

RESEARCH

Iterative 'what-if' neighborhood simulation: energy and emissions impacts

Jonathan Salter¹, Yuhao Lu², Ju Chan Kim³, Ronald Kellett⁴, Cynthia Girling⁵, Fausto Inomata⁶ and Alix Krahn⁷

Abstract

As efforts to address climate change shift to action at local scales, municipalities are called upon to develop locally specific action plans. Many municipalities lack the resources to develop energy and emissions-reducing policy interventions appropriate to their characteristics. This research synthesises urban form, scenario analysis and energy simulation into a cohesive workflow for evaluating energy and emissions policy interventions across a range of urban forms. A geospatial and census analysis of six cities across British Columbia, Canada, led to the development of seven urban neighborhood patterns. These represent neighborhood forms and densities found in cities of various sizes, densities, forms and climates. To test the approach of an urban built environment model (UBEM), retrofit and infill redevelopment 'what-if' scenarios were applied iteratively to two sample patterns comparing the relative efficacy of building technology-improvement policies versus land-use intensification policies. The future 'what-if' policy scenarios were spatially tested and validated using relevant policy. The simplified UBEM methods applied to typical patterns and development demonstrates a step towards an accessible and flexible modeling approach. Small and medium-sized municipalities can use this approach to assess and compare potential energy and emissions policy options and outcomes at building and neighborhood scales.

Practice relevance

A new, simple method has been created for municipalities to understand multiple 'what-if' scenarios for reducing energy demand and emissions from buildings. This is based on profiles from census data, geospatial analysis and energy data that characterise urban neighborhood patterns. The approach integrates building-scale and neighborhood-scale energy and greenhouse gas simulations. It can simulate a variety of policy scenarios and strategy interventions in order to show the interactions between and among urban form and retrofit options. This enables planners and decision-makers to compare the relative magnitudes of different interventions at the neighborhood or city level for energy and emissions performance. The model was developed for use by a variety of communities in British Columbia, Canada. There is potential for adapting this method for use in other locations.

Keywords: buildings; energy demand; energy model; energy policy; neighborhood; urban morphology; 'what-if' scenarios

1 Introduction

Planning for climate change mitigation has increasingly shifted to policy development and actions at local scales. Many regional and municipal governments now set their own targets and develop their own action plans over and above those of more senior jurisdictions such as federal and international agencies (Denis & Parker 2009; Schreurs

¹ Education and Research, ESRI Canada, Toronto, ON, CA. ORCID: 0000-0002-5483-5607

² School of Architecture and Landscape Architecture, University of British Columbia, Vancouver, BC, CA. ORCID: 0000-0001-8574-1999

³ School of Architecture and Landscape Architecture, University of British Columbia, Vancouver, BC, CA. ORCID: 0000-0002-5988-8230

⁴ School of Architecture and Landscape Architecture, University of British Columbia, Vancouver, BC, CA. ORCID: 0000-0002-6363-8912

⁵ School of Architecture and Landscape Architecture, University of British Columbia, Vancouver, BC, CA. ORCID: 0000-0002-0651-8244

⁶ Planning, Urban Design & Sustainability, City of Vancouver, Vancouver, BC, CA. ORCID: 0000-0002-8152-6930

⁷ MODUS Planning, Design, and Engagement, Vancouver, BC, CA. ORCID: 0000-0003-4205-9118

Corresponding author: Yuhao Lu (luyuhao@mail.ubc.ca)

2008; Yi & Feiock 2015). In most cases, the municipalities leading these mitigation planning efforts are large metropolitan centers with sufficient expertise and resources to inventory existing energy demand and emissions, and plan future interventions (*e.g.* City of New York 2014; City of Vancouver 2015; City of Toronto 2017). However, many North American municipalities are smaller and quite different from larger cities. Even with the oft-cited trend towards urbanisation (Batty 2013; United Nations 2014), significant populations live in small and medium-sized cities and municipalities that in aggregate tend to use more energy per capita (Calthorpe 2011; Province of British Columbia, Climate Action Secretariat 2012) and contribute substantially to greenhouse gas emissions. There exists a significant opportunity and challenge to address energy and emissions across a range of municipality sizes and patterns. However, as smaller cities and municipalities lack the expertise, resources and data to undertake local policy development and simulation, progress toward effective, locally calibrated initiatives and actions will require less resource-intensive approaches and tools able to simulate energy and emissions policy interventions across a diversity of community types and conditions.

