Simulation approaches to smart solar communities

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Abstract

Community energy planning requires detailed consideration of trade-offs at the building and community energy system level. As a first step, the evaluation of district energy systems requires hourly or sub-hourly profiles of building consumption. Energy modelling is a time-consuming process so methodologies which streamline these efforts are beneficial in expediting solar community design. This paper proposes a three stage approach which includes early energy estimates, detailed energy models and economic optimization. To quickly build energy models, geometry is created using a SketchUp interface. Various modelling best practices and technologies are programmed using a scripting methodology with EnergyPlus.

1 Introduction

> "Far better an approximate answer to the right question, which is often vague, than the exact answer to the wrong question, which can always be made precise.
>
> – *John Tukey* "

Modelling a net-zero energy community presents several challenges: (i) various technologies require implementation and evaluation within a common methodology; (ii) building energy load profiles are required early in the design process to evaluate the potential for district energy systems; (iii) achieving net-zero energy is difficult at building heights larger than four stories (O'Brien et al. 2010), (iv) energy model creation is a time intensive process and is required for each building type and shape. Given that energy modelling a single building in detail can take 40 or more hours, modelling a community is a major undertaking.

However, economies of scale allow for integrative design at an unprecedented scale. At a community scale, mismatches between load and generation, as described by Salom et al. (2011), can be resolved using buffering and storage techniques. For example, in the near future there may be an opportunity where a community of net-generating buildings can potentially act like a grid node which can be throttled depending on demand. Net-generating communities could be a key technology in moving away from unwanted centralized generation.

This paper describes an energy modelling processes to model a smart net-zero energy community. A goal of the paper was to develop a methodology which streamlines the modelling process while allowing for further model resolution at later design stages. The community in question is a 70 acre site located in Southwestern Ontario. It is a mixed-use community with 2000 living units which includes semi-detached townhouses, mid-rise and high-rise apartments/condos. A primary objective is a mixed-use development where residents have work opportunities within the geographic constraints of the community. Thus a large portion

of the land is intended for commercial usage. The development is sufficiently dense that it requires a detailed engineering analysis to ensure that shading from adjacent buildings does not compromise community energy performance.

In previous research, Kämpf & Robinson (2007) used a simplified two-node RC thermal network based on calibration with a detailed ESP-r model for simulation energy flow in a community of buildings. O'Brien et al. (2010) used simplified models to calculate the impact of urban density on solar buildings. Kämpf (2009) explored optimization applied to community energy fluxes. Bucking et al. (2011) explored the significance of occupant energy consumption on a net-zero energy community. Hachem (2012) evaluated the potential of non-rectangular building shapes in solar communities. However, none of these methodologies are intended to expedite the energy modelling and optimization process. The next section presents the approaches used in this paper.

2   Method

This section describes the methodology used to model the community. Three distinct stages of modelling were required: (1) early estimates of annual energy mismatch, (2) detailed energy modelling, (3) energy and economic optimization. These approaches are described in the following subsections.

Stage 1: Early Energy Estimates

This stage approximates the mismatch of energy consumption to energy generation over an annual period. An outcome of this stage was to determine what the energy efficiency targets in building design are and the opportunity for renewable energy integration at a community scale. This information aids in determining the need for other technologies to satisfy the community energy balance.

Building energy consumption was determined from annual values of energy use intensity (EUI) for various building types using national averaged data (NRCan-OEE 2010). It is important to note that this data represents the average EUI of the existing building stock and not an energy efficient building design. Thus, some fraction of published averages based on modelling experience is more appropriate. An energy reduction target of 30-55% over best practices was set in the early stages of this project.

Renewable energy production estimates were performed using the K_T method proposed by Klein & Theilacker (1981). Estimates were made by calculating available surface areas for renewable energy generation such as photovoltaics on wall and roof surfaces. A fraction of usable surface area is specified to ensure PV generation is not overestimated.

This early modelling stage yields a minimal performance target to achieve a community energy balance. The next modelling step is the development of load profiles at hourly and sub-hourly timesteps.

