Canadian Journal of Civil Engineering
Revue canadienne de génie civil

Retrofitting for resiliency and sustainability of households

Journal:	<i>Canadian Journal of Civil Engineering</i>
Manuscript ID	cjce-2016-0440.R1
Manuscript Type:	Article
Date Submitted by the Author:	20-Jan-2017
Complete List of Authors:	Bristow, David; University of Victoria, Civil Engineering Bristow, Michele; Univesrity of Waterloo
Please Select from this Special Issues list if applicable:	N/A
Keyword:	retrofit for resilience, retrofit for sustainability, climate change adaptation and mitigation, multi-objective decision support, ReSus

Retrofitting for resiliency and sustainability of households

David N. Bristow^{1,*}, dbristow@uvic.ca

Michele Bristow², michele.bristow@uwaterloo.ca

*Corresponding Author, T: +1 250.472.4814, F: +1 250.472.4028

¹PhD, Assistant Professor, Department of Civil Engineering, University of Victoria. PO Box 1700, Stn CSC, Victoria, BC V8W 2Y2

²PhD, Adjunct Assistant Professor, Department of Systems Design Engineering, University of Waterloo. 200 University Ave. W., Waterloo ON, N2L 3G1

Word count: 6,324 + 250*7 tables and figures + 719 for refs = 8,793 + refs

Abstract: Home retrofits contribute to the sustainability of residential buildings by conserving resources and energy and improving efficiency of the operations within. The resiliency of a household to disruption is usually a separate consideration, if at all. The up-front costs of both can present themselves as nonessential expenses limiting their adoption. There exist few tools to integrate design for sustainability and resiliency that are available to average homeowners. This inhibits their ability to implement climate change mitigation and adaptation measures. Herein is a systems approach to integrate sustainability efforts with resilience solutions into a computational multi-objective decision support methodology with a financial analysis. The methodology, dubbed “ReSus”, is shown here with an example case study of a midsize single detached house in southwestern Ontario, Canada through simulation of retrofitting scenarios to support decision making on building upgrades. Applying this methodology details several retrofitting pathways that have the potential to reduce energy use and greenhouse gas emissions as well as provide a positive return on investment that addresses both mitigation and adaptation.

Keywords: retrofit for resilience, retrofit for sustainability, climate change adaptation and mitigation, multi-objective decision support, ReSus

Draft

1 Motivation

It is widely accepted that adaptation and mitigation to climate change should occur in conjunction (IPCC 2014a, 2014b). This viewpoint stems from a recognition of the deep uncertainty surrounding the environmental impacts of greenhouse gas (GHG) emissions from not only a local standpoint but also from an integrated global perspective. Some of the uncertainty is due to our level of understanding of the climate system. Further uncertainty surrounds the cumulative amount and effects of anthropogenic emissions over space and time. Moreover, our responses to climate change tend to alter both how much emissions are reduced – the level of mitigation – and how well nature and society can respond to disturbances – the degree of adaptation. Some actions move both adaptation and mitigation in the same direction, others move them in opposite directions (Sugar et al. 2013; Landauer et al. 2015). Hence, customization of climate change action plans to a local context within a global framework of both natural and societal environments is increasingly becoming a requirement.

This paper is motivated by concerns for households – their occupants and assets – in a changing climate. The assets of households commonly most strongly linked to the challenge of climate change are homes and cars (Van de Weghe and Kennedy 2007). Both of these asset types are responsible for significant carbon emissions. Further, they also have a strong bearing on a household's ability to cope with climate change depending on the asset's ability to help with or be impacted by the effects of climate change such. In extreme weather, for instance spans a spectrum from a helpful shelter for safety to a dangerous structure nearing collapse or flooded. Likewise automobiles can be a useful resource and also exacerbate air quality during resource shortages due to heat waves.

In the case of residential buildings the understanding of how to address climate change is strongest from a mitigation perspective compared to adaptation. As a whole, the building sector has many prospects for climate change mitigation but lacks systemic adoption of the available tools and techniques to the existing stock. For example, building energy models such as EnergyPlus are advanced in development but these

models are yet in the early phase of technology adoption for existing residential buildings, where its users are knowledgeable sustainability leaders. Further, there exist novel means to formulate sustainable retrofit into a decision framework for home retrofits (Galiotto et al. 2015); the challenge is to progress application of these capabilities to a large degree in order to make a measurable impact on the environment, and to do so in a way that also brings adaptation benefits where needed.

For automobiles, mitigating climate change effects is possible through reduced use. Shifting to active transport and transit are useful alternatives, as is a shift to cleaner energy sources. Many existing households, predominately those in suburbs, however, are unlikely to significantly alter their mode of transport or reduce usage due to the auto-centric design of their surroundings. Cleaner automobiles are becoming available, though remain more expensive, however. Further, battery electric vehicles may also provide adaptation resilience as they can be refueled in a wider diversity of places, including the home, and may in the future provide a means to provide their power reserves for other uses in the household. The costs and benefits of this potential in relation to other alternatives is as yet unclear. Overall, there is an uncertain relationship of the potential integrating benefits of building retrofits and alternative vehicle capabilities to aid in climate change mitigation and adaptation.

More generally, there is a lack of detailed understanding of the integration potential between sustainability and resilience practices for households. Whereas environmentalist proclivities tend to emphasize a preventative, and occasionally reactionary mindset to environmental and ecological threats that are often a step or more removed from the household, the concern of the resilience mindset is with more direct impacts to a household from threats that unfold in relatively short bursts (Hay 2013). This paper aims to address the lack of integration between sustainability and resilience through an investigation of how changes to the major physical assets of households – the residence and cars – may be able to provide solutions for mitigation and adaptation.