Research built upon morphological analyses has been applied to investigations of urban form on building energy demand in various scales. Martin & March (1972) conducted early research on the relationships between building and urban geometry and light access. Baker & Steemers (2000) extended this approach leading to the development of their lighting and thermal (LT) model. Baker & Steemers (2000) and later Ratti, Baker, & Steemers (2005) identified passive versus active zones (for daylighting and ventilation) as key determinants of building energy performance. Steadman and colleagues (Evans, Liddiard, & Steadman 2017; Steadman, Hamilton, & Evans 2014) conducted extensive research on the relationships between geometric building form and energy demand. They found strong relationships between building surface area and building depth, and demand for electricity and gas in a study of the London building stock (Steadman *et al.* 2014). Salat (2009) found significant impacts on building energy demand based on a building's shape factor: the relationship between a building's surface area and its volume. In colder climates, a higher shape factor (*i.e.* more exposed envelope per unit of building volume) results in higher energy loads.

Although research has demonstrated that a dense, compact form often results in lower energy use (EU) per capita, the interaction between density and energy efficiency remains unclear depending on factors such as city size, building types, climate and energy source. Güneralp *et al.* (2017) provided a global scenario outlook on potential energy savings achieved by dense urban development and building retrofit. They suggested that, globally, urban density influences total EU just as much as EU per capita. In Canada, Larivière & Lafrance (1999) investigated the 45 most populous cities in the province of Quebec and concluded a 7% EU per capita reduction when increasing population density from 1000 to 3000 people per km². Ewing & Rong (2008) investigated the impacts of urban density on residential energy in the United States. Their conceptual model identified three causal pathways for urban form that impact residential energy consumption through urban heat island effects, and the energy impacts of varying housing stocks. Their model suggested that interactions between house type and size and the resulting urban form (*e.g.* density) have a significant impact on overall energy consumption. Silva, Oliveira, & Leal (2017) also provided a comprehensive review of urban form variables contributing to building energy performance.

These morphological and statistic approaches to energy and urban form offer valuable ways to assess the impact of individual building design and urban-scale characteristics on energy performance. However, these approaches do not account for the significant and highly variable impacts of building scale technological changes such as envelope materials and standards, heating, ventilation and air-conditioning (HVAC) systems, and controls, *etc.*, nor the potential interactions between building-scale variables and urban form attributes. For these types of analyses, more comprehensive and spatially fine-grained simulation approaches are necessary but challenging to implement at neighborhood scales.

This paper describes a hybrid approach to simulating built-environment energy and emissions policy interventions using urban neighborhood patterns characteristic in many cities in British Columbia (BC), Canada. BC was the first jurisdiction in North America to institute a carbon tax in 2008 (Murray & Rivers 2015). In parallel, the provincial government enacted Bill 27, an amendment to the Local Governments Act requiring all municipalities in the province to inventory their emissions and plan future mitigation strategies (Stevens & Senbel 2012). BC Hydro provided funding for municipalities to complete community energy and emissions plans (CEEPs) to meet Bill 27's requirements. The scope of those CEEPs is variable, and implementation has been slow in many municipalities (Stevens & Senbel 2012). The results are to assist local municipalities visualise and evaluate alternative policy interventions at a neighborhood scale. Among the contributions of this research are new methods and tools for simulating the energy and emissions consequences of policy options across various built environments in BC:

- To analyse and categorise patterns of urban form across BC's communities and to develop a set of common neighborhood scale patterns.
- To adapt an Urban Modeling Interface (UMI) to model current and future energy and emissions profiles for these neighborhood patterns.
- To simulate the effectiveness of alternative energy and emissions-reducing policy options at building and neighborhood scales.

2 Methods

In order to simulate energy and emissions interventions across a range of urban form patterns, the methods underlying this research integrate steps of urban form characterisation, scenario analysis and energy simulation into a cohesive workflow (**Figure 1**). Prior research related to the categorisation of urban form (section 2.1), the development of urban form patterns (section 2.2), and the simulation of ‘what-if’ scenarios (section 2.3) and validation of building energy demand at neighborhood scales (section 2.4) have contributed to this methodology.