Stage 2: Detailed Energy Modelling

The second stage of the modelling process was to create sub-hourly load profiles for the buildings in the community. This information is useful to evaluate the potential application of various technology and smart control strategies and needs to be emphasized early in the feasibility stage of the project.

A combination of tools were used to create load profiles for various buildings types: (i) OpenStudio (OS) for drawing geometry and window positions; (ii) Windows 7 for specifying glazing spectral properties (LBNL 2014); (iii) EnergyPlus for energy modelling and cost analy-

ses; (iv) a custom scripting process using exported OS text files to define HVAC, construction, renewable energy generation and control systems.

OpenStudio was selected over other tools due to its intuitive SketchUp interface, building component library for forming energy code compliant reference buildings, space types for defining zone functions and due to the scriptability of the OSM file format (NREL 2014). One disadvantage of using OS is that the tool does not function well with later text-file manipulations. For example, modelling specialized technologies in text files cannot be imported consistently back into OS. Since work in OS is unidirectional, having a scripting process to implement modelling best practices and technologies as a second stage eliminates repetitive text file manipulations.

For the community, a short-list of twenty technologies were considered in each building design. Technologies are only implemented if they are suitable for the building type in question. The modelling process requires EnergyPlus objects to be associated with each zone, envelope/glazing surface or centrally in the building. Since many technologies are not presently available within the OS interface, an energy modeller must resort to text file manipulations. Luckily, many of these manipulations can be automated for an arbitrary number of zones or surfaces using scripts. The time savings are significant and less error-prone than manual text-file manipulations.

Before starting the modelling process, some assumptions must be made on how the building will be used. At the early development stage, floor plans are typically unknown. However, floor area, building usage, and rough building geometry are known. The task of creating a floor plan from the above information is best left to an architect. Floor plans define the location and size of offices, living units, corridors, elevators and mechanical, electrical and storage rooms.

Figure 1 describes the modelling process for a hypothetical building which starts with a floor plan and creates a model ready for simulation and load-profile interpretation. The community load profile is created by combining the consumption profiles of each building.
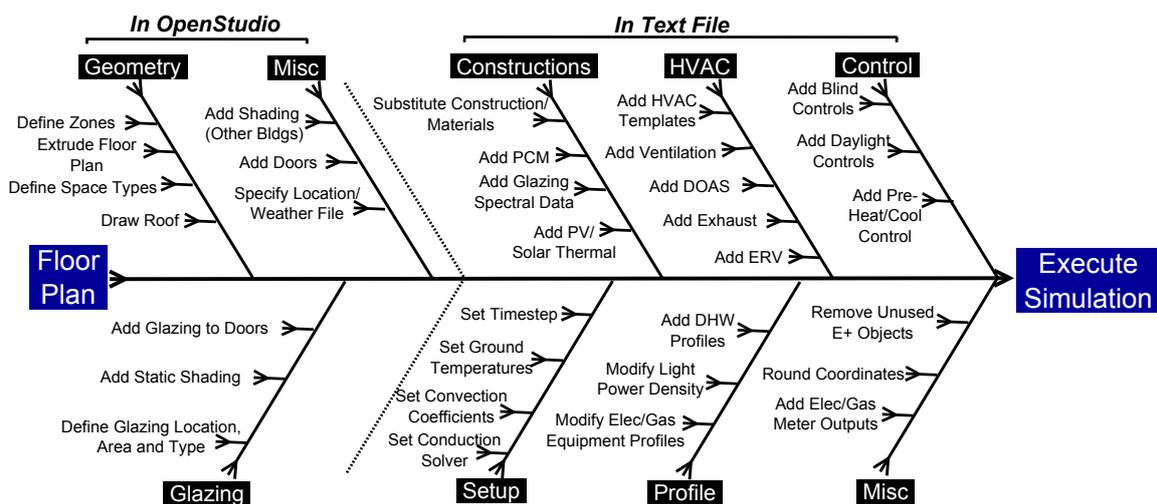

