

Methodology for energy and economic modelling of net-zero energy communities

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ABSTRACT

Net-zero energy communities are becoming pivotal to the energy vision of developers. Communities which produce as much energy as they consume provide many benefits such as reducing life-cycle costs and better resilience to grid outages. If deployed using smart-grid technology, net-zero energy communities can act as a grid node and aid in balancing electrical demand. However, identifying cost-effective pathways to net-zero energy requires detailed energy and economic models. Information required to build such models is not typically available at the early masterplanning stages where the largest energy and economic savings exist. Methodologies which expedite and streamline energy and economic modelling could facilitate early decision making. This paper describes a reproducible methodology which aids modellers in identifying energy and economic saving opportunities in the early community design stages. As additional information becomes available, models can quickly be recreated and evaluated. The proposed methodology is applied to the first phase design of a net-zero energy community

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under development in Southwestern Ontario.

Keywords: net-zero energy, solar community, energy, life-cycle cost

INTRODUCTION

The energy vision of a community begins at the earliest design stage with a masterplan. Masterplans typically define a limited amount of information such as building end-uses, areas and floor plate shapes. In order for engineers and architects to assist developers in achieving energy targets, such as net-zero energy, collaborative design must occur in the early design stages where the greatest energy and economic saving opportunities exist. Thus, the pathway to net-zero energy must be created from ill-defined masterplans. However, establishing energy and economic models requires detailed information which may not be available in early community planning. Methodologies which evolve with the project may be a key tool in achieving community energy visions.

Modelling a net-zero energy community presents several challenges: (i) various technologies require implementation within a common methodology to evaluate trade-offs and interactions; (ii) energy load profiles are required to evaluate the economic potential of energy conservation, efficiency and generation measures; (iii) achieving net-zero energy is difficult above certain building heights using present technology (O'Brien et al., 2010), and (iv) energy model creation is a time intensive process that is required for each building type and shape. Since developing one detailed building energy model can take over 20 hours, modelling a community is a major undertaking.

Design improvements may require changes in building locations, reorientation or modification of building shapes and heights. Modifications may be required

due to shading issues, poor solar exposure or changes in community planning. Developers may wish to identify such changes early to avoid additional costs later in the permitting process. Furthermore, since additional capital is required to achieve the net-zero energy target, modellers need to support energy saving estimates with economic models. This paper describes a repeatable methodology to aid modellers in addressing the above concerns.

Great opportunities exist if the aforementioned challenges are overcome. Communities allow for integrative design at an unprecedented scale. For example, on a community scale, mismatches between load and generation, as described by Salom et al. (2011), can be resolved using buffering and storage techniques. In the near future there may be an opportunity for a community of net-generating buildings to act like a grid node, which can be throttled depending on future demand. Net-generating communities could be a key technology in Ontario where policy makers must decide whether to refurbish an aging nuclear fleet or face public resistance to additional centralized generation near urban centers.

This paper describes a modelling methodology for a net-zero energy community. The paper develops a methodology which streamlines the modelling process, while allowing for further model resolution at later design stages. The proposed approach relies on several existing tools and best practices. The paper contributes a methodology which applies present best practices using customized software to address community energy planning within a reproducible and consistent approach.

CASE STUDY: A SMART NET-ZERO ENERGY COMMUNITY

The case-study is a 70 acre community situated in Southwestern Ontario. It is a mixed-use development with 2000 living units, including semi-detached townhouses, mid-rise and high-rise apartments/condos. A primary objective is enable work opportunities within the geographic constraints of the community. Thus, a large portion of the land is intended for commercial usage.

Smart community design extends beyond the limits of individual buildings. Energy plays a key role in this theme, but many other factors are equally significant. Other technical factors include, but are not limited to: water run-off management; reduction in transportation infrastructure while increasing green spaces; balancing of loads within the local and centralized grid; using technology to improve community engagement, occupant health and satisfaction; and improving the energy resilience of essential services to external grid outages.

Overview of Phase One Buildings

The first phase includes sixteen townhouses, a commercial office and a retirement home. The focus of early energy studies was to identify technologies and capital costs required to achieve net-zero energy for the entire first phase. The development and economic evaluation of community energy systems will be included in a later publication.

Figure 1 shows the phase one masterplan and building heights proposed by the developer. Note that the architectural design has been simplified in this figure. These building layouts form the basis of design for later energy modelling. Of the three building types, the retirement home is the major energy consumer from a Canadian context (NRCan-OEE, 2010).

