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WHOLE-BUILDING PERFORMANCE SIMULATION OF A LOW-ENERGY RESIDENCE WITH AN UNCONVENTIONAL HVAC SYSTEM

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ABSTRACT

This paper presents an analysis of whole-building performance modelling and simulation process of a low-energy single-family detached residence located in Northeast U.S. A total of six design alternatives are modelled with EnergyPlus to predict relative performance improvements associated with a diverse set of energy efficiency measures of both building envelope assemblies and unconventional HVAC systems with inclusion of on-site renewable energy technologies. Simulation results indicate 29.3% energy cost savings (with respect to ASHRAE 90.1 2004 Standard Model) achieved through envelope efficiency measures only and 49.1% savings through coupling with a complex HVAC configuration and renewable energy systems.

INTRODUCTION

According to current statistics (U.S. DOE, 2010), residential buildings in the U.S. are responsible for 22% (6.2×10^{12} kWh) of primary energy demand per year. 68.8% of this demand is to generate electricity for space cooling, ventilation, lighting and household appliances, which accounts for about 36% of national electricity demand. Residential sector uses 20.8% of annual natural gas production (23.4 Quads) for space heating and domestic hot water generation. Reduction of energy intensity of residential buildings started with passive solar homes movement of 1960s. It then evolved to super-insulated, highly airtight envelope designs. Technological advancements in residential HVAC systems and small-scale renewable energy technologies further led to potentially net-zero energy homes of today. Contemporary low energy residential buildings combine passive and active solar features with highly insulated and weatherized envelopes coupled with high efficiency domestic appliances, and lighting systems to minimize space heating, cooling and household electrical loads (*demand side efficiency measures*) (Parker, 2009 and Malhotra et al., 2010). Overall building load minimization paves the way to significant reductions of energy use intensities when such loads are managed by optimally controlled, high-performance and mixed mode HVAC systems coupled with air-based heat recovery equipments and ground source heat exchangers (*supply side efficiency measures*). Moreover, utilization of grid-tied building integrated photovoltaic systems together with hot water systems backed up with solar thermal collectors can shift net energy balance to potentially zero level on an annual basis (*on-site renewable energy measures*). The complex and highly integrated nature of the above mentioned efficiency strategies and related technologies pose considerable challenges for analysing and evaluating the building energy performance with simulation-based assessment techniques. For instance, Brahme et al., 2009 discussed capabilities of three whole-building energy simulation tools (eQUEST, EnergyPlus, TRNSYS) to simulate a number of zero energy building technologies common to single-family residences in Southeast U.S. It was claimed that current simulation tools are not effectively supporting passive design strategies and unconventional HVAC configurations. Literature indicates the necessity of using dynamic, and integrated whole-building energy simulation methods, which require coupling multiple modelling tools for majority of the cases. For instance, Brahme et al., 2008 conducted a study on performance-based design process of a low-energy single-family residence in Northeast U.S. involving programs of RetScreen for electricity and solar thermal energy production analysis, eQUEST for envelope, internal load and system analyses, and Trane Trace 700 for equipment sizing.

This paper presents whole-building performance simulation of a low-energy residence with an unconventional HVAC system. Emphasis is given to full exploitation of integrative simulation capabilities offered by EnergyPlus program without recourse to other simulation tools. Comparative evaluations of simulation results are also presented.

METHODOLOGY

In order to form a basis for energy performance comparison of possible design alternatives, a baseline model (referred as ASHRAE Baseline Model) is first established. Since the residential building project under consideration was already registered as a low-rise commercial building type for Leadership in Energy and Environmental Design-New Construction (LEED-NC) rating calculations, the baseline model development is in accordance with *Performance*

Rating Method described in APPENDIX G of ASHRAE Standard 90.1-2004 (ASHRAE, 2004). Proposed Design Model is determined by comparisons of annual energy use intensities (EUI) as well as calculations of percentage improvements over the ASHRAE Baseline in terms of annual energy cost and corresponding LEED-NC credit points. The Proposed Design Model is disaggregated into four sub-models for analysing the effects of demand side and supply side efficiency measures on the overall energy performance as well as contributions from renewable energy systems (Table 1). An energy effectiveness scale is introduced to compare relative efficiency gains from each sub-model with respect to total efficiency gains from the Proposed Design Model.