More specifically, the objective of this study is to combine sustainability efforts and a resilience assessment into a single computational multi-objective decision support methodology with a financial

analysis. A novel systems design methodology for resiliency and sustainability planning of the energy needs of residential buildings, called ReSus, is proposed and tested through a computational implementation and a case study application. The contribution of the approach is in the unification of assessment parameters for both resiliency and sustainability into a single computational approach. The proposed methodology builds on previous work regarding the relevant design parameters for the sustainable use of energy in households. The resiliency considerations are handled by examining how long the household can operate given various disruptions. These tolerances are a key metric in resilience planning (Bristow and Hay 2016). The emphasis is on retrofitting the existing build stock, which is subject to constraints imposed by existing space and infrastructure. In addition to building energy use, the energy use for transport is also considered due to the tight coupling of these demands in the sustainability and resiliency of the occupants, and the general need to consider aspects beyond a household to assess its potential for sustainability (Engel-Yan et al. 2005). In this way possible synergies between these different components of household operations can be explored.

2 Routine and Disrupted Performance

Consideration of sustainability and resilience of households in a changing climate requires an understanding of performance. There are two lenses on performance: 1) internal to the household delineated by property and 2) external to the household. The internal performance of the household relates to the occupants and their desires, such as their financial solvency and their safety under routine day-to-day situations, or during times of disruption when the power fails. Performance external to the household in this case relates to the quantity of carbon emissions routinely emitted, or the needs the household places on support services in times of stress, such as through insurance or home repair services following a storm.

The effects of climate change are presenting disruptive circumstances which are being experienced for the first time in current collective memory. As a result, learning how to adjust expectations and respond

accordingly is in progress. Furthermore, a new norm of low carbon living expectations as well as more extreme seasonal highs and lows are emerging. Low carbon and climate resilient infrastructure (Kennedy and Corfee-Morlot 2013), though more costly initially, may be one of many necessary coordinated responses to such disruption.

2.1 Sustainable routine performance

Buildings, like any other sector, contribute in part to the GHG emissions driving climate change. Their routine performance must, and increasingly does, in turn contribute to mitigation efforts. However, if a building is not considered as a system within a larger context, performance targets on energy use and GHG emissions will not be met. For example, the operation of residential buildings in Canada reduced average energy use per household by 24% and associated carbon emissions intensity by 35% from 1990 to 2013 as reported by the Federal Comprehensive Energy Use Database (NRCan 2013). Despite these intensity reductions, the aggregate emissions from operating residential buildings decreased by only 9% from 1990 to 2013, due largely to the overall increase in the size and quantity of buildings.

The fastest growing residential building types over this period are single detached and single attached homes which grew in number by 40% and 60% respectively and grew in total floor space by 60% and 95%. Each one of these additional homes, correlates with an extra quantity of emissions produced for ground transportation, especially private automobile use due to the lower density and road layout that tends to correspond with this form of buildings (Van de Weghe and Kennedy 2007). Indeed, partly due to the increase in these types of buildings passenger road kilometres travelled increased 41% from 1990 to 2013, resulting in an increase of emissions of 11%, despite a decrease in emissions per kilometre of 21%.

Clearly the normal day to day operations of this building stock, with its related transport demand, presents a significant potential lock-in of future emissions unless there are changes made to their energy demand and the types of energy they require.

2.2 Resilience during disrupted performance

While climate change is in itself a disruption that is creating new operating conditions for routine performance, it is also presenting more extreme natural hazards such as ice storms, heat waves and extended droughts. In these cases, operational resilience is useful as it focuses on prioritized recovery from unpredictable events. Resilience minded solutions, such as the dispersion of assets; diversification of supply; and the addition of flexibility and redundancy, however, do not exist in isolation from a building's routine operations.

An interesting relationship between resilience, through disrupted performance, and sustainable routine performance emerges when expectations of each are brought to the fore. In both resiliency and sustainability practices is typically a great deal of demand management including significant energy demand reductions to reduce the associated negative environmental impacts. Reducing the demand alters the resilience requirement for a building. For instance, reducing energy demands for critical functions and introducing prioritized circuits reduces backup power requirements. Combined with a diversity of energy sources, increased assurance of the continuance of supply to critical functions can be obtained.

Business cases for building integrated alternative energies started to emerge in the last decade with the potential for positive returns and relatively low risk from a lifecycle perspective (Bristow and Kennedy 2010). Combined with dependency and demand management such schemes can provide an integrated solution that helps with mitigation and adaptation, while also offsetting risks from commodity market volatility.

Underlying the balancing of resilience and sustainability is an understanding of interrelationships. Within the realm of operational resilience the concept of interrelationships is prevalent (Ouyang et al. 2012; O'Neill 2013). The essential point here is that, as with mitigation, the best solutions are not the ones that are accomplished in isolation. Any resilience plan for a building requires understanding of the connection

of a building to its surrounding, and especially to the services and infrastructure it relies upon most heavily.

3 Methodology

Just as there are tight interlinkages between routine and disrupted performance of households, there is necessarily linkages between options to improve on routine and disrupted performance. The proposed methodology is designed to enable integrated testing of various options to assess how the integration addresses routine and disrupted performance relative to likely requirements for managing climate change.

3.1 Overview

The overall methodology proposed herein is a systems methodology in the spirit of Bahill & Gissing (1998) but adjusted for a specific application area and purpose. That application area is integrated household asset selection and design. The purpose is energy sustainability and resiliency assessment. Dubbed ReSus, the method is depicted in Figure 1. All components of the method are implemented and integrated in the Python programming language, except for the building energy modeling which uses established building energy modeling tools to provide the detailed building scenario assessments (as described further in section 3.2.1 and 3.2.2).

To start, the procedure commences with collection and definition of contextual information. This includes the existing or base case building and site details, surrounding structures and historical weather and utility data. A standard may be used where data is unavailable. This is followed by the establishment of an initial set of alternatives, which along with combinations of these alternatives, comprise the scenarios.

