighting, there is a trade off between lighting energy reduction and heating/cooling energy increase, which depends on the climates. CFL and now LED are the technologies of choice. All tools allow for simulating the impact of lighting on energy consumption. In the WBCSD study, these technologies were simulated by reducing the peak power by 1/4th and 1/8th respectively.

HVAC options:

Low - temperature radiant heating and high temperature radiant cooling systems such as radiant floor heating and chilled ceiling are more energy efficient than forced air systems if designed and operated properly. Both EnergyPlus and TRNSYS have options to model radiant heating and cooling system in details, though eQuest has very limited capacity for radiant heating and cooling. In eQuest, hydronic radiant floor heating can be modelled approximately by lowering the space temperature, using a unit ventilator with fan power kW/cfm as zero and by including a baseboard at the zone level.

Ground source heat pump system is a heating and/or cooling system that uses the earth as heat source/sink. eQuest provides the easiest way to model ground heat exchangers by embedding the ground response functions into the program, though EnergyPlus requires these functions as inputs from the user. Users will have to calculate these response functions through other tools such as GLHEPRO (GLHEPRO 2007).

Water-side economizer provides free cooling by evaporation without operating a chiller. EnergyPlus and TRNSYS provide solutions to model waterside free cooling; however, there is not a direct and accurate way to do this in eQuest.

Control options:

Modelling of control strategies is highly dependent on the flexibility provided by the simulation tool. In this regard, TRNSYS provides the most options for modelling controls strategies with eQuest having the most restrictions. It is possible to use co-simulation platform to couple EnergyPlus with other more control-oriented tools such as Matlab/Simulink and/or Modelica to do advanced control design, although this kind of approach is still in the early development stage (Wetter and Haves 2008).

Water heating options:

Modelling of CO_2 water heaters is not supported by any of the tools. For WBCSD study, this technology was simulated by using the heat pump water heater component and an equivalent COP for CO_2 water heater.

Solar thermal water heating and space heating:

Both EnergyPlus and TRNSYS support the modelling of solar thermal systems, whereas eQuest does not support this functionality. For the WBCSD study, we used RetScreen (an excel based energy efficiency analysis tool) to understand how much of the water heating needs could be provided by solar water heater. This usage of another tool works in this case since water heating does not interact with the energy consumption of the house in any substantial way and therefore, can be simulated stand-alone.

PV:

Photovoltaic modelling is supported in all the tools with respect to the different types of PV modules and the shading aspect (either from the buildings itself, surrounding structures, or self-shading). Considering the shading is a more involved process in TRNSYS.

Table 2 shows the comparison between eQuest, EnergyPlus, TRNSYS in modelling of technologies they support directly.

Input data

Input data is related to the building technology (efficiency, sizing, etc.), the operation of the building (internal loads, system maintenance, etc.), and the weather.

The data for the building technologies itself is readily available, although sometimes not in the form that the tool needs. For example, the data provided by manufacturers for performance is not same as what is required by the tools. In most cases, it is reasonable to use the default curves/examples provided by the tools. Some tools like EnergyPlus provide auxiliary toolkit to convert data from manufacturers' catalogue into the performance curves used during the simulation.

Another input which is dependent on the construction of the building is infiltration. Infiltration makes a substantial difference if the air-change rates are high. For example, when a leaky residence is made airtight, the difference in annual energy consumption can be as much as 10%. One of the first steps towards net-zero energy residence is to have a very tight envelope and introduce ventilation air if the infiltration rate is less than 0.35 ACH. In the WBCSD case, we assumed an infiltration rate of 0.35 ACH for the highly efficient envelope cases.

The most important factor is about the input of building schedules (how the occupants use the building) – people flow, lighting usage, amount of plug load etc. For residential modelling, the data from Building America can be used (Hrendon, 2007). For commercial/institutional buildings, if the building is monitored in some way, then there is a way to estimate people flow, lighting and equipment usage by using some estimation techniques, based on either statistic model or reduced order physical model and some real time data from the building (Tomastik et al. 2008).

Weather data: It is reasonable to use the TMY weather data for whole year energy usage. When trying to make the building net-zero energy, it might be worthwhile to consider the variability in solar radiation and the HDD, CDD. Paper by Brahme (Brahme, R. et.al. 2008) shows that a residence can go from net-zero energy, with electricity sold to the grid, to consuming electricity depending on the weather variability. The variability can be included in the simulations by considering the typical range for these variables over a 10-30 years time frame. For example, 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.).