Table 1 EnergyPlus model alternatives

MODEL	DEFINITION
ASHRAE Baseline Model	ASHRAE 90.1 2004 compliant model (for Climate Zone 4A)
Demand Side Efficiency Model (DSEM)	Thermally resistant and air-tight envelope (external walls and roof) + Insulated Glazing Units + Reduced Lighting Power Densities (LPD)
Supply Side Efficiency Model (SSEM)	Water-to-water geothermal heat pumps with ground source heat exchangers + Energy recovery ventilators (ERVs) + Demand Controlled Ventilation (DCV) + Whole house ventilation fan + Radiant floor heating system + Efficient hot water system
Renewable Energy Model (REM)	Solar thermal collectors + Solar power generation (PV) system
DSEM + SSEM	Sub-model excluding renewable energy features
Proposed Design Model (DSEM+SSEM +REM)	Final design model combining all efficiency sub-models

Case of this study is an unusually large (753.6 m^2) two-storey single-family residence (for a household of 6 people) with a conditioned basement floor, 5 bedrooms and 5 bathrooms together with a library and a double-volume lounge area for meetings (Figure 1). The short axis of the building is oriented 27^o east of North. Total window to wall area ratio (WWR) is 21.6%.

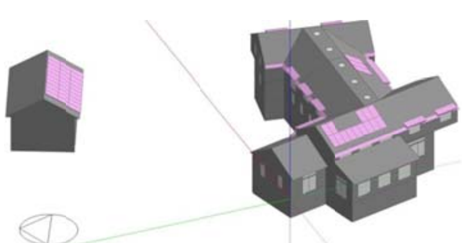

Figure 1 3D View of Proposed Design Model

The thermal envelope encloses all conditioned spaces which include the attic space and the basement. Location is New Jersey, U.S. with a heating dominated climate (HDD-18 ^{o}C and CDD-18 ^{o}C are 5060 and 1037) classified as Zone 4A according to ASHRAE 90.1 2004 standard.

SIMULATION MODEL DEVELOPMENT

Building Envelope

The baseline model represents a lightweight construction (steel joist external walls and floors, and a metal deck roof). Envelope assemblies of ASHRAE Baseline model are developed based on requirements provided in ASHRAE 90.1 standard with U-values in accordance with minimum allowances for Climate Zone 4A. Insulation levels are R-2.3 and R-2.6 for walls and roof (where insulation is entirely above deck), respectively. Instead of layer-by-layer definitions, basement walls are developed by an alternative method in EnergyPlus, which requires C-factor and height of the underground wall to define an entire construction assembly. Windows are equally distributed to all orientations with WWR of 21.6%, which is the same as the Proposed Design Model. Overhangs and other forms of shading devices are omitted and windows are assumed to be flushed with the external wall surface. The DSEM Model and its combinations are equipped with R-35 insulated concrete frame (ICF) (above and below grade) external walls composed of mineral fibre insert and concrete filled core between two layers of permanent thermal wall forms. Roof construction comprises wooden joists and deck with up to 20.32 cm of R-28 icynene spray insulation. Heated basement concrete slab is insulated with 7.62 cm of R-13 expanded polystyrene insulation (Table 2).

Table 2 Comparison of opaque envelope assemblies

ENVELOPE ASSEMBLY	ASHRAE BASELINE	DSEM ALTERNATIVE
	U-value (W/m^2K)	
External Walls	0.703	0.216
Basement Walls	C-6.473 (1)	0.216
Roof (Exposed)	0.360	0.182
Basement Floor	0.372	0.372
Note: (1) C-Factor (steady-state heat flow through unit basement wall area excluding heat resistance of soil/air film) is used as a simulation model input.		

Envelope infiltration rate is upgraded from 0.30 to 0.25 ACH for the DSEM Model having double-pane low-E with Argon gas (6-12-6 mm) windows instead of ASHRAE compliant windows (Table 3).

Table 3 Comparison of windows

WINDOW TYPE	U-VALUE (W/m^2K)	SHGC	V_T
ASHRAE Baseline	3.224	0.39	0.495
DSEM Alternative	1.793	0.27	0.220

Internal Gains and Exterior Lights

Reductions of interior lighting power densities (LPD) are reflected on all models alternatives except for ASHRAE Baseline model, and SSEM model (Table 4). However, equipment power densities (EPD) and exterior lighting levels (2.2 W/m^2 for 961 m^2 of illuminated wall surface) are kept constant between models with respect to Performance Rating Method. An astronomical clock control is assigned for automatically switching off exterior lights after sun-rise and vise versa. For all model alternatives, radiant fraction of heat gain from equipments is set to 0.5. Lighting fixture type is assumed to be suspended with radiant and visible fractions of 0.42 and 0.18, respectively. Total number people occupying the building is not more than 6 which is also the peak occupancy for living, dining, and circulation spaces, and reduced to its one third for bedroom spaces.