Next, the scenarios are then modeled and simulated in three distinct but connected modules: 1) building, 2) transport, and 3) energy backup. The initial set of alternatives are assessed and iterated on in order to discard low performing alternatives for now and focus in on alternatives with greater potential. At the conclusion of the building and transport phases the hourly energy use and GHG emissions are computed for normal operations, with no utility outages, for each of the scenarios. Subsequently backup energy

systems can be selected and sized appropriately based on energy use expectations and the types of energy that can be employed by the building and the vehicles.

Finally a financial analysis is conducted that examines the building on its own, transport on its own and then finally the combination of building and transport alternatives with the backup energy systems. At the end of each stage the intermediate outputs can be assessed, and re-evaluated. Commonly this process reveals new scenarios that are worth assessing. Altogether, the output for each scenario include energy use and emissions estimates; financial costs, savings and rates of returns; and performance through energy utility failures and damage from natural hazards.

3.2 Case study implementation

The intention of the case study is a proof of concept of the proposed integrated sustainability and resiliency assessment methodology for retrofit of existing household assets. The methodology is intended to be general and repeatable with customized contextual details and scenarios for each application. The parameters and set of alternatives considered here are thus bounded by the case study specifics defined by the contextual information of the building as well as products on the market. Other parameters include the preferences and restrictions of the client who may be an occupant and/or owner of the building.

Altogether approximately 500 scenarios involving different combinations of building retrofits, car options, and backup energy systems are computed for the case study. The alternatives considered are detailed in this section. Some of the combinations and alternatives are not explored in depth here in order to focus on the most promising and edifying cases.

3.2.1 Base case building

The case study house is located in a neighbourhood of the city of Waterloo, Ontario, Canada, population 98,780 (2011). It is located in the region of Waterloo, population 507,096 (2011), about 110 km west of Toronto. The 1,832 square foot home (2,709 square feet including the finished basement), constructed in 2001, has the original envelope, natural gas furnace, air conditioner (AC), and no fireplace, but includes

updated energy efficient appliances and natural gas water heater. The front has a southwestern exposure, the roof is suitable for a southeast facing solar collector. There is a single neighbour to the right (south west); further specifications of the house are included in the Supporting Information.

3.2.2 Building upgrade scenarios

Upgrades are considered in four categories: 1) demand reduction, 2) space conditioning, 3) water heating, and 4) solar energy capture. Scenarios are constructed by making changes in these individual categories and then in combinations of alternatives from multiple categories. The initial selection of alternatives includes those with the potential for positive financial returns that are relatively non-invasive from a retrofit perspective. This precludes most changes to the building envelope, which are typically quite expensive and invasive endeavours. The building energy model for each scenario is constructed using BEopt 2.4.0, a residential interface over EnergyPlus 8.1.9.

The alternatives within each category are as follows. The demand reduction alternatives include upgrading from an asphalt shingled roof to a steel roof, upgrading lighting from compact fluorescent lamps (CFLs) to the newer light emitting diodes (LEDs), upgrading the attic insulation from R-30 fibreglass to R-60 cellulose and efficient major appliances. In this case only the washer and dryer were not currently high efficiency models. In considering a steel roof upgrade, it was hypothesized that a steel roof might lower energy use due to a reduced cooling load but this was almost exactly matched by the increased winter heating load and so is not considered in any further detail. Window overhangs, also, had a negligible impact on emissions. In initial testing of the LED and attic insulation upgrades, either separately or made together, current space heating and cooling systems requirements were adequate and would not need to be changed.

Several alternatives for the space conditioning systems, which are nearing their end of life, are considered. These include mid and high efficiency furnace and air conditioner replacements - the mid efficiency being the same as those systems already in place; and heat pumps. The furnace alternatives have annual fuel utilization efficiencies (AFUE) of 80% and 98% (AFUE) and the air conditioners have

seasonal energy efficiency ratios (SEER) of 13 and 21. Air source and ground source heat pump (GSHP) with vertical boreholes are also examined, with SEERs of 17 and 18.4, respectively. The air source heat pump (ASHP) is a modern cold climate air source heat pump that in practice is shown to function in the Ontario climate (Sager et al. 2013).

The natural gas water heater will require replacement in a few years and is hence included in the study. The alternatives considered include another natural gas heater with tank; a similar electric model; and on demand tankless natural gas and electric systems. The rated energy efficiencies are 67%, 95%, 82%, and 99%, respectively.

Finally, both photovoltaic (PV) and solar water heating (SWH) systems are analyzed. These are southeast facing systems with slope equal to the roof slope of 30 degrees. The PV systems are grid tied and range from rate outputs of 4.5 kW to 3.5 kW. The SWH system cases are closed loop flat panel collectors with areas of 6 m² and 3.7 m², respectively.

3.2.3 Transport scenarios

The case study includes a single car. For the transport scenarios two different car classes are considered based on the preferences and restrictions of the client. The first class is the compact four door and the second, a luxury sedan. In these scenarios the base case does not represent the current state but rather a standard carbon option, which is an internal combustion engine (ICE). The low-carbon alternative is mainly a battery electric vehicle (BEV). Moreover, the transport schedule is based on the average pattern of drivers in the Waterloo region (DMG 2011). The same hourly driving schedule is used each day which sees the bulk of the routine travel in rush hours, with the remainder in the afternoon and evening for a total of just over 20 km per day. Furthermore, charging of the electric vehicles, for the scenarios that include them, is set to start at nine o'clock each night.

The compact base case is a Nissan Versa Note S, which is compared against alternative compact battery electric vehicles (BEVs): the Nissan Leaf S and SV. The SV model, compared to the S model, includes a

faster charging capability with a price adjustment to reflect the added capability. The luxury base case is an Audi A7 Sportback. The luxury electric cars are the Tesla 70D and 85D models. The electric vehicles are all eligible for Ontario's full electric car incentive of \$8,500 and 50% off charger and charger install costs. All of the transport scenarios assume an eight year lifetime of the vehicle. Relevant specifics on all of these models are available in the Supporting Information.