2.1 Urban form characterisation

There is a long tradition of analysis and categorisation of urban forms (Kropf 2009). Clifton *et al.* (2008) reviewed the quantitative approaches to the study of urban form, identifying five approaches based on disciplines of study, including landscape ecology, economic structure, transportation planning, community design and urban design. The community design category, typified by the work of Song & Knapp (2004, 2007), relates closely to the research reported in the present paper. Song & Knapp (2004, 2007) used geographic information system (GIS) and spatial analysis methods to measure characteristics of urban patterns such as land use, intensity, parcelisation and street networks, and subsequently to categorise urban form based on those parameters. Similar approaches have been used in mobility research, connecting urban form to health outcomes (Frank *et al.* 2005).

Doxiadis (1968) and Salat (2011) investigated the morphological attributes of urban form patterns across scales to analyse important processes and interactions that occur at different urban scales. Doxiadis (1968) used a multi-scalar grid to examine human settlements, in many ways anticipating later fractal approaches (*e.g.* Salat 2011; Batty 2013). When studying urban form at the village to city scale, Doxiadis primarily used 100 or 200 m grids. Salat (2011) used a similar approach, but subdivided patterns into 200 × 200 m (group of blocks), 400 × 400 m (neighborhood) and 800 × 800 m (district) grids. Within those grids, constituent characteristics such as block and dwelling density, block coverage, urban form, dwelling types, *etc.* were measured. Rode *et al.* (2014) applied this subdivision and categorisation of urban form, identifying and measuring homogenous 500 × 500 m patches of urban form in London, Paris, Berlin and Istanbul, and simulating the heat energy demand associated with these different forms of development. The analysis of urban form patterns and development of the urban form patterns in the present study drew from this body of research.

Six cities across BC were selected to test a pattern characterisation methodology that combined census data analysis, spatial analysis and qualitative input from professionals. These cities were selected based on four primary criteria:

- data accessibility: at the time of study only 13 municipalities in BC had open data
- population size: a distribution of city sizes from a small to a large municipality
- population growth rate: a distribution from low to negative growth rates, to high growth rates for the period 2006–11
- geographical and climatic context: BC has extremely varied climatic conditions; these climate conditions have significant impact on EU and emissions.

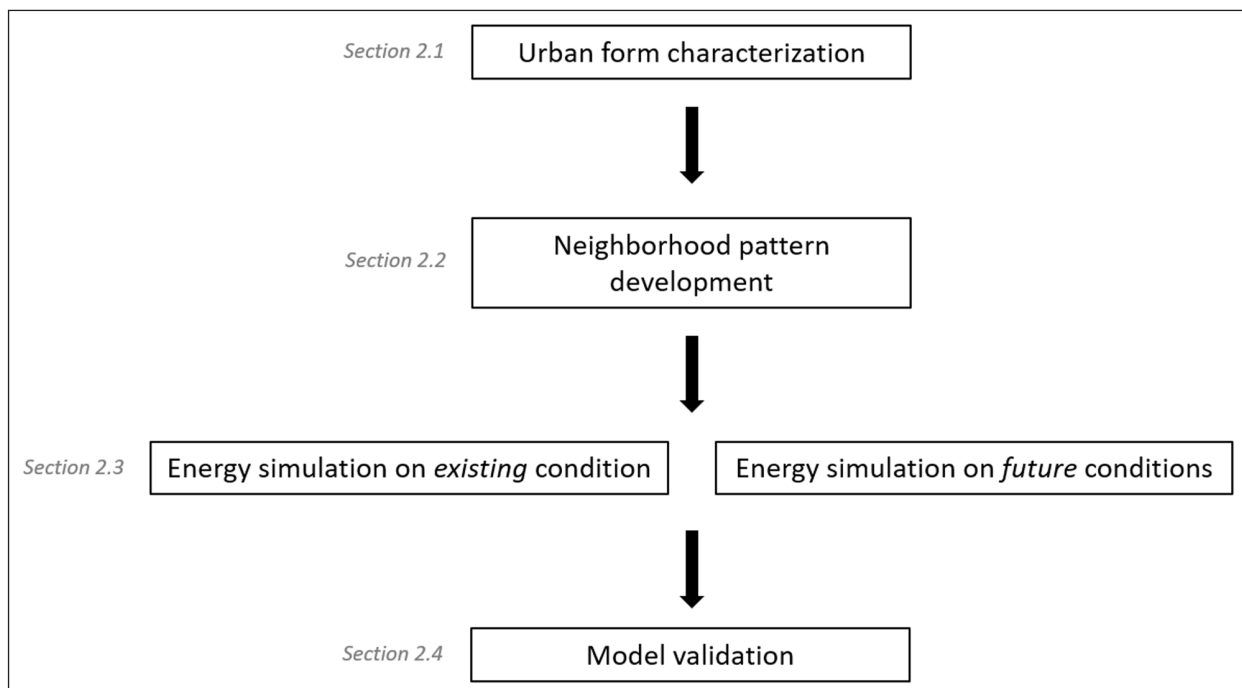


Figure 1: Key stages of the proposed methodology.