Table 4 Comparison of Internal Gains

SPACE USE TYPE	ASHRAE BASELINE		DESIGN ALTERNATIVES	
	LPD	EPD	LPD	EPD
	W/m^2			
Living Room (1)	12.0	8.07	3.1/1.6/ 2.4/1.8	Same as ASHRAE Baseline
Dining Room	12.0	8.07	4.5	
Circulation (1)	6.0	5.0	3.8/2.3	
Bedroom (1)	12.0	8.07	1.8/2.0	
Mechanical	3.0	5.0	3.1	
Note: (1) Has multiple rooms under the same space use type but with varying LPDs.				

Environmental Controls and Schedules

All building models have the same thermal zoning layout including 13 different thermal zones. Basement and 1st floor has living room spaces and 2nd floor has bedroom spaces linked with respective occupancy profiles given in Figure 2. Environmental control variables at thermal zone level are set-point and set-back temperatures for space heating and cooling, and minimum outside air ventilation rates all of which are kept constant throughout all simulation models (according to Performance Rating Method of ASHRAE 90.1 2004). Temperature-based control variables (dual-band thermostat settings) are derived from design specifications as 20 ^oC, and 23.33 ^oC for heating and cooling set-points with setbacks of 16.67 ^oC and 26.67 ^oC for heating and cooling modes, respectively. Minimum outdoor air ventilation rates are aggregated from discrete inputs (sum method) for minimum flow per floor area (0.3 L/sec-m^2) and per person (2.5 L/sec-person) in compliance with related ventilation standards (ASHRAE 62.1-2004 Ventilation for Acceptable Indoor Air Quality).

Operational schedules for HVAC system, equipment and lighting are coupled to occupancy schedules (Figure 2). HVAC system control is based on the set-point temperatures during occupied periods and set-back temperatures during unoccupied ones. Equipment and lighting densities are set to their maximums during occupied periods and reduced to 5% of maximum power (to account for parasitic losses) for the rest of the times.

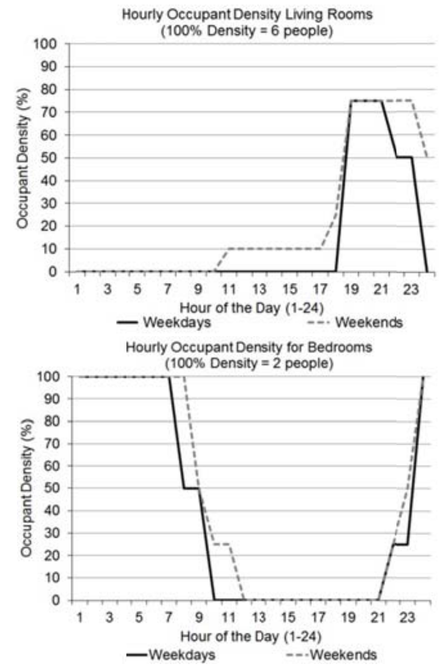

Figure 2 Occupancy schedules for living rooms (top) and bedrooms (bottom)

Domestic Hot Water (DHW) System

DHW system for model alternatives (excluding REM and Proposed Design Model) includes a 20500 W propane fired gas storage water heater (detached from the plant loop) with 0.284 m^3 (75 gallons) of storage tank. Energy factor (EF) of this heater is calculated as 0.477 for ASHRAE Baseline Model, whereas for SSEM and its combinations an EF of 0.580 is assumed (according to mechanical specifications). Each water use equipment (sinks, tubs, showers, dishwasher and clothes washer) is individually modelled in EnergyPlus with a total water flow rate of 0.50448x10^{-4} m^3/sec (corresponding to 84 gallons/day typical hot water usage of a U.S. family of six). Peak flow rates are modified with hourly fractional schedules of water use equipments. Delivery water temperature assumptions are 43.3 ^oC, and 50.0 ^oC for sinks/showers and washing machines, respectively. Water mains temperature is predicted by EnergyPlus based on a correlation method taking into account average outdoor dry-bulb temperature (12.2 ^oC) of the building's location and the maximum difference between average monthly outdoor air temperatures (22.9 ^oC).