3.2.4 Backup energy scenarios

The house currently uses natural gas for heating as does almost half of Canadian single detached houses. If the electricity grid fails, then heating, nonetheless, will not be available despite that alternative energy source. As with other typical Canadian houses, the thermostat and control system require electricity and these almost never include a backup electricity supply. The result is that a winter power outage means no heating to households across the affected area. Further to this, the natural gas supply requires power to operate, and while there are backups in place, a long enough power outage leads to natural gas supply interruption. Currently in Ontario an increasing supply of electricity is based on natural gas, and since legislation changes in 2005, increasingly more backup generators in non-residential facilities are natural gas powered as opposed to diesel powered. This puts additional demands on the natural gas system, and its backup systems, whose degree of reliability and security can vary (Isherwood 2012).

Consequently, the backup energy alternatives include battery and gasoline generator systems sized to meet the peak critical demands of the building and transport requirements. As is required, the sizing is done on a power basis. The peak power capacity of the backup systems is the limiting constraint that defines the required size of the system. It turns out that this also leads to safe sizes in terms of available energy to meet the critical needs. Since the hourly simulation is performed it is possible to size the generator to cover the maximum critical hourly load in the year.

In this case the focus is on the needs for survival and protection of property. For this study, the critical load includes space heating, food storage, and food preparation. As a buffer, all appliance energy needs are included as opposed to just those for food preparation and storage so that there is residual capacity.

Space cooling is not deemed critical here as the finished basement can be used in hot weather to keep cool, while space heating is essential for life safety and to guard against damage to the home in cold weather from burst frozen pipes. It should be noted that the selection of these categories are subject to the expectations of the decision maker, normally influenced by the risk context, and could also include factors such as lighting and transport.

Since space heating is included as a critical need special attention must be paid to the meaning of resilience, specifically the expectations that the backup system is to provide for. Consider the current natural gas furnace. In a power grid failure, natural gas will usually last for a day or more but this restriction limits the resilience possible in these scenarios as there is no backup natural gas supply available specifically for conventional natural gas furnaces in individual houses. All that can be done is to size the backup energy systems to support the controls and pumps of the heating system in these cases and hope for the best in terms of natural gas supply. The heat pump scenarios on the other hand use power and hence the backup systems can be sized to meet their total energy needs and keep the house warm passed the time natural gas would fail. In effect, protection of property is lacking in the furnace scenarios as the house may freeze given a long enough power outage.

The backup systems considered include the standard gasoline-powered generators available from the local hardware store. Both the battery and generator cases assume the PV supply can be used in a net metering fashion and help meet critical demands. The battery cases, however, are more speculative. Groupings of the 10 kWh Tesla Powerwall, with peak power rating of 3.3 kW are considered as are the use of the BEVs, when present in the scenario. However, the control systems for the use of these cars in this fashion are not currently available on the market, so this portion of the analysis serves to inform the market on some of the potential or challenges in this space.

3.2.5 Financial specifics

The financial analyses are completed by computing twenty years of projected cash flows and then computing the internal rate of return (IRR) as has been done elsewhere (Bristow and Kennedy 2010).

Each of the new scenarios is compared to a base case scenario. Operating costs are simply based on costs of the energy used. Local prices and billing structures for electricity, natural gas, and gasoline are used, including in the case of electricity and natural gas monthly charges that vary with quantity and time of use. Maintenance costs are assumed to be similar across all cases thus negligible for comparison purposes, and salvage values are considered zero, predominately as the products and systems are used to the end of their life and the aftermarket for home products and systems is practically nonexistent. The obvious exception to this is automobiles which may have a salvage value after the set lifetime used in this study. However, as the automobile case studies are computed relative to a base case with the same lifetime the salvage value differences can be safely assumed as negligible for the purposes of this introductory case study. Lifetimes and total up-front costs, including installation where applicable, are listed in Table 1.

3.2.6 Other factors

All simulations are performed hourly. Historic hourly weather data and electricity grid generation data for Ontario is used for the year 2014. Greenhouse gas emissions are computed hourly for electricity based on the hourly output of each power plant in Ontario and with respect to the power produced by the rooftop photovoltaic systems in the cases where the scenario includes such systems. This computation is explained in more detail in previous work (Bristow et al. 2011). The emissions factors used for electricity are the life cycle based median values from the IPCC (Moomaw et al. 2011). The same median value is used for natural gas burnt in the furnace since these are effectively the same (IPCC 2006). For gasoline the life cycle tool GHGenius value is used (S&T Consultants 2009).

4 Results

The results are divided into three sections: 1) building upgrade scenarios, 2) transportation scenarios, and 3) backup energy scenarios.

4.1 Building upgrade scenarios

As Figure 2 illustrates there are positive returns possible for a variety of different building upgrade scenarios. The ones that are labelled in the figure are on or near the Pareto optimal frontier with respect to energy and IRR. These range from two extremes: (1) high return but high remaining emissions and energy use; and (2) low return and deep cuts in energy use and emissions. The highest return alternative which is the LED upgrade is not pictured. The LED upgrade costs less, in terms of capital and operating, than replacing the CFL bulbs because of government incentive coupons. This upgrade leads to a small energy savings, but a small increase in GHGs because the heating load in winter becomes higher due to the efficiency of the lights and this demand is met by natural gas in the base case.

The highest return pictured is the combination of the LEDs and the attic insulation upgrade. This is followed by the 4.5 kW photovoltaic upgrade, for which returns are made possible by price drops over the last decade and the Ontario tariff program for small PV systems. When PV is grouped with a variety of options as shown in the labelled cluster just to the left, nearly identical returns are possible with added energy and emissions reductions. The careful grouping of options is necessary to ensure these returns, however. As can be seen by the remaining labelled results to the right, increasing reductions in energy and emissions come at the cost of lower returns. Noticeably the returns for the heat pumps are quite low while the energy and emissions reductions are quite high. This is due to a disappearance of incentives, in the Ground Source Heat Pump (GSHP) case, and a reduction in natural gas prices in the last several years since fracking grew in popularity in North America.