The cities ultimately selected included two smaller, lower density, low-growth examples from the cold Northern and Eastern Interior (Prince George, Revelstoke), two mid-sized, less dense but high-growth examples from the Southern Interior (Kelowna) and Vancouver Island (Saanich), and two larger, denser, high-growth examples from the Lower Mainland (Vancouver, Surrey). These examples range in population from 7000 to 600,000 and represented over half of BC's population in 2011.

Within each selected city, four filters, two quantitative and two qualitative, were applied to categorise census dissemination areas (DAs) into representative land-use and population density categories. Census DAs were quantitatively sorted by population density. Coarse census-based population density categories were then overlaid spatially on land-use and urban-form patterns. In a first qualitative analysis pass, the categorised DAs were presented to an advisory group of planners and urban designers to identify most characteristic spatial patterns. Based on a review of the literature (Salat 2011, Kellett 2009, Rueda 2017, Song & Knapp 2004, 2007), seven metrics were selected to further analyse and categorise urban form patterns, including proportions of land uses (total area of each land use type divided by each DA area), lot density (quantity of lots divided by each DA area), median lot area (median lot area in each DA), median footprint area (median footprint area in each DA), median footprint to lot area ratio (median of footprint area divided by lot area), three-way intersection density (number of three-way intersections divided by the corresponding DA area), and four-way intersection density (number of four-way intersections divided by the corresponding DA area). Also calculated were the same metrics aggregated by population density and by municipality. To achieve that, all lots, footprints and intersections from all chosen municipalities were added to locate representative metrics that take all the selected DAs into consideration. This process yielded spatial metrics that would define the archetypal neighborhood patterns. The DAs selected in the first qualitative pass were then quantitatively ranked by population density and grouped using these measures. The ranked DAs were then presented to the advisory group in a second qualitative step where seven most common urban neighborhood patterns were identified and categorised by population density ranges, street patterns and land-use mix.

2.2 Developing urban neighborhood patterns

These top-ranked DAs were then generalised into 400×400 m urban neighborhood patterns, drawn in GIS and modeled in Rhino (**Figures 2 and 3**). Each pattern closely resembles population density, parcel density, street patterns, block sizes, parcel sizes and land-use proportions associated with the selected source DAs, but is generalised to be more broadly applicable to a range of similar DAs. In a second step (**Figure 3**), generalised building types were assigned to each parcel, based on visual surveys and BC Assessment (2017) data (which ties building type, age, use, occupancy, construction type, and date and fuel sources to each parcel of land). This process replicates prior urban planning and design simulation approaches conducted by the authors and affiliated researchers (Senbel *et al.* 2011, 2013; Van der Laan, Kellet, & Girling 2013), and is similar to the approach described by Rode *et al.* (2014). These seven neighborhood patterns (**Figure 2**), characteristic of a broad range of urban development patterns in BC, enable iterative and comparable building energy and emission 'what-if' simulations at a neighborhood scale. It is explained below how two possible energy-mitigation policies applied to one of the neighborhood patterns—the 15–35 people per ha (pph) single-family loops—were tested using urban building energy modelling software.

2.3 Adapting and applying the Urban Modeling Interface (UMI)

Reinhart & Cerezo Davila (2016) reviewed 'urban building energy modeling' (UBEM) that aggregated simulations of individual buildings at district and city scales. Two notable examples are the SimStadt model from Hochschule fur Technik in Stuttgart, which uses CityGML and its energy Application Domain Extension to simulate steady-state heat-balance models at neighborhood to city scales (Wate & Coors 2015; Nouvel *et al.* 2013); and the UMI, an open-source tool developed in MIT's Sustainable Design Lab, which conducts dynamic building simulations based on the US Department of Energy's (US DOE) EnergyPlus simulation engine (Cerezo Davila, Reinhart, & Bemis 2016).