Renewable Energy Systems

Both REM and Proposed Design Model alternatives incorporate a solar thermal collector system composed of three flat plate solar collectors (3x2.96

m^2 with a tilt and azimuth angles of 34^o and 139^o), a 0.45 m^3 (119 gal) storage tank, a 0.284 m^3 (75 gal) gas storage water heater, a collector loop pump, and a tempering valve (to avoid scalding temperatures at the faucets) (Figure 3). Solar collectors' perfomance data is derived from U.S. Solar Rating Certification Corporation's (SRCC) database already included into EnergyPlus input data sets. Solar thermal system is utilized as a backup to gas storage water heater and its operation is contolled by a differential thermostat (by sensing temperatures at Node A and B in Figure 3). Upper and lower thresholds of the differential thermostat is assumed as 10 ^oC and 2 ^oC, respectively. System overheating is avoided by a cut-off (Node D) temperature control (60 ^oC maximum) at the tank outlet, whereas freezing is prevented by re-circulation of hot water (generated by gas water heater) in the collector loop and controlled by temperature of one of the collector's outlet (Node C).

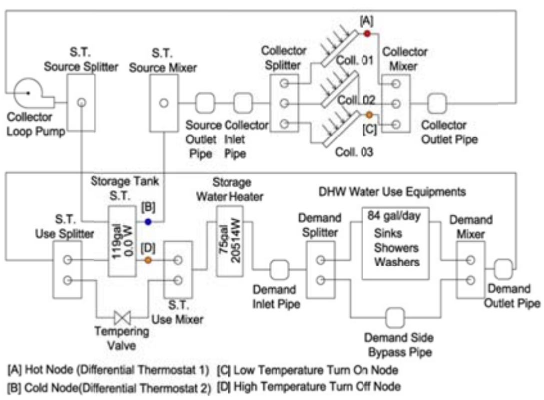

Figure 3 Schematic diagram of solar collector system

Solar electrical power generation system of REM and Proposed Design Model includes two different roof-mounted, grid-tied PV arrays comprising a total of 44 modules (specific power of 225 W at maximum power point - MPP) with a total DC rating of 9.90 kW_p (at STC). Solar cell technology is mono-crystalline silicon (c-Si). Tilt angle of all modules is 34^o, whereas azimuth angle of 30 modules is at 178^o and the remaining is at 212^o. Total active PV area is calculated as 54.6 m^2 based on single module performance data imported from certified Sandia PV dataset of EnergyPlus data library. A simple DC-AC inverter model with an efficiency of 0.89 is assumed for the entire PV system. PV modules are assumed to be decoupled (heat transfer integration mode is "Decoupled NOCT Conditions") from the building envelope where there exist no thermal interaction affecting solar cells' back-face temperatures. Due to current limitations of EnergyPlus, ancillary equipments of the PV system other than inverter are not modeled and it is assumed that system is always operating at MPP without mismatch losses.

HVAC Systems

As the building case is less than 3 floors with a total floor area smaller than 7000 m^2, HVAC system for ASHRAE Baseline Model, SSEM and REM models is assumed to be packaged single zone rooftop air conditioner with an electric heat pump (ASHRAE 90.1 2004 Appendix G System 4, PSZ-HP). HVAC system model is imported and adapted from a sample building model developed by the use of web-based EnergyPlus Example File Generator (U.S. DOE, 2011) program considering the same climate zone as well as Appendix G HVAC type. System fans (with efficiency of 0.60) are constant volume continuously operated during occupied hours and cycling to meet heating or cooling loads imposed by set-back temperatures during unoccupied periods. A night cycle availability manager is established in EnergyPlus forcing individual zone fans to start operation to meet setback loads with a tolerance of 1 ^oC. With respect to ASHRAE requirements, no economizer is modelled for Climate Zone 4A. Direct expansion (DX) cooling coil's COP is set to 3.0, and heating efficiency of electric heat pumps to 0.80. HVAC system components are auto-sized by EnergyPlus with sizing factors of 1.25 and 1.15 for heating and cooling, respectively. An all-electric HVAC system (PSZ-HP) is assumed for the baseline model considering the fact that HVAC system of the Proposed Design Model is also relying on an all-electric system without gas boilers on the plant side. Therefore, reductions due to variations of site-to-source conversion factors of utilized energy sources (reflected on energy cost and savings) between baseline and Proposed Design Models are avoided.

HVAC system modelled for SSEM, DSEM+SSEM, and Proposed Design Model includes a ground source heat pump (GSHP) and a heat exchanger-(GSHX), three air handling units (AHUs), three energy recovery ventilators (ERVs), a whole-house ventilation fan (WHVF), a demand controlled ventilation system (DCV), and a radiant floor heating system (RFHS).

