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Upgrading the Design of an Existing Residential Unit to Net-Zero Energy Level through Computational Performance Modelling

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ABSTRACT: *This paper presents energy design process of upgrading an existing residential unit located in Pittsburgh, Pennsylvania (PA), U.S.A. to net-zero energy level through the use of Energy Gauge[™] software. Computational models were developed and necessary simulations were performed to quantify energy related aspects of passive design measures, such as improving thermal resistance and airtightness of building envelope and design of fixed shading devices in the form of overhangs. Energy simulations were also performed to reveal performance improvements due to active design features of sustainable home technologies including a water-to-water ground source heat pump for space heating and cooling, an energy recovery ventilator for outdoor air supply, compact fluorescent light bulbs for artificial lighting, Energy Star[™] certified domestic appliances, a high-efficiency instantaneous hot water system backed up with a closed loop flat plate solar collector, and a roof-mounted photovoltaic array for on-site electricity generation. Findings of the study are presented by comparative performance assessments which are based on disaggregated energy use intensity (EUI) levels as well as rating scores of U.S. based green building standards and home certification schemes.*

Keywords: *net-zero energy buildings, computational modelling, energy simulation*

1. INTRODUCTION

A net-zero energy building is defined by [1] as a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies (e.g., solar thermal and solar photovoltaic systems). This definition implies that space conditioning energy requirements and electrical power demand of net-zero energy buildings are significantly reduced to a level that can be met on an annual basis from renewable energy sources. Pertinent literature [2,3] clearly indicates that achieving net-zero energy level can only be made possible by utilization of solar thermal and solar photovoltaic technologies and a thermally resistant and airtight building envelope coupled with high efficiency heating ventilating and air-conditioning (HVAC) systems as well as domestic home appliances, hot water generation and lighting systems. It is so evident that combination of different building systems and design strategies to achieve energy efficient design (which is capable of generating on-site renewable energy) requires extensive use of whole-building and dynamic energy simulation tools. Therefore, informed design decisions for net-zero energy buildings can only be made possible by the help of quantified feedbacks provided by such tools.

Process of upgrading the design of an existing residential unit to net-zero energy level by the help of computational building analysis and modelling tools is summarized in this paper. Main objective here is to demonstrate technical feasibility of designing a net-zero energy home under predominantly cold climate by using state of the art building technologies and environmental systems. Basic approach in achieving this objective is to develop computational models of current state of the residential unit (referred as Base Case) and its upgraded alternative (referred as Zero Energy Case) by the use of Energy Gauge [4] software and to conduct comparative assessments on the results of simulations performed for these two building models. Performance metrics are specified as disaggregated energy use intensity (EUI) levels by end-uses (kWh/m² of useable floor area) as well as rating scores of U.S. based green building standards (National Green Building Standards) and home certification schemes (LEED for Homes and Home Energy Rating System – HERS). Analyzed building case is an example of a townhouse unit which is part of a recent urban development project that took place in 2009 for the uptown area of Pittsburgh City, PA. This is a three bedroom and a three storey residential unit with a total useable floor area of 130 m² and a total conditioned volume of 593.2 m³ (Fig. 1). Long axis of the unit is facing east-west orientations. There is no basement and attic space is unoccupied and unconditioned.



Figure 1: 3D view of the building case with floor plans Source: RDC Design Documents [5]

Accepted definition of a zero energy building throughout this study is net-zero “site” energy building as explained by [1] which stated that annual energy balance of such a building is counted at its site without considering conversion factors from site to source energy sources. Surplus electricity generated by on-site solar power systems is assumed to be instantaneously transferred to city grid by the use of net-metering.