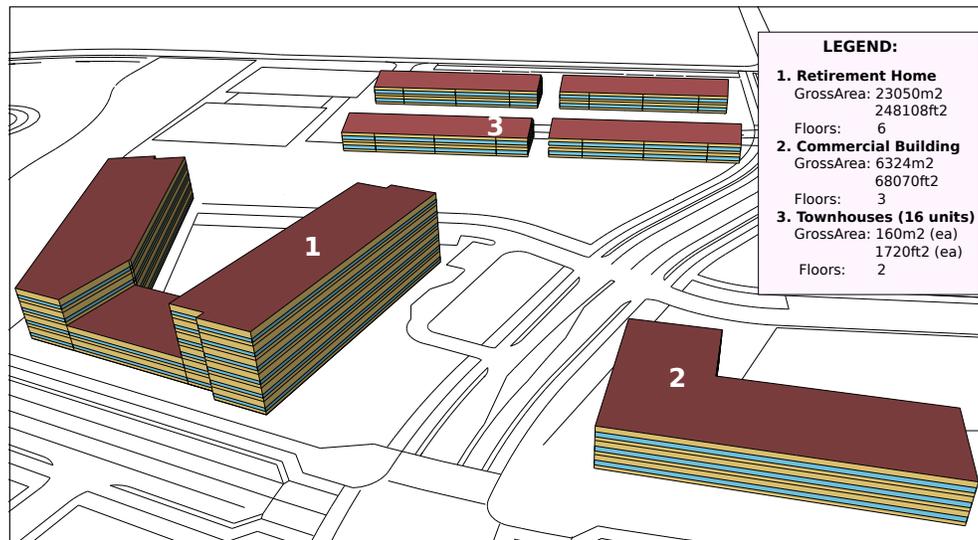


Figure 1: Masterplan and building renderings of phase one.

METHOD

The proposed methodology requires an energy and economic model. The energy model describes the incremental energy savings required to achieve net-zero energy over a reference building. Thus two energy models are required—a proposed and reference design. ASHRAE standard 90.1 (ASHRAE, 2010) defines the reference building using current energy code best-practices. Incremental building upgrade measures form the proposed building design.

The economic model uses a life-cycle approach to associate incremental costs with incremental energy savings. Various performance indicators are developed using annual cash flow differences and cumulative cash flows over a defined life-cycle period.

Energy Model

The energy model identifies the mismatch in energy consumption to energy generation over an annual period. This information aids in determining the need for additional technologies to satisfy the community energy balance. The energy model created sub-hourly load profiles for the buildings in the community. This information is useful to evaluate the potential application of various technologies and smart control strategies and must be emphasized early in the feasibility stage of the project. Sub-hourly profiles also enable peak load predictions of mechanical, storage and district systems.

A combination of tools were used to create load profiles for various buildings types: (i) OpenStudio (OS) for drawing geometry and window positions (NREL, 2014); (ii) WINDOWS for specifying glazing spectral properties (LBNL, 2014b); (iii) THERM for specifying envelope properties (LBNL, 2014a); (iv) EnergyPlus for energy modelling (EnergyPlus, 2014); and (v) a custom scripting process for technology implementation and modelling best-practices.

Since various tools are required, user interaction is necessary to form early building models. Before starting the modelling process, some assumptions must be made on how the building will be used. At the early development stage, detailed floor plans typically do not yet exist. However, floor area, building usage, number of stories and rough building geometry are known. Experienced users are required to transform the above information into a floor plan which defines the location and size of offices, living units, corridors, elevators and mechanical, electrical and storage rooms. Floor plans are used as inputs to the modelling methodology.

The OpenStudio model formed a basis of design for further energy modelling

in EnergyPlus. EnergyPlus models explored the energy savings from various technologies. Manipulations, both geometric and technological, were conducted using this foundational EnergyPlus model. Over twenty technologies were considered in each building design. Depending on the building type, 5–10 design strategies were sufficient to reach NZE. Technologies were only implemented if they were suitable for the building type under consideration. The modelling process associated EnergyPlus objects to each zone, envelope/glazing surface or in other locations of the building. Since many technologies were not presently available within the OS interface, an energy modeller must resort to text file manipulations, of which many could be automated for an arbitrary number of zones or surfaces using scripts. The time savings were significant and less error-prone than user-driven text file manipulations.

Figure 2 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 adding the consumption profiles of each building.