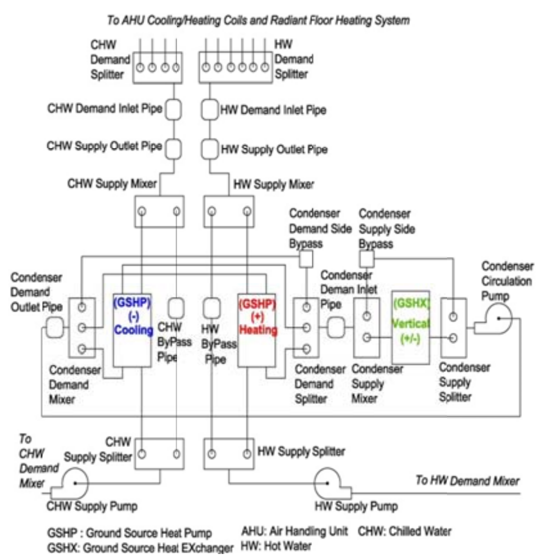

Figure 4 Schematic diagram of plant loop

HVAC system includes a water-to-water ground source heat pump connected to chilled water and hot water loops serving cooling and heating coils of AHUs as well as radiant floor heating system (Figure 4). GSHPs are circulating R22 refrigerant in the condenser loop, which includes a vertical ground source heat exchanger on the supply side. Since EnergyPlus has no functionality for auto-sizing the GSHX, it is assumed that a single bore hole with 0.1524 m diameter and 45.72 m lenght is capable of satisfying 1 ton (3517 W) of heating and cooling load of the building (Rafferty 2008). Therefore, GSHX is sized so as to handle pre-calculated GSHP capacity (Table 5). The plant loop pumps for hot water and chilled water are auto-sized by EnergyPlus with flow rates of 0.0024 and 0.0014 m^3/s, respectively.

HVAC topology is the same for SSEM, DSEM+SSEM, and Proposed Design Model. However, HVAC input parameters given here are representing only Proposed Design Model attributes. Assumptions for such input parameters are derived from manually calculated values based on design principles, values from EnergyPlus auto-sizing routines and from sample EnergyPlus models inputs.

Table 5 GSHX and GSHP system design parameters

PARAMETER		ATTRIBUTE
GSHX	Maximum Flow Rate (1)	0.0035 m^3/s
	Number of Bore Holes (2)	12
	Bore Hole Length (2)	45.72 m
	Bore Hole Radius (3)	0.0762 m
	Pipe Thickness (3)	0.0024 m
GSHP	Heating - Cooling Capacity(2)	41 kW and 28 kW
	Heating – Cooling COP (3)	2.36 and 4.10
Notes: (1) Autozised values (2) Manually calculated values (3) Sample model values		

Main air loop components are three AHUs serving each floor of the building. AHU 1 and 2 are operating under daytime schedules for living spaces of basement and 1st floor, respectively. AHU 3 is serving night time zones of 2nd floor (bedrooms). All AHU coils are auto-sized by EnergyPlus (Table 6).

Table 6 Air handling units design parameters

PARAMETER	AHU 1	AHU 2	AHU 3
Max Air Flow Rate (m^3/s)	0.70	0.93	0.77
Min Air Flow Rate (m^3/s)	0.09	0.12	0.07
Supply Fan Power (W)	938	1352	1275
Heating Coil Hot Water Maximum Flow Rate (l/s)	0.54	0.60	0.47
Cooling Coil Chilled Water Maximum Flow Rate (l/s)	0.39	0.64	0.38

System fans are variable volume draw-through type with total fan efficiencies of 0.7. Night-cycle availability managers are defined for each AHU so as to avoid unnecessary system operation during unoccupied hours. Minimum supply air temperatures of 20 °C and 12 °C for heating and cooling are assumed with maximums of 30 °C and 18 °C, respectively. System set-point temperatures are sensed by AHU heating coil outlet (heating) and AHU supply fan outlet or mixed air node (cooling). Energy recovery ventilators (ERVs) are connected in series to each outdoor air mixing box of the three AHUs. 300 W ERVs are flat-plate type and recover both sensible and latent energy in the return air loops with sensible and latent effectiveness of 0.76 and 0.68 at maximum heating air flow. Capacity of each ERV equipment is optimized so that average air flow rate of each AHU can stay between 50% and 130% of nominal supply air flow rate of an integrated ERV equipment for maximum heat recovery. ERV operations are in tandem with AHU availability schedules and frost control is deployed with a threshold of 1.7 °C on supply outdoor air inlets for exhaust recirculation. In EnergyPlus there is no direct way of modelling a single whole house ventilation fan (WHVF) (for the Proposed Design Model) which assumes hybrid operation of HVAC system air loop under certain acceptable conditions for indoors and outside environment. Therefore, proposed 1118 W WHVF with maximum flow rate of 1.89 m^3/s is discretized into 6 individual zone ventilation objects (of exhaust type) which have varying flow rates (with a constant pressure rise of 414 Pa) and fan power ratings. Linear correlations are established between ventilated zone volume and corresponding flow rates. Zone ventilation objects (1st and 2nd floors) are then coupled with a hybrid ventilation availability manager controlling the alternating operation of respective AHUs with WHVF. The control logic is based on indoor and outdoor ambient conditions (Figure 5).