2. CLIMATE ANALYSIS AND GENERATION OF DESIGN GUIDELINES FOR UPGRADING

Building case of this study is located in Pittsburgh, PA, U.S.A. (40.35°N, 79.92°W). Weather data for this location is obtained from EnergyPlus Weather Database [6] of U.S. Department of Energy and loaded to a stand-alone climate analysis and design support tool known as Climate Consultant 4.0 [7]. This tool is used not only to summarize and interpret building’s climate and location but also to generate a list of specific design guidelines for improving energy efficiency. Climate of Pittsburgh is heating dominated and classified as mixed-humid/moist-continental type with warm summers and cold winters. Majority of the time in a year outside dry-bulb temperatures fall below the comfort band of 21 to 24°C (with an annual average of 11.17°C). Wet-bulb temperatures range between -5 to 20°C (with an annual average RH of 71.16%). Heating Degree Days (HDD) and Cooling Degree Days (CDD) based on 18°C are calculated as 5240 and 785, respectively. Climate categorization is 5A according to IECC 2006 (International Energy Conservation Code) which was accepted as a reference for code compliance requirements of Pittsburgh City. Design guidelines generated by Climate Consultant 4.0 and followed throughout this study are listed below:

- Guideline # 3: Lowering indoor comfort temperatures at night and during times of no occupancy
- Guideline # 4: Applying extra insulation to building envelope (super insulation)
- Guideline # 5: Carefully sealing building to minimize infiltration and eliminate drafts (House wrap, weather stripping, tight windows)
- Guideline # 11: Using heat gains from equipment, lights, and occupants to reduce heating needs by air-tight and well-insulated building envelope
- Guideline # 20: Providing double/triple-pane high performance (Low-E coated) glazing on west, north and east but clear on south for maximum passive solar gain
- Guideline # 37: Using window overhangs (designed for the latitude of the building’s location)
- Guideline # 63: Using low-mass and tightly sealed envelope to provide rapid morning heat build-up
- Guideline # 15: Using high efficiency central heating system (at least Energy Star[™] rated)

3. DESIGN PARAMETERS ASSUMED FOR COMPUTATIONAL MODELS

Below are given detailed explanations of building design parameters assumed for computational models of Base Case and Zero Energy Case developed by Energy Gauge software which is based on whole-building, dynamic and hourly simulation engine of DOE-2.

3.1 Opaque Envelope Assemblies

Opaque envelope assemblies of the building case include external wall, slab-on-grade floor, ceiling under attic space, roof, and external doors. Exterior wall construction of Base Case model is assumed as R-23 wood frame walls with R-19 fiber-glass (FG) batt insulation (between 5.08x15.24cm wood studs – 40.64cm OC) sheathed in 1.27cm of OSB on the outside. External siding is brick veneer and inside finish is a dry wall system of gypsum wall board (GWB). Zero Energy Case model has advanced wall system composed of R-39.9 structural insulated panels (SIP) (R-control SIPs). Exterior siding is chosen as fiber cement panels protected by a rain screen. Interior finish is GWB. SIP wall system has no thermal bridging due to framing. As the thermal boundary of the envelope excludes attic space, ceiling assembly separating indoor spaces from attic above becomes critical

in thermal design of the building. Base Case model of this study has R-39 wood joist ceilings with R-38 FG batt insulation (between 5.08x15.24cm wood studs – 40.64cm OC) with a thickness of 30.48cm sheated in 1.27cm of OSB on the attic side. Inside finish is GWB. Zero Energy Case model assumes the same constructional layers for the ceilings as those of Base Case except for FG Batt insulation which has a thickness of 48.26cm (R-60 ceiling insulation) (Table 1).

Table 1: Comparison of opaque envelope assemblies of the thermal boundary Source: Energy Gauge Software

Type of Assembly	BASE CASE MODEL			ZERO ENERGY CASE MODEL		
	U-factor* (W/m ² K)	R-factor (m ² K/W)	Thickness (cm)	U-factor (W/m ² K)	R-factor (m ² K/W)	Thickness (cm)
Exterior Wall	0.25	4.00	29.82	0.13	7.70	28.10
Ceiling Under Attic	0.14	7.14	33.02	0.09	11.11	50.8
Slab-on-Grade Floor	F-factor = 0.767		28.57	F-factor = 0.767		28.57
Exterior Door	0.35	2.85	2	0.20	5	5

*U-factors are not area-weighted (i.e., Framing factors are not taken into account during calculations)