All but one of the scenarios in the label frontier include a 4.5 kW PV system. In isolation, the PV system brings meager energy and emissions cuts. Noticeably absent from all of the scenarios near the Pareto optimal frontier are natural gas to electric, or tank to tankless, changes to the hot water systems. Solar water heating systems are present in two scenarios near the frontier, however. This is likely due to the reduction in electricity demand from pre-heating the water with solar energy.

4.2 Transport scenarios

The alternative BEV drive trains use less energy and produce far less emissions as shown in Figure 3. This is due in part to the alternative drive train and the relatively clean electricity grid in Ontario, which has emissions that averaged around 55 tCO₂e/GWh in 2014, well below the 600 tCO₂/GWh value required for carbon parity between BEV and ICE cars (Kennedy et al. 2014).

Of the scenarios analyzed the 70D is the only alternative to result in a positive return compared to its respective base case, as shown in Table 2. The primary parameter of interest to this calculation is the years between purchases of a new vehicle. All other factors being equal, an increase in this quantity improves the business case for all of the BEVs, though this amount is unlikely to be large enough in practice to create positive returns for the other scenarios. With a fifty year horizon and a vehicle life of 20 years all of the BEV scenarios result in positive returns. In particular, the Leaf S for this horizon could produce a positive return at a 13 year lifetime.

4.3 Backup energy scenarios

Given that the location of the building is in an area with cold winters, stipulation of space heating as a critical demand, and the unavailability of reasonable backup systems for natural gas furnaces, the scenarios with furnaces cannot achieve the same level of resilience as those with heat pumps. The scenarios with furnaces and those without are hence discussed separately.

4.3.1 Scenarios with a conventional furnace and air conditioner

In the scenarios where a conventional furnace remains in the design then the backup energy system can, in terms of the critical heating need, only serve to enable the thermostat and control systems for the furnace. In these cases the conventional gasoline backup generator vastly outperforms the currently available battery options in terms of costs and run time for the expected critical peak energy needs.

In all cases where the initial building scenario with a furnace has a positive return, either a single 1 kW generator with a typically sized full tank or a 10 kWh battery can serve the critical energy needs for a

week or more. The generator is less expensive, despite the higher fuel costs of gasoline – around \$1,700 including install, versus over \$7,000 for the battery. The runtime for the generator ranges from 21 to 29 days, whereas the battery lasts from 7 to 10 days. The long running time, however, is not as encouraging as it first sounds since the natural gas supply would start to fail well after a couple of days. After which the choice of backup system is largely inconsequential.

4.3.2 Scenarios with heat pumps

As with the cases utilizing a furnace, the generator, on a single tank, outperforms the battery backup system both in terms of days of run time ranging from 46 to 180 days and in terms of costs. Selected system sizes are summarized in Table 3 along with the days of run time. Clearly, meeting the peak critical load also provides significant days of run time.

While a generator appears to be a better option over a battery, given a certain context, a battery has certain advantages over a generator. The primary problem with gasoline generators is that they must be quite large to meet peak load. Furthermore, gasoline presents a logistical burden in that you must go buy it and use it with some frequency because it can go bad. Going out to buy gasoline once a blackout has happened in the middle of winter due to an ice storm or blizzard may not even be possible hence leading to a failure of the backup strategy. On the other hand, a battery coupled with a BEV provides automated charging of the backup battery that can occur on site which maintains resilience of the battery option. Still, the car must be kept charged and the need to drive somewhere during an outage, such as to get supplies, must be balanced with energy needs for heating and food storage and preparation.

Overall, the use of a BEV (Tesla 70D, in this case) reduces the required backup energy system sizes, which helps alleviate some of the sizing issues with the generator. The assumption that the 70D can provide the power capacity of two batteries due to it being a double charger, however, means the available run time is decreased in the case of a backup generator. In any event as prices in BEV and battery backup technologies continue to fall (Nykqvist and Nilsson 2015), it is clear that development of

the necessary charging control systems is a desirable pathway of innovation in the pursuit of resilient and sustainable households.

A speculative financial assessment of the backup options provides yet another different perspective and is presented in Figure 4. This analysis assumes a loss to the household per power outage of \$1,700, which is based on estimates of wastage of refrigerator and frozen food, a stay in a hotel and the insurance deductible for addressing a leak resulting from a burst frozen pipe with an occurrence of one every twenty years. When simulated, only three scenarios in this study produce positive returns regardless of the backup energy option. Each has a GSHP and 4.5 kW PV system and include small variations in demand reduction. These three are nearly the lowest energy, lowest emitting solutions. The only other scenarios that would be lower would also include the Nissan Leaf as the car. These three scenarios can meet critical energy needs for two months with a backup generator or indefinitely with the battery system. That such a sustainable and resilient household can be established through retrofit is quite encouraging. Indeed, this is a bit speculative, and the returns would be lessened by a luxury car. Conceivably, however, the business case could be made even stronger if the avoided interruption in desirable living circumstances during the hotel stay and flood remediation could also be quantified or if the home insurance premiums due to the flood protection afforded by the backup systems could be reduced.

5 Discussion

A methodology for sustainable and resilient design of an individual residential building as a system subject to specified environmental and economic contexts was presented. A midsize single detached house was modelled and the effects of various combinations of retrofits on the performance of the building was simulated through an initial case study. The systems framework focused in on the energy needs of a single detached house. Through the case study, business cases of many home retrofits could be made and unique combinations were found to bring up to over a quarter in energy use reduction and

emissions mitigation while providing good returns. Others approached an elimination of emissions with a small return.