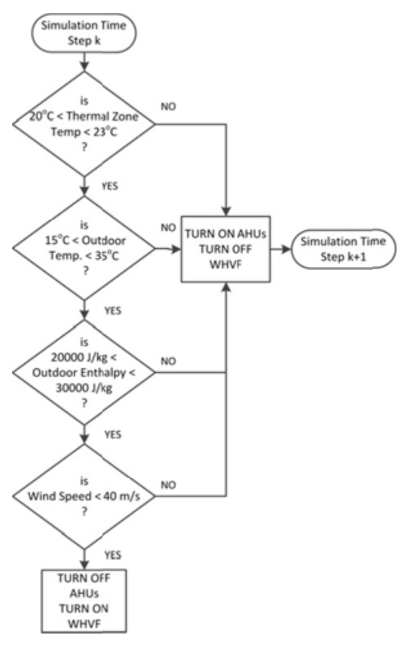

Figure 5 Control logic of WHVF

Outdoor air controllers of each AHU (using deterministic operational schedules for minimum flow rates per unit area and per person) are coupled with a demand controlled ventilation (DCV) system performing first order evaluations of carbon dioxide concentrations (CO_2) in pre-defined control zones. DCV objects of the mechanical ventilation controllers assume Indoor Air Quality Procedure (IAQP) for minimum outdoor airflow rate determination. At each simulation time step EnergyPlus evaluates the indoor CO_2 concentration levels generated by occupancy (with a rate of 3.82×10^{-8} m^3/s-W of metabolic activity) and modulates outdoor airflow rate to keep concentration levels below 900 ppm with the assumption that outside environment has a constant CO_2 source of 400 ppm. A CO_2 controller object is developed for a representative zone of each AHU under "Zone Control: Contaminant Controller" class in EnergyPlus. In addition to system fans, and WHVF, the building models (of all alternatives) include five 132 W exhaust fans with maximum exhaust rates of 0.059 m^3/s. Exhaust fan operation is coupled with hourly occupancy schedules of bathrooms and restrooms to model light-switch control system.

Radiant floor heating system is the water-side HVAC component and classified as zone type low temperature variable flow radiant object in EnergyPlus. This system consists of 7 radiant zones with embedded hydronic tubing (of 0.012 m inside diameter). EnergyPlus auto-sized tube spacing, total hydronic tubing length (in the range of 522 to 1127 m per zone) as well as maximum hot water flow rates (varying between 0.076 to 0.214 l/s per zone). Radiant system heating set point control type is specified as zone mean air temperature and assumed to be 4-5 ^{o}C (derived from manual generate and test routines for each zone) lower than room heating set-point with a throttling range of 2 ^{o}C. Special construction objects are created for radiant slabs with the positional indication of internal heat source in the ordered list of material assemblies. Specific building surfaces of radiant slabs are also identified and area weighted fractions are applied to hot water flow rates of radiant slabs consisting of multiple floor surfaces. RFHS is connected to plant side HVAC system through hot water demand splitter connected to GSHP on the supply side.

Energy Sources and Rates

Electricity and propane are the energy sources for all building models. Energy rates for residential buildings in New Jersey are used to calculate energy costs and associated savings. (Table 7).

Table 7 Energy sources and rates

ENERGY SOURCE	ENERGY UNIT	KWH CONVERSION	ENERGY RATE
Electricity	1 kWh	1 kWh	0.11 $/kWh
Propane	1 Gallon	27 kWh	1.4 $/gallon

SIMULATION RESULT ANALYSIS

Annual Energy Consumption and Cost Analysis

A comparison of annual site energy use intensities (EUI) (cumulative energy consumption normalized by floor area of 753.6 m^2) without the contribution of PV-generated electricity is given in Figure 6 below. The largest EUI reduction (36.8%) with respect to ASHRAE Baseline Model is observed for the Proposed Model including all possible efficiency measures discussed in this study. Deployment of demand side efficiency measures focused on building envelope alone can provide about 28.2% EUI reduction as opposed to 7.8% reduction achievable through incorporation of a complex (supply side) HVAC system without recourse to demand side measures.