Both computational models have slab-on-grade floors composed of a concrete slab, expanded polystyrene (XPS) layer, and OSB sub-floor underneath carpeting. Base Case model has a typical R-10 (1.27cm of Expanded Polystyrene Insulation) perimeter insulation with a depth of 61cm. Zero Energy Case has both 61cm perimeter insulation and 121cm of horizontal insulation. Both models also have similar roof assemblies which composed of wooden structural framing, decking, waterproofing and finished with asphalt shingles. The only difference is that Zero Energy Case has radiant barrier system applied to floor of attic space. U-factor of roof is not investigated due to the location of thermal boundary as mentioned above. External doors of Base Case are specified as 2cm solid wood doors without a storm door. Zero Energy Case has 5cm solid core flush external doors with storm doors to increase winter time U-factor given in Table 1 above.

3.2 Windows and Local Shading Devices

Pertinent documents [5] about Base Case building state that windows should be double-hung and equipped with insulated glazing (double pane with Low-E coating) with vinyl frames. Window selection process for the Zero Energy Case is carried out using window selection tool provided by Efficient Windows Collaborative [8] which listed certified window types according to user specified criteria. In this study, window selection criterion was to select highly insulated frames and a glazing that would result in high solar gain yet enough resistance to excessive heat losses during times of low or no solar radiation.

Table 2: Comparison of window design parameters Source: Energy Gauge Software

Window Design Parameters	BASE CASEMODEL	ZERO ENERGY CASEMODEL
U-factor (W/m ² K)	1.98	1.02
SHGC (-)	0.40	0.40
Visible Transmittance (-)	0.50	0.50
Type of Frame (-)	Vinyl	Insulated Vinyl
North Facing Area (m ²)	6.12	3.41 (44% decrease)
East Facing Area (m ²)	8.34	11.56 (38% increase)
West Facing Area (m ²)	3.25	4.55 (40% increase)

All window types offered by window selection tool are Energy Star qualified and National Fenestration Rating Council (NFRC) certified. Selected window type is labelled as Window 33 which was defined as a triple-glazed with high solar gain Low-E. Argon is the mid-pane gas and frames are insulated vinyl (Table 2). Parametric studies are conducted on window sizes to achieve optimum performance within the limitations of existing architectural design and space limitations. Due to limited window size options, such a study was not found to be effective in providing considerable reductions in annual total energy use. For optimum achievable performance north facing window sizes are reduced by 44%, east and west facing windows were increased by 38% and 40%, respectively.. No windows are located at south facing wall which is a shared blind wall. Optimum dimensions of local shading devices applied in the form of overhangs to east and west facing windows are derived from a web-based tool (Sustainable by Design) [9] which accepts input data for window dimensions, orientations, longitude and latitude of the building, together with date and time of analysis (chosen as noon time of summer solstice of Northern hemisphere). The outputs of shading design tool are near optimum overhang design data (depth, width, and height above windows). These outputs are transferred to Energy Gauge so that all of east and west facing windows of Zero Energy Case model have overhangs with depth of 76.2cm and separation (vertical distance of the shading device from the upper frame of window) of 60.9cm.

3.3 Infiltration and Ventilation

Infiltration rates of computational models are specified based on [10] which compares air tightness of conventional wood frame construction and SIP wall systems. Base Case model assumes an infiltration rate of 5.83 air changes per hour (ACH) at 50Pa pressure difference ($ACH_{50}=5.83$). Whereas, Zero Energy Case model has ACH of 1.8 at 50Pa delta pressure ($ACH_{50}=1.8$). Outdoor air supply rate of Base Case for ventilation is based on the requirement of $0.0078\text{m}^3/\text{s}$ per occupant given by design documents [5]. Base Case model was a three bedroom building with an estimated total occupancy of 4 people maximum. Therefore, total supply ventilation rate is calculated as $0.0078 \times 4 = 0.0312\text{m}^3/\text{s}$. Zero Energy Case was assumed to be equipped with an energy recovery ventilator (ERV) system selected from certified product list of Home Ventilating Institute (HVI) [11]. So as to meet similar ventilation requirement mentioned above, this equipment has a gross air supply and exhaust of 0.0354 and $0.0396\text{m}^3/\text{s}$ at 50Pa pressure, respectively. Energy Gauge modelling inputs for ventilation power and sensible ERV efficiency are specified as 95W and 77%, respectively.