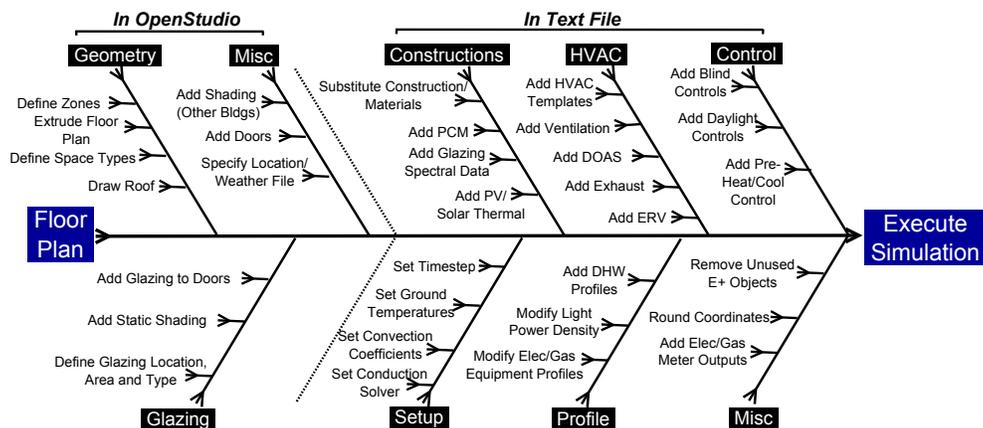


Figure 2: Methodology for building energy model creation.

The modelling process in the OpenStudio SketchUp interface was as follows:

1. Define spaces on the two-dimensional floor plan such as corridors, offices and living units.
2. Extrude the 2D floor plan vertically to the number of required floors. If a basement is required, it is added to the extrusion and later moved within SketchUp to below grade (negative z-axis coordinates).
3. Draw shading and obstructions from other buildings or trees around the site.
4. Use the *intersect spaces* function in OS to ensure that partition walls relate to each other and have adiabatic boundary conditions.
5. Once interior partitions are created, window and glazing surfaces are defined. Windows can be defined within OS by specifying a window-wall ratio (WWR), or manually drawn on each building surface.
6. 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) estimated ventilation demands. Select ASHRAE 90.1 as an energy standard when defining space types (ASHRAE, 2010). In this step, ensure that each space has a thermostat defined and ideal loads set as a mechanical system.
7. Run the *convert spaces to thermal zones* function to convert OS space 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;

8. (Optionally) open the file in the OpenStudio, set the weather file, and ensure all zones are set to ideal loads.
9. (Optionally) run in EnergyPlus and correct errors (if any) to identify model errors before proceeding to the next step.

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.

The scripting process is a continuation of the modelling process defined in Figure 2. 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.

Table 1 shows a short-list of modelling best practices and implemented technologies.

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 IDF's. To script HVACTemplates one must define a central mechanical system template and then iterate over each relevant zone and add a terminal unit template. EnergyPlus has a tool called *ExpandObjects*

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 conditioned zones
Modify Azimuth/Orientation	Reorientate the building
Modify Envelope Insulation	Modify insulation levels in Walls, Slabs, and Roofs
Modify Window Type	Modify window types used by azimuth (double/triple glazing)
Modify Window to Wall Ratio	Modify window to wall ratios by azimuth
Modify Ground Temperature	Modify ground temperature profile using weather data
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
PV Field/Array	Add a PV array near the building (no shading), ex. on parking lot
Dedicated OA Systems	Add DOAS to each applicable zone
Domestic Hot-Water Loads	Add DHW loads to each applicable zone
Domestic Hot-Water Heat Pump	Add hot-water heat pump to meet DHW loads
Domestic Hot-Water Boiler	Add hot-water heat pump to meet DHW loads
Exhaust Ventilation	Add ventilation fan loads to each applicable zone
Reduce Infiltration	Reduce envelope infiltration losses
Reduce Light Power Density	Reduce light power density by specified amount
Add Elevator Electrical Load	Add elevator electrical loads to building
Window Shading & Control	Add controllable window shades to each applicable glazing surface
Window Static Shading	Add static exterior window shades to windows within specified orientation
Daylighting	Add daylighting sensors and tie into window controls
Energy Recovery Units	Add ERVs to each applicable zone. Control using CO2 sensors

which expands HVACTemplates to create node lists, mixers, diverters and equipment lists/connections (EnergyPlus, 2014). Based on Appendix G of ASHRAE 90.1 (ASHRAE, 2010), a variable air volume system with electric reheat (VAV) was implemented. For proposed buildings, variable refrigerant flow (VRF) (Rausstad, 2013) (commercial) or package terminal air source heat-pumps (PTHP) (retirement) were used. Since heat pump coils cannot be used in dedicated outdoor air systems (DOAS) HVACTemplates (as of EnergyPlus version 8.1), a separate boiler and heating coil was defined to condition ventilation air.