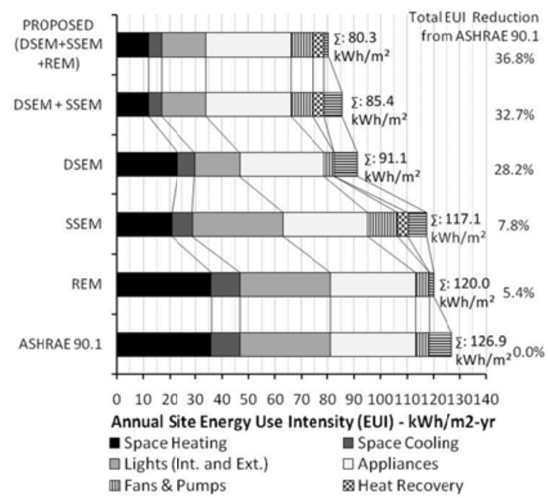

Figure 6 Analysis of energy use intensities

Coupling supply side and demand side measures (DSEM+SSEM) yields considerable reductions in space heating energy (48.4%) due to ground source heat exchange and ERVs. However, total efficiency gain (6.3%) is diminished due to increased fan and pump energy usage of the centralized HVAC system.

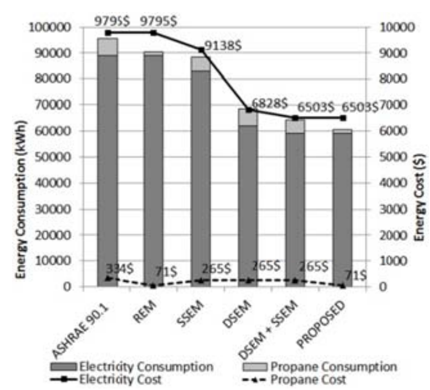

Figure 7 Analysis of energy consumption and cost

Unlike DSEM, SSEM alternative cannot provide a significant reduction in space cooling energy (26.9%

compared to ASHRAE 90.1) due to high internal heat gains from unchanged LPDs. EPDs are kept constant between altenatives and result in 32.07 kWh/m^2 of annual EUI with increasing percentages in end-use energy breakdowns as total EUI tends to decrease. Auxiliary system components (AHU fans, pumps and ERVs) of models equipped with advanced HVAC system are responsible for about 13 to 15.5% of total energy consumption. Baseline HVAC system (without pumps on the plant side and ERV equipment) includes auxiliary components contributing not more than 4% to total consumption. Majority of the energy is coming from electricity fuel where propane is used for water heating purposes (Figure 7). Energy cost for propane consumption can be decreased from $334 to $71 with solar thermal collectors coupled with high-efficiency water heaters. DSEM only has the potential of decreasing annual total electricity cost by a factor of 0.697. Furthermore, the Proposed Design Model achieves a reduction of 33.6% on annual electricity cost with a saving of $3292 per year. DSEM also provides a considerable amount of annual electricity cost reduction (30.2%) with a saving of 2967$.

Renewable Energy Systems Contribution

9.90 kW$_p$ solar PV system assumed for REM and Proposed Design Model yields approximately 12,912 kWh (17.1 kWh/m^2) of electricity on an annual basis. Such generation capacity is enough to cover 15% and 22% of total electricity demand of REM and Proposed Design model, respectively.

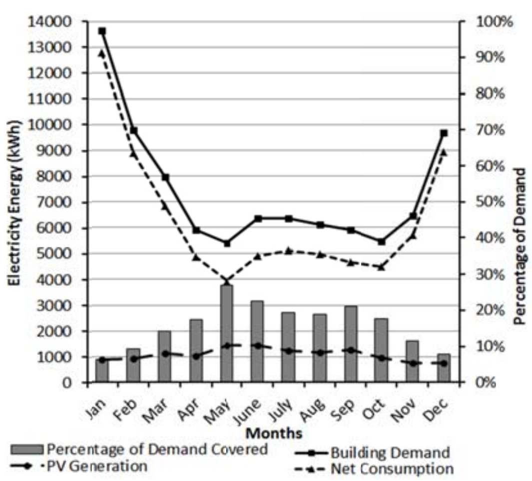

Figure 8 Proposed Design Model- Monthly electricity demand and generation

Increased PV generation (Figure 8) provides increased demand coverage in the range of 36% to 27% between May to September for the Proposed Design Model. Highest electricity generation is predicted for May (with relatively clear skies coinciding with milder ambient temperatures) with a peak of 1452.9 kWh covering 36% of monthly electricity demand of 3999 kWh. 8.88 m^2 solar thermal collector system generates 1388.6 kWh heat energy per year. When used as a backup to a high efficiency water heater, this on-site renewable energy system provides 78.6% reduction in water heating energy requirements. Annual air to air thermal energy recovery is about 701.3 and 6344.9 kWh for cooling and heating, respectively. Three 300W ERV equipments consume 3088.8 kWh electricity energy for such a recovery rate (annual overall resulting in a total system efficiency of 43.8%).