The UMI was developed in association with the City of Boston to simulate existing energy demand for the entire city. To accomplish energy simulation at this urban scale, UMI makes several simplifications, including the development of a shoebox model (Dogan & Reinhart 2013) to optimise building-scale simulation, and the definition of a smaller set of building patterns (Sokol, Cerezo Davila, & Reinhart 2017) to represent the diversity of built forms. UMI uses building geometry and building template files that describe construction materials, window to wall ratios, equipment, *etc.* for a given pattern. Similar to SimStadt, UMI also simulates the effects of inter-building shading and insolation. These new UBEM approaches present the opportunity to simulate the impacts of urban form with technological and behavioral interventions to provide an integrated view of built-environment energy demand. However, these approaches bring significant data requirements (Reinhart & Cerezo Davila 2016; Swan & Ugursal 2009) beyond the reach of many municipalities.

The methodology developed for this research adapted UMI for the simulation of future scenarios based on its capability to simulate land use, urban form and technological at urban scales with local weather profiles. The authors applied UMI to one of the patterns and ran two different energy-mitigation scenarios, one involving renovating or replacing existing building stock at similar densities and form, and the other involving the redevelopment of a portion of the neighborhood pattern at significantly higher densities.

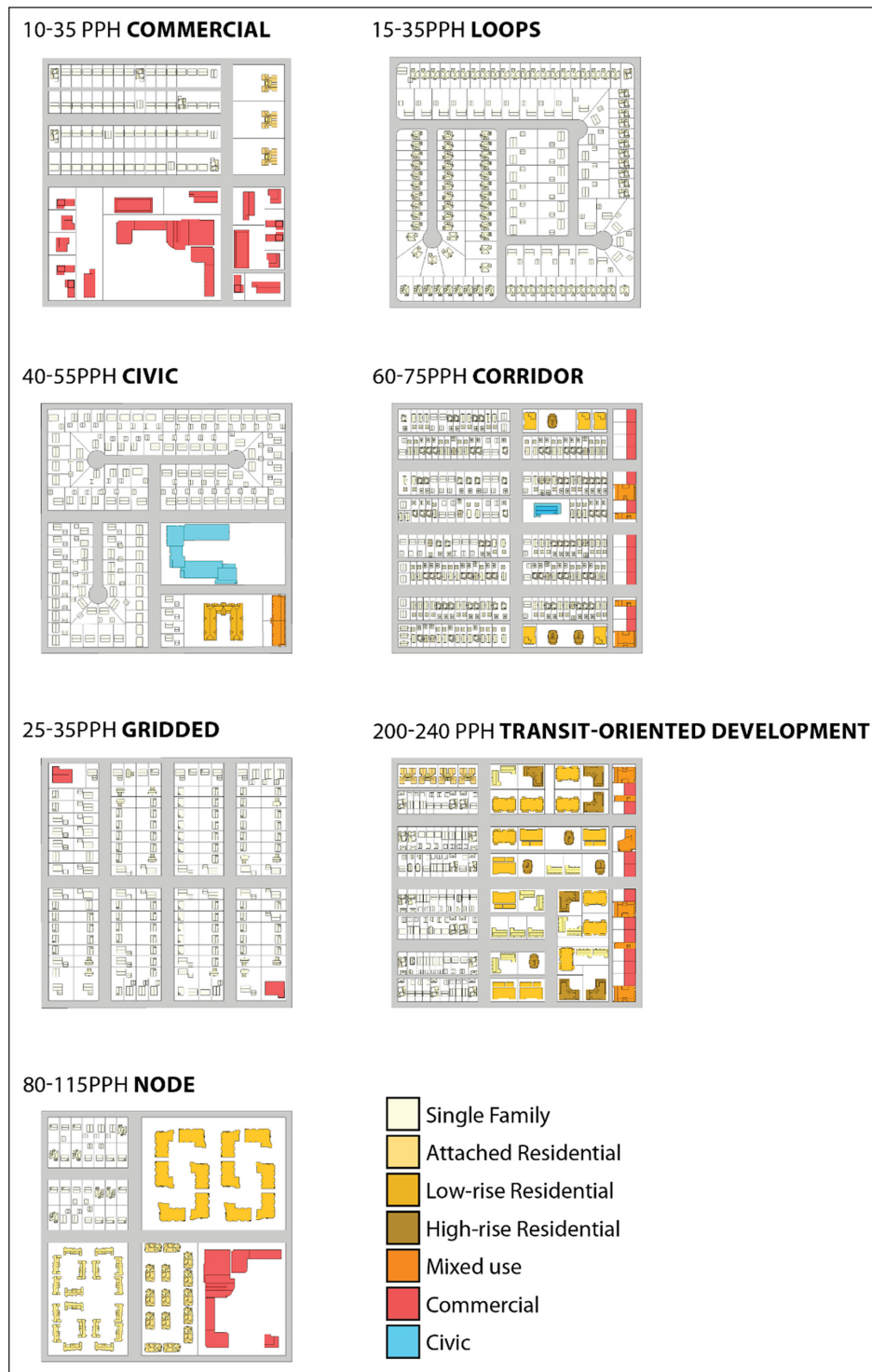


Figure 2: Seven urban neighborhood patterns (400 × 400 m) developed to represent various communities in British Columbia.

Note: pph = people per ha.

The UMI derives building geometry and building spatial arrangement information and connects that geometric information to a building template file that contains information such as window, wall and roof materials, orientation-specific window/wall ratios, presence or absence of specific equipment such as heat-recovery ventilators, building occupants, etc., and it uses that building template to populate EnergyPlus. A separate building insulation and shading model uses radiance to account for inter-building effects. Using UMI's building templates, it is possible to change building information while maintaining the geometry to investigate the impacts of envelope retrofits. It is also possible to change the geometry while holding construction materials constant to investigate the impacts of urban form.

Parcel and block information was imported from ArcGIS data associated with the neighborhood patterns. Building geometry and data, such as window/wall ratios for the generalised building types, were initially sourced from an online