Figure 1: Methodology for building energy model creation

The modelling process in the OpenStudio SketchUp interface is as follows: (1) define spaces on the two-dimensional floor plan; (2) extrude the 2D floor plan vertically to the number of required floors. If basement floors are required, these are added to the extrusion and later moved within SketchUp to below grade (negative z-axis coordinates); (3) the *intersect spaces*

function in OS ensures that partition walls relate to each other and have adiabatic boundary conditions; (4) once interior partitions are created, window and glazing surfaces are defined. Windows can be defined using the OS script using a specified window-wall ratio (WWR), or manually drawn on each building surface; (5) define the space type of each OS space (e.g. classify corridors, mechanical rooms, elevators, living units, storage, etc.). Defining the space type associates the following information to each zone: (a) occupancy, (b) lighting power density, (c) electrical/gas equipment loads, (d) infiltration, (e) approximate ventilation demands. Select ASHRAE 90.1 as an energy standard when defining spaces types (ASHRAE 2011*b*). In this step, ensure that each space has a thermostat defined and ideal loads set as a mechanical system; (6) run the *convert spaces to thermal zones* function to convert OS spaces types to thermal zones. This is useful in cases where modellers want to explore the effect of combining smaller OS spaces into a larger thermal zone. Optionally, users can name spaces/zones manually within OS to reflect their function. For example, thermal zones which are corridors use this description in their name; (7) optionally, open this file in the OpenStudio tool and set the weather file and ensure all zones are set to ideal loads; (8) run this file in EnergyPlus and correct errors (if any) before proceeding to the next step.

The scripting process is a continuation of the modelling process defined in Figure 1. Scripting automates the process of adding or modifying EnergyPlus objects within the text file to implementing modelling best practices or various technologies, controls or mechanical systems. Scripts were written using the Python programming language.

The scripting process created both proposed designs and reference buildings. Developers want to know the incremental energy savings and subsequent economic payback of new technology. Thus, two models are required: (1) a reference building which defines present best practices, and (2) the proposed building which utilizes various technologies to further reduce energy demand. Reference buildings were defined by ASHRAE (2011*b*, 90.1). By determining incremental energy savings and associating an incremental cost for various technology, various economic metrics can be evaluated.

Tables 1 shows a short-list of modelling best practices and technologies modelled.

Table 1: Summary of modelling best practices and technologies implemented in scripts

ITEM	IMPLEMENTATION
HVACTemplates (5 systems)	Add central equipment. Add thermostats and terminal devices to each conditioned zone
Constructions	Substitute existing Construction and Material objects
Phase-Change Material	Add PCM to relevant Construction objects
Window 7 spectral data	Associate spectral data to each glazing object
PV on Exterior Surfaces	ID acceptable surfaces. Add PV objects. Build Inverter/Generator List
Dedicated OA Systems	Add DOAS to each applicable zone
Domestic Hot-Water	Add DHW loads to each applicable zone
Exhaust Ventilation	Add ventilation fan loads to each applicable zone
Window Shading & Control	Add controllable window shades to each applicable glazing surface
Daylighting	Add daylighting sensors and tie into window controls
Energy Recovery Units	Add ERVs to each applicable zone. Control using CO2 sensors
Air flow Networks	Add an airflow network between zones. Required for free cooling from actuated windows
Actuated Windows	Free cooling from operable windows. Requires air-flow networks
Cogeneration Plant	Combined heat and power plant

Heating, ventilation and air-conditioning (HVAC) systems were modelled in EnergyPlus using HVACTemplates. This approach greatly simplified the mechanical system modelling process while still maintaining the flexibility to model more detailed system using expanded IDFs. To script HVACTemplates one must define central templates and iterate over each relevant zone and add a terminal unit template. EnergyPlus has a tool called *ExpandObjects* which expands HVACTemplates to create node lists, mixers, diverters and equipment