Augmenting the studies' sustainability cases with energy resiliency solutions illustrated several promising pathways in the area of backup energy preparedness. For one, home energy resilience in a cold climate is difficult to achieve when natural gas furnaces are utilized, at least as far as taking individual action is concerned. Hence, to improve resilience at an individual level, homeowners could be empowered by new technology development in the area of BEVs and the automated control and scheduling of battery charging. When a household employs a BEV, size requirements of a backup generator is significantly reduced which saves on initial capital costs and reduces fuel demand as well as associated fuel storage risks. When a battery is implemented as the backup energy system, sized to meet peak critical energy needs, a BEV more than doubles the runtime of the backup system thereby providing more resilience in extreme circumstances. That extended periods of energy self-sufficiency is achievable through the backup energy system design of a building with transport considerations in this case study gives an insightful finding. That is, synergies through an integration of options reinforces the need to consider resiliency and sustainability of the building as well as transport together in a systems approach.

Moving forward these synergies can be investigated with consideration of further factors. First, resilience to utility disruption is not the only hazard homeowners face in a changing climate. For instance, water and energy are tightly coupled (Gleick 1994). Water shortages might be experienced at the same time as utility failures. Follow-up study can expand on the methodology proposed here with an all-hazards approach that can map all these interrelationships and support recovery planning (Bristow and Hay 2016). Further, future work can consider a wider parameter space, such as building deterioration over time, occupant behaviour and changing ownership so as to be able to capture the potential impacts of applying this context-specific integrated analysis process across an entire building stock over time. Finally, pairing these dynamical considerations with sensed data has the potential to result in a robust dynamic learning solution for planning retrofits and equipment changes.

6 Conclusion

This paper started by citing the IPCC consensus that mitigation and adaptation to climate change requires solutions that balance one another and that are built for the specific context. The consensus enlightened an exploration on how the performance of households contribute to mitigation and how well they stand up to emerging and extreme hazards due to climate change. The growing evidence points to the need for novel integration of the decisions and operations within a household to the world beyond the walls of the building.

The results of this integration study shows that there are various custom retrofits available for the home that produce a positive return and advance the sustainability of the building. To progress the resiliency of the household, as a whole, however, the solutions with the best returns include a battery electric vehicle as a contributor to the backup energy supply. Hence, in addition to contributing a novel method for conducting this form of analysis, this paper also shows this heretofore unknown synergy that is available as soon as automakers complete the addition of recharge capability to their electric vehicles.

As a first step towards a detailed systems understanding of the potential for advancing the household-wide climate change resilience and sustainability this work lays a foundation for further studies that can be scaled up to large-scale building-stock computational assessment of retrofit potential in cities. Such advancement has the potential for steering retrofit policy or incentives that can be customized to the building type and automotive needs of a household.

7 References

- Bahill, A.T., and Gissing, B. 1998. Re-evaluating systems engineering concepts using systems thinking. IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews, 28(4): 516–527. doi:10.1109/5326.725338.

- Bristow, D., and Hay, A. 2016. A graph model for probabilistic resilience and recovery planning of multi-infrastructure systems [online]. *ASCE Journal of Infrastructure Systems*. doi:10.1061/(ASCE)IS.1943-555X.0000338.
- Bristow, D.N., and Kennedy, C.A. 2010. Potential of building-scale alternative energy to alleviate risk from the future price of energy. *Energy Policy*, 38(4): 1885–1894. doi:10.1016/j.enpol.2009.11.067.
- Bristow, D.N., Richman, R., Kirsh, A., Kennedy, C.A., and Pressnail, K.D. 2011. Hour-by-Hour Analysis for Increased Accuracy of Greenhouse Gas Emissions for a Low-Energy Condominium Design [online]. *Journal of Industrial Ecology*. doi:10.1111/j.1530-9290.2011.00335.x.
- DMG. 2011. Transportation Tomorrow Survey: Waterloo Region [online]. Available from <http://dmg.utoronto.ca/transportation-tomorrow-survey/tts-reports> [accessed 1 July 2015].
- Engel-Yan, J., Kennedy, C.A., Saiz, S., and Pressnail, K. 2005. Toward sustainable neighbourhoods: the need to consider infrastructure interactions. *Canadian Journal of Civil Engineering*, 32(1): 45-57.
- Galiotto, N., Heiselberg, P., and Knudstrup, M. 2015. Integrated Renovation Process: Overcoming Barriers to Sustainable Renovation. *Journal of Architectural Engineering*, 21(3): 04015007:1-12. doi:10.1061/(ASCE)AE.1943-5568.0000180.
- Gleick, P. 1994. Water and Energy. *Annual Review of Energy and the Environment*, 19(1): 267–299. doi:10.1146/annurev.eg.19.110194.001411.
- Hay, A. 2013. Operational Survival: Putting resilience at the core of infrastructure planning. Explora Research, London, UK.
- IPCC. 2006. Chapter 2: Stationary Combustion. In *IPCC Guidelines for National Gas Inventories* [online]. Available from http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf [accessed 31 July 2015].
- IPCC. 2014a. Summary for Policymakers. In *Climate Change 2014 Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on*

- Climate Change [online]. Available from http://ar5-syr.ipcc.ch/ipcc/resources/pdf/IPCC_SynthesisReport.pdf [accessed 31 July 2015].
- IPCC. 2014b. Summary for Policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.
- Isherwood, M. 2012. The future of Ontario's natural gas infrastructure. Presentation to the Ontario Energy Board, Union Gas [online]. Available from <https://www.uniongas.com/~media/storage-transportation/communications/pdf/presentations/2012/OEBPresentationMay302012.pdf> [accessed 8 September 2015].
- Kennedy, C.A., and Corfee-Morlot, J. 2013. Past performance and future needs for low carbon climate resilient infrastructure— An investment perspective. *Energy Policy*, 59: 773–783. doi:10.1016/j.enpol.2013.04.031.
- Kennedy, C.A., Ibrahim, N., and Hoornweg, D. 2014. Low-carbon infrastructure strategies for cities. *Nature Climate Change*, 4(5): 343–346. doi:10.1038/nclimate2160.
- Landauer, M., Juhola, S., and Söderholm, M. 2015. Inter-relationships between adaptation and mitigation: a systematic literature review. *Climatic Change*, 131(4): 505–517. doi:10.1007/s10584-015-1395-1.
- Moomaw, W., Burgherr, P., Heath, G., M. Lenzen, J. Nyboer, and A. Verbruggen. 2011. Annex II: Methodology. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Edited by O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer, and C. von Stechow. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp. 974–1000.