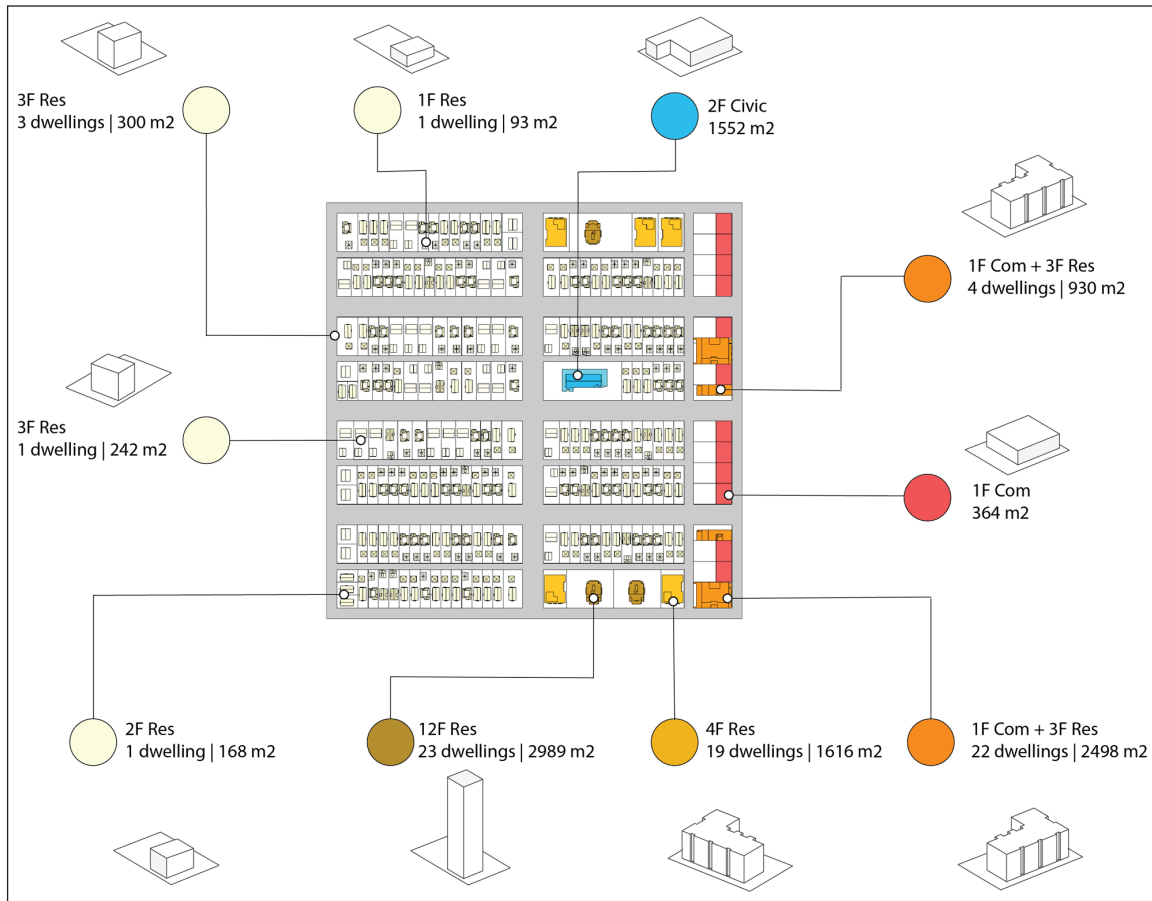


Figure 3: Example of a neighborhood pattern (400 × 400 m) with a series of simplified building typology models.

Table 1: Vintages used to develop British Columbia building code templates for Part 3 (complex buildings) and Part 9 (simple buildings).

Part 3	Part 9
Pre-1991	Pre-1975
1992–2006	1975–92
2007–12	1992–2006
Post-2012 (current code)	2006–12
	Post-2012 (current code)

urban design reference (<http://elementsdb.sala.ubc.ca>), then further simplified to the narrower set of building types used. Building template files for construction materials were developed using the BC Building Code (2012). This code separates buildings into two primary types: Part 3, or complex buildings, are buildings over three stories in height, or over 600 m² in footprint; and Part 9, or simple buildings, are buildings less than three stories and less than 600 m² in footprint. The vintages (**Table 1**) used correspond to periods where large changes in the building code resulted in significant improvements in building energy performance.

2.3.1. Retrofit ‘what-if’ scenario

A ‘what-if’ retrofit and replacement scenario was developed to measure possible alternative futures with incremental replacement of building technology upgrades (**Table 2**) through energy retrofits while holding urban form, demographics and behavior constant. The scenario (**Figure 4**) showed homes replaced (1% per year) and retrofit (2% per year) to 2050 (Dixon & Eames 2013). **Table 2** provides a synopsis of the types of interventions used, including new construction to the current code, new construction