Energy Cost Savings and LEED-NC Credit Points

Comparisons of relative energy cost savings achieved with the Proposed Design Model with respect to ASHRAE 90.1 Baseline form the basis of credit point calculations for LEED NC EA Credit 1-Optimize Energy Performance section. Similarly, for EA Credit 2-On-Site Renewable section, positive contribution of renewable energy systems is calculated as shown in Table 8.

Table 8 Energy cost savings and PV contribution

MODEL	ENERGY COST SAVINGS WITH PV (%)	LEED EA CREDIT 1 AND 2 POINTS	% PV (%)
DSEM	29.3	6/0	0.0
SSEM	7.2	0/0	0.0
REM	16.6	2/3	14.4
DSEM +SSEM	33.2	7/0	0.0
PROPOSED	49.1	10/3	21.6
Percent saving = 100x(1-Alternative Cost/ASHRAE 90.1) Percent PV = PV generation/(Alternative + PV Generation)			

With the contribution of PV generated electricity, the Proposed Design Model achieves 49.1% of energy cost saving (corresponding to 50.2% of energy saving) and receives all possible LEED EA Credit points. Compared to baseline, DSEM+SSEM alternative without renewable energy systems can achieve 33.2% total energy cost savings. DSEM alone can achieve 29.3% savings before coupling with supply side efficiency measures. SSEM cannot pass the threshold of significant energy performance improvements for achieving LEED EA Credit 1 points. On-site renewables alone has the potential of collecting a total of 5 LEED EA points for both energy performance and on-site renewables. In order to facilitate comparisons of relative energy cost performance of alternative models based on a normalized effectiveness concept, an effectiveness scale (from 0.0 to 1.0) is developed (Figure 9) where energy cost saving of each model is divided by maximum achievable savings percentage among all possible model alternatives. Maximum energy cost saving percentage is 49.1% with Proposed Design Model. ASHRAE Baseline Model and Proposed Design Model are found at lower and upper bounds (0 to 1) of the energy cost effectiveness scale. SSEM has index point of 0.14, which lies close to lower limit, whereas DSEM model (0.59 point) covers almost 60% of all possible efficiency gains. Coupling DSEM with advanced HVAC can only increase index point by 0.08. REM alternative achieves 0.34 point by utilization of solar PV and thermal energy systems only.

Effectiveness Scale	Model Alternative/ Effectiveness Index	Total LEED EA Credit Points
0.0	ASHRAE 90.1/0.0	0
0.1	SSEM/0.14	0
0.2		
0.3	REM/0.34	5
0.4		
0.5	DSEM/0.59	6
0.6	DESM+SSEM/0.67	7
0.7		
0.8		
0.9		
1.0	PROPOSED DESIGN/1.0	13

Figure 9 Energy cost effectiveness scale

CONCLUSIONS

This paper evaluates whole-building energy performance of a relatively large single-family residence design equipped with state-of-the-art efficiency measures on the demand side and supply side energy flows together with contributions from on-site renewable energy technologies. Through energy simulations and comparative performance assessments of 6 different building models following conclusions are drawn:

- Considerable energy performance improvements (29.3% cost reduction) can be gained by giving highest priority to envelope-based demand side energy measures before incorporating unconventional HVAC system components. Coupling high-end HVAC systems with thermally resistive and air-tight envelopes becomes even more significant with 33.2% maximum energy cost reduction.
- On-site renewable energy systems (particularly solar electric power generation) can provide significant improvements of net-energy balance (49.1% energy cost reduction) and associated LEED-NC credit points collection from multiple sections of Energy and Atmosphere category (Credit 1 and Credit 2).
- Complex HVAC systems with centralized AHUs present inefficiencies and increased energy consumption for auxiliary system components (e.g., fans, pumps, ERVs) for residential buildings having relatively large volumes requiring diversified operational schedules. Under the climatic and geologic conditions of the investigated buildings case, cooling energy recovery through ventilation as well as using ground as heat sink provides marginal reductions in overall building energy performance.
- Combined system configuration and operational strategies of complex HVAC systems for low-energy residential buildings can be handled without recourse to multiple simulation tools by the use of integrated, simulation engines (i.e., EnergyPlus).
- Current whole-building performance simulation tools are not suited to provide effective support for modelling of hybrid HVAC systems (e.g., whole house ventilation fans alternating with central AHUs for fan-assisted ventilation for space cooling purposes).

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