lists/connections. Based on Appendix G of ASHRAE 90.1 (ASHRAE 2011*b*), a variable air volume systems (VAV) was used for commercial reference buildings and four-pipe fan-coil units were used for residential towers. For proposed buildings, variable refrigerant flow (VRF) or package terminal air source heat-pumps (PTHP) were used. As of EnergyPlus version 8.1, heat-pump coils cannot be used in dedicated outdoor air systems (DOAS). Thus, a separate boiler and heating coil was defined to condition ventilation air for DOAS implementations. In some cases, district systems energy systems were defined using electrical load following combined heat and power systems. Note that the thermal zoning strategies should depend on the HVAC system selected. For example, a VAV system with perimeter reheat requires core and perimeter zoning. Domestic hot-water profiles were taken from ASHRAE HVAC Applications (ASHRAE 2011*a*). The modelling process may require iterations due to changes in the community design.

The final step in this process, not discussed in this paper, was to satisfy community energy loads using district systems. One tool which accomplishes this is Homer Energy (2014). Other popular tools, such as TRNSYS, allow for much more flexibility and will be used in later stages of the project. Future building codes require some new building types to have 100% back-up power. For example, soon in Ontario, retirement homes will be required to provide 100% redundancy in power systems. The technology mix which cost effectively meets loads is an important aspect of the community design process. However, energy conservation and efficiency opportunities within the building maybe more cost-effective than district systems. Due to the size of the solutions space, an optimization process is required to navigate such trade-offs.

Stage 3: Design Optimization

Optimization explores all possible design options and identifies which approaches yield the best performance. In this paper, an optimization study is conducted on a single townhouse unit. Two objective functions are defined: the net-energy consumption, and life-cycle net-present value. The incremental energy savings of technologies and design approaches are justified by an incremental initial cost. Details related to the zoning, loads, economics and occupancy are documented in a separate paper (Bucking et al. 2013).

The first objective function is the net-energy consumption described by equation 1 and evaluated using EnergyPlus.

$$f(\mathbf{x}) = Q_{heat}/COP_H + Q_{cool}/COP_C + E_{elec} - E_{PV} \qquad (1)$$

where: $\mathbf{x} = (x_1, x_2, \cdots, x_N)^T$ is a design variable vector. Table 2 shows the discrete variables and step-sizes used in the optimization analysis; $f(\mathbf{x})$ is the annual net-electricity consumption of the building (*kWh*); *COP* is the coefficient of performance of the heat pump in heating and cooling mode; *Q* is the annual heating and cooling load of the house (*kWh*); E_{elec} is the gross annual electricity consumption in lighting, domestic hot-water, appliances and plug-loads (*kWh*) and; E_{PV} is the electricity generated by roof-top PV (*kWh*). NZE is achieved when $f(\mathbf{x}) \leq 0$ implying an annual energy balance.

The second objective function is the incremental cost of materials and operational energy costs over the life-cycle, see equation 2. Materials were scheduled for replacement based on an expected serviceable lifetime (RSMeans 2013). A marginal electricity rate of 12¢ with an escalation rate of 2.0% was used (London Hydro 2012). Note that all monetary amounts refer to Canadian dollars. Life-cycle costs were calculated over a 30 year time horizon. Initial costs (including technology) are amortized over 25 year timespan with a 6% interest rate and 25% down on the principle amount.

Table 2: Sample of influential model variables for a NZEH

Variable	Units	Min.	Max.	No. Steps	Description
aspect	–	0.7	2.2	16	Aspect ratio (south facing width to depth ratio)
azi	degrees	-45	45	32	Building orientation/azimuth
wall_ins	m^2K/W	3.5	13.0	8	Effective resistance of wall insulation
ceil_ins	m^2K/W	5.6	15.0	8	Effective resistance of ceiling insulation
base_ins	m^2K/W	0.0	7.0	8	Effective resistance of basement wall insulation
slab_ins	m^2K/W	0.0	2.3	4	Effective resistance of slab insulation
infil	ACH	0.025	0.179	8	Natural infiltration rate
occ_loads	$\% CAD_{avg}$	50	80	8	Occupant loads (percent of Canadian average consumption)
ovr_south	m	0.00	0.45	4	Width of Southern Window Overhangs
pv_area	%	0	90	8	Percent of PV area on roof
pv_eff	%	12	15	4	PV efficiency
roof_slope	degrees	30	47	8	South facing roof/PV slope
wwr_s	%	5	80	8	Percent of window to wall ratio, south (also N,E,W)
GT_s	–	1	4	4	Glazing type, south (also N,E,W)
FT	–	1	2	2	Window Framing Types (1:Wood, 2:Vinyl)
slab_th	m	0.1	0.2	8	Concrete slab thickness
vwall_th	m	0.00	0.35	8	Concrete wall thickness (basement)
zone_mix	L/s	0	400	4	Air circulation rate between thermal zones