3.4 Domestic Appliances and Lights

Domestic appliances of clothes-washer, dryer, range, refrigerator, and a dishwasher are specified for Base Case model. Default efficiency rates (of Energy Gauge) and default operational schedules (of IECC 2006) are assumed for domestic appliances of Base Case model. On the other hand, Zero Energy Case assumes high performance appliances (selected from Energy Star rated product lists) with increased energy factors (except for dryer and range equipment). Modified Energy Factor of clothes washer is selected as 2.55 and a high efficiency dishwasher is assumed with an Energy Factor (EF) of 0.92. Energy consumption of the refrigerator is reduced from 775kWh/year to 517kWh/year with necessary efficiency improvements. Base Case Model is equipped with 20 artificial lighting fixtures and 10 of them are assumed to be compact fluorescent light bulbs (50% CFL ratio). However, Zero Energy Case has 20 CFL bulbs out of 20 artificial lighting fixtures (100% CFL ratio).

3.5 Hot Water System and Solar Collectors

Base Case model is assumed to be equipped with a tankless hot water heater operating on natural gas. Hot water usage of the household is taken as 227.1L (60 gallons) per day and set temperature is entered as 48.8°C . Such a water heating system achieves energy factor (EF) of 0.59 highest. On the other hand, Zero Energy Case model is equipped with an Environmental Protection Agency (EPA) and Energy Star certified whole-home tankless gas water heater with an improved EF factor of 0.98 due to the fact that this equipment uses an advanced heating technology (condensing heat exchangers and built-in air and gas pressure sensors for optimum and stable combustion). Hot water system of Zero Energy Case is backed up by a flat plate solar collector system which was a closed loop, anti freeze (pressurized glycol) and indirect forced circulation type (circulation pump is powered by PV generated electricity). Solar hot water system has two flat plate collectors ($187 \times 115\text{cm}$) with a total area of 4.29m^2 . Collector tilt and azimuth are 59° (North-East) and 90° (East), respectively. Storage tank of this system has 303L volume with a surface area of 2.32m^2 .

3.6 Heating and Cooling System

According to design documents [5], Base Case model is assumed to be heated and cooled by a central air-based system (using a natural gas furnace and an electric chiller) (Table 3). A ground source heat pump (GSHP) with a vertical closed loop heat exchanger is modelled for Zero Energy Case model. There is no combustion unit in this system instead a refrigerant and a compressor is used for both heating and cooling depending on the direction of refrigeration cycle. The required equipment is selected from Air Conditioning, Heating and Refrigeration Institute's (AHRI) listings under the title of water-to-air and brine-to-air heat pumps (Table 3). Supply and return ducts of the system as well as Air Handling Units (AHU) are assumed to be located inside the thermal boundary of the building envelope for Zero Energy Case. However, Base Case model assumes that ducts are located in the attic space (outside of the thermal boundary).

Table 3: Comparison of HVAC system design parameters Source: Energy Gauge Software

HVAC Design Parameters	BASE CASE MODEL	ZERO ENERGY CASE MODEL
Heating System Capacity	11.95kW	4.75kW
Heating AFUE (Annual Fuel Utilization Efficiency)	0.95	0.98
Cooling System Capacity	6.35kW	6.62kW
Cooling SEER (Seasonal Energy Efficiency Ratio)	14.5	18.0
Cooling Coil Air Flow Rate	$0.31\text{m}^3/\text{s}$	$0.16\text{m}^3/\text{s}$

3.7 Temperature Schedules

HVAC systems of Base Case model follow single set-points for heating and cooling (20°C heating and 25.5°C cooling) which are kept constant throughout weekdays and weekends. As can be seen from Fig.2 below, Zero Energy Case has thermostat set-points (during occupancy) and thermostat set-backs (during away hours – no occupancy) varied throughout the day for heating and cooling.