Table 2
Capability of whole building energy simulation tools to simulate net-zero energy building technologies

Net-zero Energy Strategy	eQuest	EnergyPlus	TRNSYS
Building massing	Yes	Yes	Yes
Trees	No	No	No
Natural ventilation	Yes	Yes	Yes
Ceiling fans	No	No	No
Thermal mass	Yes	Yes	Yes
PCM	No	Yes	Yes
Lighting	Yes	Yes	Yes
Radiant cooling and heating	Partially	Yes	Yes
Ground Source heat pump	Yes	Yes	Yes
Water-side economizer	Partially	Yes	Yes
Controls	Partially	Partially	Yes
CO_2 water heater	No	No	No
Solar thermal	No	Yes	Yes
PV	Yes	Yes	Yes

Quality assurance – output data

In the WBCSD case, the output data is compared with the market segment data (RECS 2001) to make sure that the results are reasonably close to the benchmark. Table 3 and 4 show the comparison between the eQuest energy consumption data calculated using eQuest and the segment data from RECS 2005. Given that most well calibrated simulation models estimate the energy consumption within 10-15%, a 15% error is reasonable and to be expected for comparison of large groups of buildings.

Table 3
Comparison of simulated energy consumption with RECS 2005 energy data

2005 Segment Energy Data	*1.36E+11*	*kWhr/yr*
2005 Segment Energy Data Calcd	1.36121E+11	kWhr/yr
Computed Segment Energy Sum	1.56,548,E+11	kWhr/yr
Checksum	**15%**	Error
Buildings in the segment	4,054,942	

Both eQuest and EnergyPlus produce outputs in the form that are equivalent to typical benchmark numbers. TRNSYS can produce output numbers in any form that the user wants. It needs the user to add this functionality to the model.

Table 4
Comparison of simulated energy consumption, by fuel, with RECS 2005 energy data

(kWhr/yr/ building)	*Electri city*	*Nat. Gas & LPG*	*Fuel Oil & Kero sene*	*Coal*	*District Heat / Steam*
Segment Energy Data	19,688	11,336	190	206	2,149
Computed Segment Energy	25,237	13,370	0	0	0
Error	17%	6%	-1%	-1%	-6%

Ease of use

With a nice graphic interface, eQuest is the easiest tool to use though it has limited capability to model some systems as mentioned before. EnergyPlus is able to model many net zero energy technologies, but it is not easy to use due to lack of graphical interface. With the development of third party interfaces, it is likely that EnergyPlus will get easier to learn and use in the near future. TRNSYS has the most flexibility but comes with a steep learning curve.

CONCLUSIONS

The paper has shown that it is possible to reach the net zero energy building goal with existing technologies and looking at the energy consumption of the building holistically. A considerable reduction in energy consumption is achieved by using high efficiency technologies and the reminder of the energy (about 30%) is provided by the renewable technology options.

On the analysis side, the whole building analysis tools do a good job of simulating technologies that are commonly used. Passive design strategies and new technologies or configurations have the least support from these tools. For not so common or new technologies/system configurations, one has to still rely on indirect ways of simulating them and use expert judgement for output quality.

Some of these challenges can be easily addressed in the current simulation tools by the interface developers (for e.g. by including comparison with benchmarks), others need some research for simplifying the concept (for e.g., natural ventilation is not very straightforward or easy to simulate within the whole building energy analysis tools). Another way to support the modeling process is by making available typical input files for technologies/systems that cannot be directly simulated. This can be done either by manufacturers/vendors (as in the case of simulation of GSHP in eQuest) or by organizations/developers (Underfloor systems implementation in eQuest indirectly and directly in EnergyPlus).

As the WBCSD case study shows, in spite of these shortcomings in the tools, the results from the tools, with appropriate quality control in place, give a good estimation of the energy consumption and savings from energy efficiency technologies.

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NOMENCLATURE

ACH – Air changes per hour

CDD – Cooling degree days

COP – Coefficient of performance

EEB – Energy Efficiency in Buildings

GSHP – Ground source heat pump

HDD – Heating degree days

HVAC – Heating, Ventilation, and Air-conditioning

HWHP – Hot water Heat Pump

NV – Natural ventilation

PV – Photovoltaics

R – Resistance (h-ft^2-F/Btu)

SC – Shading coefficient

SEER – Seasonal energy efficiency ratio

SHGC – Solar heat gain coefficient

SHW – Solar hot water

TMY – Typical meteorological year

U – Conductance (Btu/h-ft^2-F)

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