$$g(\mathbf{x}) = C_{NPV} + E_{NPV} + R_{NPV} - S_{NPV} - I_{NPV} \qquad (2)$$

where: $g(\mathbf{x})$ is the net-present value of all cash-flows; C_{NPV} is the capital costs of materials and equipment; E_{NPV} is the operational energy costs; R_{NPV} is the replacement cost for materials and equipment; S_{NPV} is the salvage or residual value using a linear depreciation method; and I_{NPV} is the income generated through incentives such as feed-in tariffs.

A customize multi-objective optimization algorithm was used for this analysis. The algorithm extracts information regarding design variable interactions and conducts specialized sub-searches to expedite and improve the optimization process. This optimization approach was previously presented in Bucking et al. (2013).

3   Results and Discussion

Table 3 shows the incremental cost of various building upgrades to achieve net-zero energy. Net-zero energy is achieved for a $22,600 cost premium. When amortized, only 25% of this amount is paid by the consumer.

Table 3: Sample of incremental costs of renewable energy and building upgrades over reference building

PV Upgrades, 7 kW Description	Cost, $	Building Upgrades Description	Cost, $
Inverter	1740	Insulation	5000
PV panels	6100	Air-Source Heat Pump	4000
Other Hardware	860	DHW Heat Recovery	800
Labour	2600	High Eff Water Heater	1000
–	–	Variable Speed HRV	500
Total	11300	Total	11300

Figure 2 shows a cash-flow diagram of the incremental cost of a NZE townhouse unit. The capital payback on the investment is 8.6 years.

Table 4 shows the optimal NZE townhouse parameter set. In Southwestern Ontario, diminishing returns are found for wall insulations levels above R40 and ceiling levels of R50.
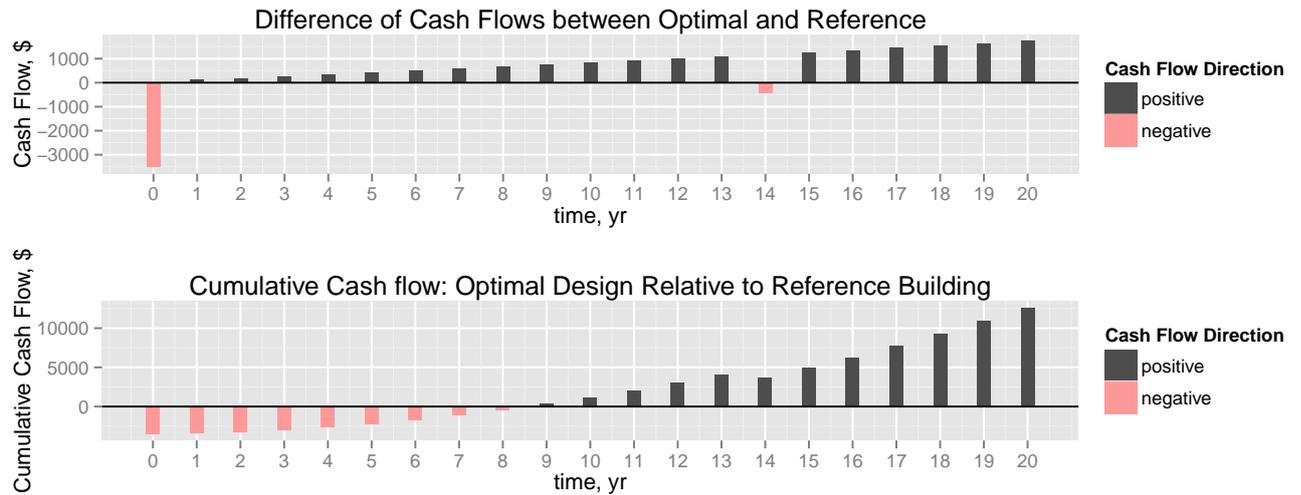
Figure 2: Townhouse optimization cash-flow diagram