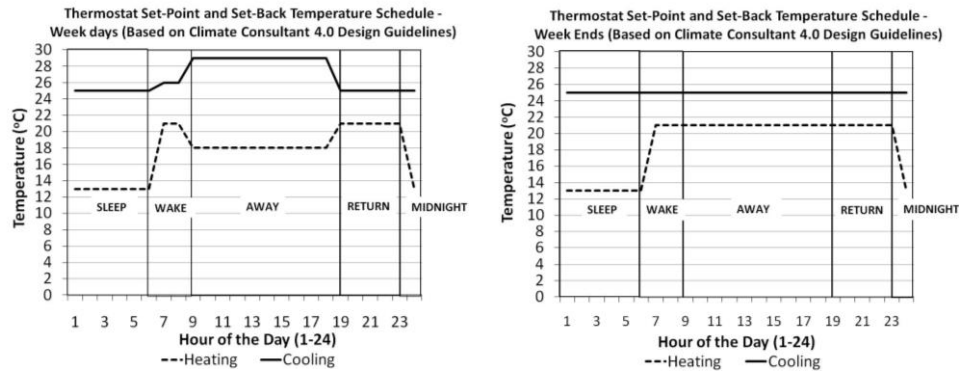


Figure 2: Thermostat set-point and set-back temperatures of Zero Energy Case

3.8 Photovoltaic System

Only Zero Energy Case incorporates a solar power system in the form of roof-mounted photovoltaic (PV) arrays. PV modules of this system are specified as hybrid mono-crystalline silicon type (surrounded by ultra-thin amorphous silicon layers) which has relatively more power per unit module area. The module efficiency is 16.7% with a cell efficiency of 18.9% and a maximum power out of 210W per PV module. Analysis of building's roof shape, slope, possible areas and orientations reveals that a total of 42 PV modules (158cmx80cm) with a total area of 52.9m² can be mounted on 78.13m² roof area (with 70% area efficiency). Cumulative PV array power output is calculated as 8.82kW. Three different inverters (0.88 efficiency) with a total power output of 7.14kW are specified to convert PV generated DC current to useable AC current.

4. RESULTS OF ENERGY PERFORMANCE SIMULATIONS

According to simulation results obtained from Energy Gauge software, total annual Energy Use Intensity (EUI) level of Base Case Model was predicted to be 185kWh/m² of useable floor area. All the upgrading measures applied to Zero Energy Case model resulted in an annual EUI of 58kWh/m² (68% energy savings). Fig.1 given below shows disaggregated EUI levels by different end-use categories. Highest reduction was achieved in space heating energy consumption (84.5kWh/m² reduction with respect to Base Case). Smallest amount of energy saving was observed for space cooling category (only 1.3kWh/m² annually – 1% of total reduction), this was followed by domestic appliances category with an annual reduction of 2.3kWh/m² – 1.8% of total reduction). PV generated energy was not taken into account during EUI analysis given above.

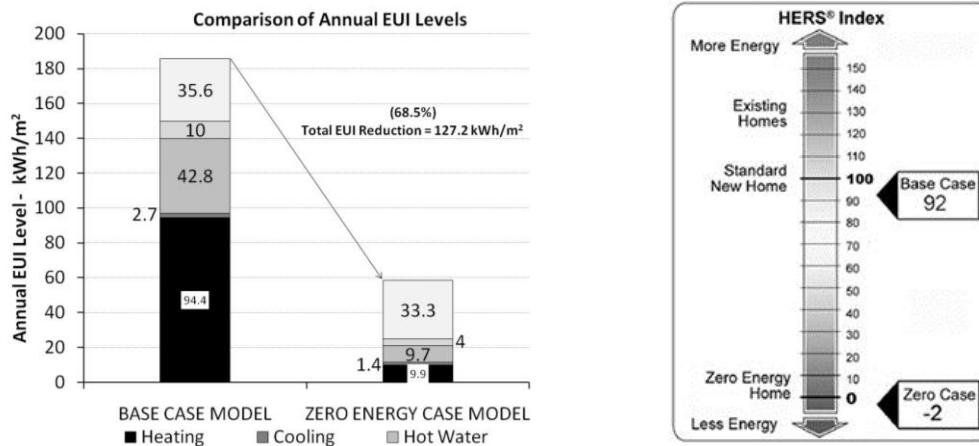


Figure 3: Comparison of disaggregated annual EUI levels by end-uses and HERS index points