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 Applica-

tions (ASHRAE, 2011).

EnergyPlus results were reported using metered comma separated files and SQLite databases. For some technology implementations, presimulation was required. For example, one script function adds PV to all exterior walls and roof surfaces which are near south facing and builds an electrical generator list. In EnergyPlus, PV is added directly to sun exposed building surfaces such as wall and roof surfaces. Although exterior walls orientations can be calculated from surface geometry in a EnergyPlus input description file, a simpler implementation uses SQLite to retrieve this information with a single select statement. SQLite databases were created by running the EnergyPlus model for a reduced time period. Presimulation slightly increases execution time but greatly reduces software development time and maintenance.

Economic Model

There are four key elements to achieving a cost-effective NZE building: (i) energy conservation and efficiency measures to reduce operational energy costs, (ii) net-metering laws which enable the resale of renewable energy at time-of-use utility prices, (iii) escalation of fuel prices which accelerates economic savings, and (iv) upfront financing absorbs the capital cost of technology to achieve NZE. Note that NZE can be achieved cost-effectively without financing, however this is not a general rule. Renewable energy purchasing programs, such as feed-in tariffs, can provide additional financial aid for on-site energy production and accelerate economic returns.

Operational energy costs were calculated by post-processing hourly EnergyPlus results. Table 2 shows the time-of-use electricity billing rate (London Hydro, 2012). An electricity escalation rate of 3.0% was used and a demand charge of

\$6.83/ kW was used with an escalation rate of 3.0% (London Hydro, 2012). A marginal natural gas rate of 18¢/ m^3 with an escalation rate of 2.0% was used.

Table 2: Commercial and Residential Time of Use Billing

PRICING SCHEDULE	HOURS	TOU	PRICE (¢)
Summer Weekdays	21:00–07:00	off-peak	7.2
	07:00–11:00	mid-peak	10.9
	11:00–17:00	on-peak	12.9
	17:00–21:00	mid-peak	10.9
Winter Weekdays	21:00–07:00	off-peak	7.2
	07:00–11:00	on-peak	12.9
	11:00–17:00	mid-peak	10.9
	17:00–21:00	on-peak	12.9
Weekends and Holidays	00:00–24:00	off-peak	7.2

Equation 1 defines the incremental cost of materials and operational energy costs over the life-cycle.

$$g(\mathbf{x}) = C_{NPV} + E_{NPV} + R_{NPV} - S_{NPV} - I_{NPV} \quad (1)$$

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.

Materials were scheduled for replacement based on an expected serviceable lifetime, see Table 3 (RSMeans, 2014). As per *EN 15459: Energy performance of buildings—economic evaluation procedure for energy systems in buildings*, life-cycle costs were calculated over a 30 year time horizon (EN15459, 2010). Initial costs (including technology costs) were financed over a 10 year timespan with a

5% annual interest rate with payment beginning in year one.

Including replacement costs creates a potential problem—the possibility that costs are incurred just before the end of the life-cycle which results in a misleadingly large NPV (Anderson et al., 2006). Salvage values were incorporated using a linear depreciation method (Doty and Turner, 2012).

Table 3 shows the replacement schedule used in the economic model. Key technology replacement times, such as light emitting diodes (LEDs) versus fluorescents for lighting, are pivotal to representative life-cycle cash flows.

Table 3: Replacement Schedule Used in Economic Model

MATERIAL CATEGORY	REPLACED?	REPLACEMENT PERIOD (YEARS)
Cellulose insulation in Walls (Townhouse)	✓	25
Cellulose insulation in Attic (Townhouse)	✓	25
Windows (broken seals)	✓	30
Boilers and Air Handlers	✓	20
Heat Pumps	✓	25
Fluorescent Lights (20,000hr)	✓	5
LED Lights (50,000hr)	✓	10
Roof Material	✓	25
Inverters	✓	15
PV Panels	✓	40
Miscellaneous PV array costs	✗	–

Although a PV feed-in tariff exists in Ontario (OPA, 2014), this incentive was not used in the economic model. The intent is to show that PV is cost effective without subsidy. However, a feed-in tariff could be leveraged to accelerate financial returns. It was assumed that net-generated electricity was purchased at market rates.