Table 4: Optimization Results for Complete Redesign

VARIABLE	DESCRIPTION	UNITS	REFERENCE VALUES	OPTIMAL VALUES
azi	Building orientation/azimuth	degrees	0	0
aspect	Aspect ratio (south facing width to depth ratio)	–	1.4	1.4
wall_ins	Effective resistance of wall insulation	m^2K/W	4.4	7.0
ceil_ins	Effective resistance of ceiling insulation	m^2K/W	8.80	8.80
base_ins	Effective resistance of basement wall insulation	m^2K/W	2.11	3.52
slab_ins	Effective resistance of slab insulation	m^2K/W	0.88	1.39
ovr_south	Width of Southern Window Overhangs	m	0.0	0.34
pv_area	Percent of PV area on roof	%	0	90
pv_area_e	Percent of PV on east facade	%	0	0
pv_area_w	Percent of PV on west facade	%	0	0
pv_eff	PV efficiency	%	–	18
roof_slope	South facing roof/PV slope	degrees	33	45
wwr_s	Percent of window to wall ratio, south	%	15	40
wwr_n	Percent of window to wall ratio, north	%	10	10
wwr_e	Percent of window to wall ratio, east	%	10	10
wwr_w	Percent of window to wall ratio, west	%	10	10
GT_s	Glazing type, south (also N,E,W)	–	Double Low-E Arg	Double Low-E Arg
FT	Window Framing Types (1:Wood, 2:Vinyl)	–	2	2
slab_th	Concrete slab thickness	m	0.05	0.25
vwall_th	Concrete wall thickness (basement)	m	0.15	0.15
infil	Envelope air-tightness (natural infiltration rate)	ACH	0.15	0.025
HVAC_sys	Heating and Cooling System	–	NG Furnace w AC	Cold Climate ASHP
$f(\mathbf{x})$	Net-Energy Consumption of Individual	kWh	21,800	-4250
$g(\mathbf{x})$	Net-Present Value of Individual	$	87,800	46,735

4 Conclusion and Future Work

This paper proposed a modelling methodology using OS and a customizable script which can presently implement over 20 technologies. This approach can be customized for any building type by limiting the number of technologies implemented. Since the process relies on EnergyPlus, models defined during the early design stage can be modified and fine-tuned as more information is gained. The required modelling time was reduced from 10-20 hours to less than an hour for each building model. One disadvantage is that information is lost when models are imported back into OS after implementing additional technology in text files. This issue may be resolved in later versions of OS.

Once load profiles are created, the process of designing district systems can be decoupled from each building. However, the process is still one-directional meaning that energy is not exchanged between exterior storage and thermal mass in the building.

Future work can be summarize as follows: (i) implement quality assurance processes;

(ii) explore methods of performance visualization; (iii) uncertainty and sensitivity analyses on a community-scale; (iv) optimization of other building types; (v) automation of geometry manipulation; (vi) monitoring to confirm as-functioning designs.

The modelling process creates an enormous amount of data. An energy study on a building with 100s of zones creates several gigabytes of information which requires interpretation. Even though the modelling process can be expedited, there is no replacement for detailed quality control of modelling assumptions. Techniques which can quickly assess energy operations and comfort while identifying atypical results is a key area of future work. Uncertainty and sensitivity analyses can aid in understand the significant assumptions when evaluating how a community works from a systems level.

There are undoubtedly many other areas for future work as smart communities continue to gain industry traction.

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