- NRCan. 2013. Comprehensive Energy Use Database [online]. Available from http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm [accessed 3 January 2017].
- Nykqvist, B., and Nilsson, M. 2015. Rapidly falling costs of battery packs for electric vehicles. *Nature Climate Change*, 5(4): 329–332. doi:10.1038/nclimate2564.
- O'Neill, P. 2013. Protecting Critical Infrastructure by Identifying Pathways of Exposure to Risk. *Technology Innovation Management Review*, 3(August 2013: Cybersecurity): 34–40.
- Ouyang, M., Dueñas-Osorio, L., and Min, X. 2012. A three-stage resilience analysis framework for urban infrastructure systems. *Structural Safety*, 36–37(May–July 2012): 23–31. doi:10.1016/j.strusafe.2011.12.004.
- Sager, J., Armstrong, M., and Szadkowski, F. 2013. Cooling and heating season performance assessment of a cold climate air source heat pump. CanmetEnergy, Natural Resources Canada.
- S&T Consultants. 2009. The Development of Provincial Inputs for GHGenius. NRCan Office of Energy Efficiency, Ottawa, Ontario [online]. Available from <http://www.ghgenius.ca/reports/ProvincialModelsFinalReport.pdf> [accessed 31 July 2015].
- Sugar, L., Kennedy, C., and Hoornweg, D. 2013. Synergies between climate change adaptation and mitigation in development: Case studies of Amman, Jakarta, and Dar es Salaam. *International Journal of Climate Change Strategies and Management*, 5(1): 95–111. doi:10.1108/17568691311299381.
- Van de Weghe, J.R., and Kennedy, C.A. 2007. A Spatial Analysis of Residential Greenhouse Gas Emissions in the Toronto Census Metropolitan Area. *Journal of Industrial Ecology*, 11(2): 133–144. doi:10.1162/jie.2007.1220.

8 List of Figures

Figure 1: ReSus Systems Methodology Overview

Figure 2: Rate of return with respect to percent GHG reduction and net annual energy usage after solar energy capture. Not pictured: LED upgrade which has a lower first cost and lower operating cost than the base case due to Ontario incentives. Note that the base case energy use and emissions are 40.6 MWh/year and 16 tCO₂e/year, respectively (tCO₂e is metric tons = 1,000 kg of carbon dioxide equivalent emissions). DM means demand management and includes lighting, insulation, and appliance upgrades.

Figure 3: Automobile Energy Use and GHGs by Scenario

Figure 4: Example rate of return with backup systems. Scenarios include Tesla 70D and the building upgrades stipulated on the vertical axis. This speculative example assumes BEV capacity can be used by the household critical loads, that the average loss per power outage is \$1,700 (including loss of fridge contents, stay in a hotel and insurance deductible for addressing leak resulting from frozen burst pipe) with an occurrence of one every twenty years. The potential for reduction in home insurance premiums due to the added protection afforded by the backup systems is not included but is an area of future research. Ins. means insulation.

9 List of Tables

Table 1: Summary of case study system costs and lifetimes

Table 2: Automobile financial analysis results for BEV scenarios relative to base case.

Table 3: Backup sizes and days of runtime by backup type, with and without BEV backup included. The BEV scenario is for the Tesla 70D. Blanks in scenario are for the base case. All scenarios in this table include water heaters with tanks. Both in the demand reduction column refer to LEDs and attic insulation. An ∞ symbol means the critical demand can be met by the PV system. All system sizing is based on a heating set point of 15°C.

Draft

Table 1: Summary of case study system costs and lifetimes

System	Total First Cost (\$)	Lifetime (years)
Photovoltaic		
4.5 kW	21,100	20
4.0 kW	20,100	20
3.5 kW	19,100	20
Solar Water Heating		
6.0 m ²	6,940	20
3.7 m ²	4,340	20
Attic Insulation		
Ceiling R-60 Cellulose	885	20
Lighting		
40 CFLs*	376	7
40 LEDs	251	20
Washer		
Base case	621	14
High Efficiency	677	14
Dryer		
Base case	593	14
High efficiency	734	14
Water Heating		
Gas*	958	13
Electric	525	13
Electric Tankless	2,130	20
Gas Tankless	1,970	20
Space Conditioning		
Gas Furnace, 80% AFUE*	3,650	17.5
AC, SEER 13*	3,860	17.5
Gas Furnace, 98% AFUE	4,850	17.5
AC, SEER 21	5,140	17.5
ASHP, SEER 17	8,880	20
GSHP, SEER 16.6	23,000	20
Automobiles		
Audi A7 Sportback	75,500	8
Tesla 70D	82,200	8
Tesla 85D	92,400	8
Nissan Leaf S	23,700	8
Nissan Leaf SV	27,700	8
Vauxhall Corsa S	16,000	8
Backup Energy		
Gasoline Generator (1 kW)	1,700	10
Battery (10kWh, 3.3kW)	7,140	10

Prices in Canadian Dollars. * Refers to base case. If no base case is listed then that building component is left unchanged in the base case so no cost is incurred. All costs are net of incentives. For the Teslas and Nissan Leafs this equates to a discount of \$8,500 on the car and 50% of the charger and charger installation. For the LEDs this corresponds to a \$5 discount per light. Prices vary in the actual simulation by system size.