Equation 2 shows the life-cycle cost as net-present value (NPV). This equation can be solved for NPV or several interesting economic metrics by setting NPV to

zero.

$$\text{NPV} = \sum_{t=0}^N \frac{C_t}{(1 + \bar{r})^t} \quad (2)$$

When set to zero, equation 2 can be solved for the internal rate of return (IRR), \bar{r} , or tolerable initial cost, C_t , which yields an acceptable IRR.

Cash-flow diagrams were created by evaluating the economic performance of a proposed building relative to a reference design. The difference between these two cash-flows determined incremental costs and economic viability. A cumulative sum determined how quickly capital costs were paid off through energy savings.

It is recommended that a cost model be built by post-processing EnergyPlus results. Note that life-cycle economic models can be built directly into EnergyPlus. However, running economic scenarios requires model resimulation which can add hours of unnecessary analysis time. Economic scenarios using a post-processing approach expedites exploration of cost model assumptions. Another advantage is that maximum flexibility in financing, utility billing structures, depreciation methods and material cost specification is attained.

The SQLite interface to EnergyPlus results is an effective means to retrieve key information for cost analyses. For example, area information of exterior windows and walls is required to estimate envelope costing. Although this information could be calculated from the EnergyPlus IDF, it is simpler to query using SQLite.

As technology is implemented and tested in the scripting methodology, iteration may be required between the cost and energy models. This is a key quality assurance process to ensure energy savings are reasonable and justifiable by an incremental cost. Having both energy and economics in a common methodology

aided in encompassing several important interactions. For example, adding insulation not only reduced operational energy costs but also reduced the initial size and thus cost of mechanical equipment.

RESULTS AND DISCUSSION

Table 4 shows incremental energy savings and subsequent rate of returns for each building type. Each upgrade measure is described to achieve the NZE target.

Table 4: Pathway to Net-Zero Energy for each Building Type

DESCRIPTION	Energy Use Intensity		Rate of Return	
	<i>kWh/m²</i>	<i>kBtu/ft²</i>	w/ fin	w/o fin
COMMERCIAL OFFICE WITH RETAIL	120	37.9	–	–
1. Added Insulation	112	36	13%	8%
2. VRF Heat Pump with DOAS	87	28	9%	6%
3. LED Lighting	78	25	10%	6%
4. EnergyStar Office Equipment	70	22	8%	6%
5. PV on building exterior: South, East, West	-6.8	-2	13%	8%
Combined Upgrades	-6.8	-2	12%	7%
RETIREMENT HOME	225	71	–	–
1. Added Insulation	218	69	9%	4%
2. Packaged Terminal Heat Pump with DOAS	126	40	12%	4%
3. LED Lighting	104	25	5%	2%
4. Reduced plug and equipment loads	81	26	22%	5%
5. Glazing: Triple/Double Glazing with low-e	73	23	6%	4%
6. Reduction Window sizes on East, West, North	65	21	–	–
7. Low-flow water fixtures	61	19	15%	8%
8. PV on building exterior: South, East, West	17	5.4	8%	5%
9. PV Array on Parking Lot (450kW)	-2	-0.6	15%	7%
Combined Upgrades	-2	-0.6	10%	5%
TOWNHOUSE	136	43.1	–	–
1. Cold Climate Air Source Heat Pump	89	28	9.8%	–
2. Envelope Air-Tightness	75	24	50%	–
3. Smart Thermostat Control	61	19	18%	–
4. High Eff HRV with ECM	57	18	5%	–
5. DHW Heat Recovery	48	15	40%	–
6. Glazing Upgrade	36	11	8%	–
7. PV on roof (7.5kW)	-18	-6	22%	–
Combined Upgrades	-18	-6	15.4%	–

The energy use intensities (EUI) reported in Table 4 represents the net-energy consumption. The reference building EUI is reported with the building description. Table 4 identifies the pathway to NZE from a typical reference design. Roughly five to ten design strategies were required. With proper financing, NZE was achieved cost-effectively. However, the retirement home design required an additional PV array on the parking lot to reach an annual energy balance. In a later charrette, this design will be reconsidered to rectify inefficiencies in the original design such as overheating reductions on the exposed western facade and better exploitation of passive solar resources.

Figure 3 shows the cumulative cash-flow diagrams for each building type using the previously described financing strategy.

Notably, Figure 3 shows that NZE buildings are profitable over a long-period life-cycle. Financing packages allow for paybacks in the five to nine year range with a low upfront capital cost. In fact, the reduction in operation energy cost in the townhouse design was sufficient to pay the additional financing fees. However, this was not the case in the commercial and retirement designs. In all cases, economic savings accelerated after financing repayment in year ten.