Simulation results revealed that PV system of Zero Energy Case produced 7,666kWh of electricity annually. It was also found that total energy consumption of Zero Energy Case was not more than 7,573kWh. Such an annual energy balance clearly indicated that all energy requirements of Zero Energy Case were offset by on-site renewable systems (with a surplus electricity of 93kWh sold to the city grid each year). Calculation of HERS index points showed that Base Case model could only achieve HERS 92 (corresponding to 8% reduction of annual energy costs with respect to IECC 2006 reference home). Performance of Zero Energy Case was associated with HERS -2 (corresponding to 102% reduction) (Fig.3) where HERS 0 indicating net-zero energy level. According to National Green Building Standards [12], Base Case building would not get any qualification with 8% reduction from IECC 2006 reference home. However, with over 100% energy cost reductions from

reference home, Zero Energy case building would be qualified to “Emerald” category (which required at least 60% improvement). When energy performance levels of building cases were evaluated from the perspective of U.S. Green Building Council’s LEED (Leadership in Energy and Environmental Design) Homes rating system, it was seen that Base Case would not achieve any LEED credits from Energy and Atmosphere (EA) category 1 (Optimization of Energy Performance). On the other hand, Zero Energy Case would earn a total of 34 LEED for Homes EA-1 credits. According to Energy Smart Home Scale (E-Scale) developed by the U.S. Department of Energy [13], Zero Energy case building would result in annual energy savings of \$2,335 relative to a typical existing home. Furthermore, if every home built between 2010 and 2030 achieved such an energy performance level it would be equivalent of removing or not building 264 500-megawatt power plants in the U.S.

5. DISCUSSION OF FINDINGS

Without taking into account PV generated electricity, predicted annual energy performance of Zero Energy Case was about 58kWh/m² which is 58.1% lower than EUI of current residential usage as stated by [14] (137.9kWh/m²). However, Zero Energy Case had 27.5% higher energy consumption compared to CEPHEUS (Cost Efficient Passive Houses as European Standards) [15] standard home which consumed only 42.0kWh/m² energy annually. It was found that such a difference was mainly due to increased hot water consumption and home appliance usage associated with the U.S. households. Performance of Zero Energy Case fell into the very first category of home energy performance classification provided by [16]. This first category included EUI levels from 0 to 64.56kWh/m² and it was stated in [15] that for building of this category small energy savings were possible, they had tight and well insulated shells and highly efficient mechanical systems and appliances. This performance definition was totally reflecting the design of Zero Energy case presented in this study. Furthermore, [1] states that net-zero energy buildings usually provide energy savings in the range of 25% to 68% compared to conventional buildings (that are minimum energy-code compliant). Findings of current study was also in parallel with this statement since Zero Energy Case model showed energy savings up to 68% compared to an actual design case and savings up to 58.1% with respect to current residential energy usage.

6. CONCLUSION

This paper reveals that a number of building energy technologies with their current state of technical development can be used in an integrated manner for upgrading an existing residential unit (designed to be code compliant under a heating dominated climate) to net-zero energy level. As indicated by simulation results, significant energy saving impacts can only be achieved by upgrading space heating and cooling systems by keeping existing ducting network and substituting supply side components with ground source heat pumps instead of using natural gas furnaces or electric chillers. Although hindered by cost effectiveness issues, solar power generation systems (PV systems) pose no considerable technical barriers against integration to existing roof constructions (as long as changes in structural system loads are considered). Another conclusion that can be drawn from simulation results presented in this study is that at situations where upgrading external envelope is constrained by site-specific constructional limitations, highest priority should be given to upgrading glazing properties of vertical fenestrations. It is also concluded that for residential buildings already designed to meet pertinent code requirements (e.g. IECC 2006), potentials of achieving considerable energy savings are highly limited for domestic home appliances and lighting equipment which shows almost no technical adaptation problems in terms zero-energy upgrading.

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