Table 2: Automobile financial analysis results for BEV scenarios relative to base case.

	First Cost	Approximate Operating Cost	IRR
Leaf S*	\$7,750	-\$754	n/a
Leaf SV*	\$11,680	-\$754	n/a
Tesla 70D**	\$6,730	-\$1,230	11%
Tesla 85D**	\$16,930	-\$1,210	n/a

* Relative to Nissan Versa Note S

** Relative to Audi A7 Sportback

Draft

Table 3: Backup sizes and days of runtime by backup type, with and without BEV backup included. The BEV scenario is for the Tesla 70D. Blanks in scenario are for the base case. All scenarios in this table include water heaters with tanks. Both in the demand reduction column refer to LEDs and attic insulation. An ∞ symbol means the critical demand can be met by the PV system. All system sizing is based on a heating set point of 15°C.

HP	Scenario				Peak Size in kW		Run Time in Days	
	PV kW	SWH m ²	Water Heating	Demand Reduction	Gen (+BEV)	Battery (+BEV)	Gen (+BEV)	Battery (+BEV)
ASHP	4.5		Electric		12(6)	13(6.6)	102(57)	12(27)
ASHP	3.5	6.0		Both	11(5)	13(6.6)	46(27)	6(13)
ASHP	4.5		Electric	Both	11(5)	13(6.6)	109(63)	14(31)
GSHP	3.5	6.0	Electric		6(0)	7(0)	123(94)	14(50)
GSHP	3.5	6.0	Electric	Both	6(0)	7(0)	160(122)	19(66)
GSHP	3.5	6.0			6(0)	7(0)	134(102)	16(55)
GSHP	3.5	6.0		Both	6(0)	7(0)	180(137)	21(74)
ASHP	4.5				12(6)	13(6.6)	108(60)	13(28)
GSHP	4.5		Electric		6(0)	7(0)	$\infty(\infty)$	$\infty(\infty)$
GSHP	4.5		Electric	Both	6(0)	7(0)	$\infty(\infty)$	$\infty(\infty)$
ASHP	4.5			LEDs	12(6)	13(6.6)	105(58)	12(28)
ASHP	4.5			Both	11(5)	13(6.6)	116(67)	15(33)
GSHP	4.5				6(0)	7(0)	$\infty(\infty)$	$\infty(\infty)$
GSHP	4.5			Both	6(0)	7(0)	$\infty(\infty)$	$\infty(\infty)$
GSHP	4.5			LEDs	6(0)	7(0)	$\infty(\infty)$	$\infty(\infty)$

Supporting Information

Contents

1	Contextual Information.....	1
1.1	Hourly historical weather.....	1
1.2	Hourly historical electricity generation by generator.....	1
1.3	Life cycle emissions intensity factors for electricity generators.....	1
2	Reference case building specifications	1
2.1	Insulation.....	1
2.2	Automobile Data.....	2
3	Backup energy system details.....	2
4	Financial Information.....	2
4.1	Solar PV Tariff Rate	2
4.2	Utility rates.....	2

1 Contextual Information

1.1 Hourly historical weather

Environment Canada Historical Climate Data, <http://climate.weather.gc.ca/>

1.2 Hourly historical electricity generation by generator

IESO Generator Output and Capability Reports, <http://reports.ieso.ca/public/GenOutputCapability/>

1.3 Life cycle emissions intensity factors for electricity generators

Moomaw, W. et al., 2011. Annex II: Methodology. In O. Edenhofer et al., eds. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 974–1000.

2 Reference case building specifications

The circa 2001 building follows upon construction was subject to the 1997 Ontario Building Code¹.

2.1 Insulation

The building is located in heating degree day zone 1 (<5000) and hence the insulation RSI values are as follows:

	RSI	R-Value
Ceiling below attic or roof space	5.4	31

¹ <https://www.ontario.ca/laws/regulation/970403> [Accessed July 13, 2015].

Roof assembly without attic or roof space	3.52	20
Wall other than foundation wall	3	17
Foundation walls enclosing heated space	1.41	8
Floor, other than slab-on-ground	4.4	25
Slab-on ground containing pipes or heating ducts	1.76	10
Slab-on-ground not containing pipes or heating ducts	1.41	8

2.2 Automobile Data

	hp	Fastest Full Charge Time* (hr)	Net Price**	l/100km City	l/100km Hwy
Tesla 70D	329	8.5	\$82,249	2.33	2.31
Tesla 85D	422	9.6	\$92,449	2.48	2.22
Nissan Leaf S	107	8	\$23,748	1.9	2.3
Nissan Leaf SV	107	5	\$27,676	1.9	2.3
Nissan Versa Note S	109	n/a	\$16,000	8.6	6.5
Audi A7 Sportback	240	n/a	\$75,520	13.1	8.4

* With best charging capability available by car model (note according to Tesla, charging time is linear with kWh). Charging efficiency is assumed to be 85% as opposed to the ~90% Tesla suggests given experiential data.

Sources: www.nissan.ca, www.teslamotors.com/en_CA, www.audi.ca, www.fueleconomy.gov, ecomento.com, www.mto.gov.on.ca, www.teslarati.com

** Price are net of incentives and include fees, charger and install (roughly \$250 for the leaf S and just under a thousand for the other electric vehicles net of incentives).

3 Backup energy system details

Text...

4 Financial Information

4.1 Solar PV Tarrif Rate

<http://microfit.powerauthority.on.ca/sites/default/files/page/FIT%20Price%20Schedule%202014-09-30.pdf>

4.2 Utility rates

Electricity: <http://www.wnhydro.com/en/your-home/time-of-use-rates.asp>

Natural Gas: <https://www.uniongas.com/residential/rates/current-rates>