The additional capital and replacement cost of technology lead to several payback periods. In the retirement home design, the replacement costs of LEDs was substantial in year ten which required a few additional years to payoff relative to the reference design. The present retirement home design was not optimized for daylighting, so it is likely that this issue can be mitigated in later design iterations.

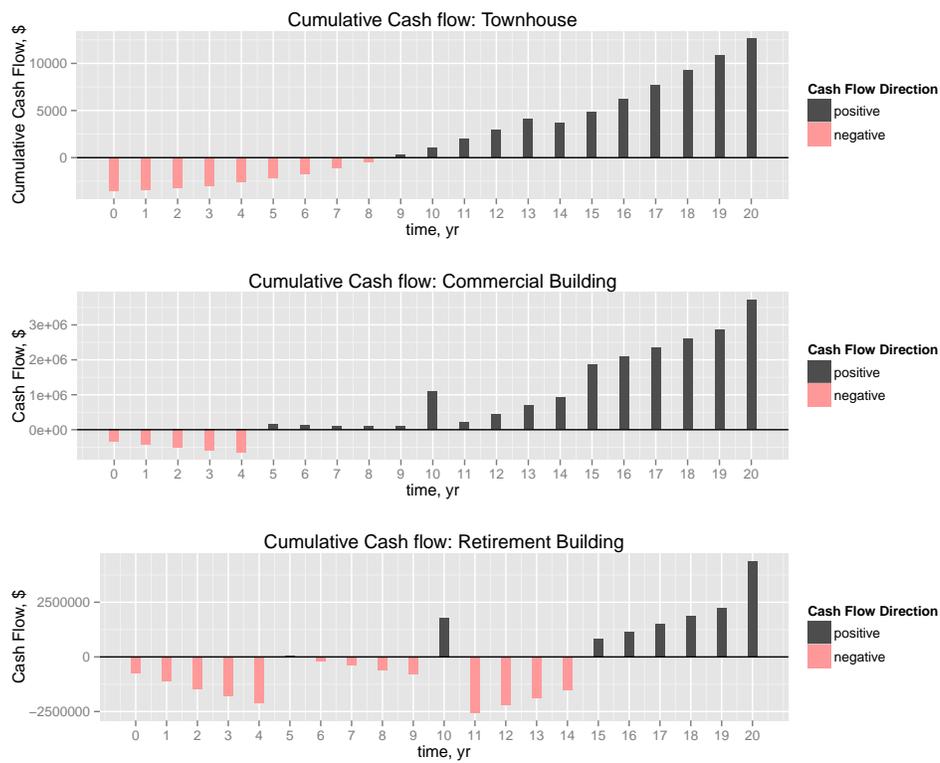


Figure 3: Cash-flow diagram: townhouse, commercial and retirement buildings (with financing).

CONCLUSION AND FUTURE WORK

This paper proposed a modelling methodology using OpenStudio, EnergyPlus and a customizable scripting process. The proposed methodology reduced the time requirements to model NZE communities with a consistent and reproducible approach. The development time of individual building models was reduced from dozens of hours to approximately an hour, depending on the building size. The methodology emphasized forming a basis of design model from a floor plan in OpenStudio. Various technologies and energy modelling best-practices were implemented using a customized scripting process. As a case study, the methodology was applied to the first phase of a development located in Southwestern Ontario, including 16 townhouse units, a commercial building and a retirement home.

Future work can be summarized as follows: (i) redesign of retirement home for improved energy savings; (ii) conduct an uncertainty and sensitivity analysis on the energy model to identify significant model parameters (Bucking et al., 2014); (iii) integrate optimization approaches using the proposed scripting methodology (Bucking et al., 2013); (iv) extend the case-studies to later development stages in the community; (v) implementation of peak load and generation management using smart grid technologies; and (vi) additional implementation of advanced energy systems and control strategies such as combined heat and power systems and geothermal seasonal storage.

Net-zero energy community design presents new challenges and opportunities. Challenges include rectifying community programming and transportation plans with energy models. Accomplishing this in the master planning process can require dozens of iterations. However, economies of scale at a community level enable achieving NZE targets cost-effectively. Having adaptable methodology to

explore the feasibility of technology can facilitate the decision making process from early to late community design stages. Methodologies which synchronize energy and economic models are a key approach to identifying cost-effective pathways to NZE targets.

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