to Passive House standards, basic building roof retrofits (CA\$5000) and retrofit to Passive House’s EnerPHit standard (PHI 2016). In this example, HVAC systems, fuel sources, domestic hot water, number of occupants and occupancy schedules were held constant.

This policy intervention achieved a modest improvement in total neighborhood energy, illustrating the negative consequences of the ‘rebound effect’, where the improved energy efficiency of renovations and new homes is counteracted by a growing house size (Calthorpe 2011; Ewing & Rong 2008). While high-performance Passive House

Table 2: Sample input variables for the retrofit and replace scenario shown in Figure 4 (not all interventions or variables are included).

House type	Scenario	Treated floor area (m ²)	U-value (W/m ² K)			Window/wall				Heat recovery	Infiltration ACHnat ^a
			Wall	Ground	Roof	N	S	E	W		
Pre-1975	Base	150	1.73	1.17	1.65	0	20	10	10		0.125
Pre-1975 EnerPHit	1	150	0.15	0.15	0.10	0	20	10	10	0.75	0.050
Pre-1975 Basic	1	150	1.73	1.17	0.37	0	20	10	10		0.125
1975	Base	180	0.58	0.57	0.60	10	40	20	30		0.125
1975 EnerPHit	1	180	0.15	0.15	0.10	10	40	20	30	0.75	0.050
1975 Basic	1	180	0.58	0.57	0.27	10	40	20	30		0.125
1992	Base	360	0.47	0.20	0.20	10	30	10	30		0.125
1992 EnerPHit	1	360	0.15	0.15	0.10	10	30	10	30	0.75	0.050
1992 Basic	1	360	0.47	0.20	0.14	10	30	10	30		0.125
2006	1	461	0.36	0.21	0.21	10	30	10	30		0.125
2006 EnerPHit	1	461	0.15	0.15	0.10	10	30	10	30	0.75	0.050
Current code	1	461	0.36	0.21	0.21	10	30	10	30		0.125
Passive House	1	361	0.15	0.15	0.10	10	40	30	10	0.75	0.030

Note: ^aAir changes per hour at natural pressure.

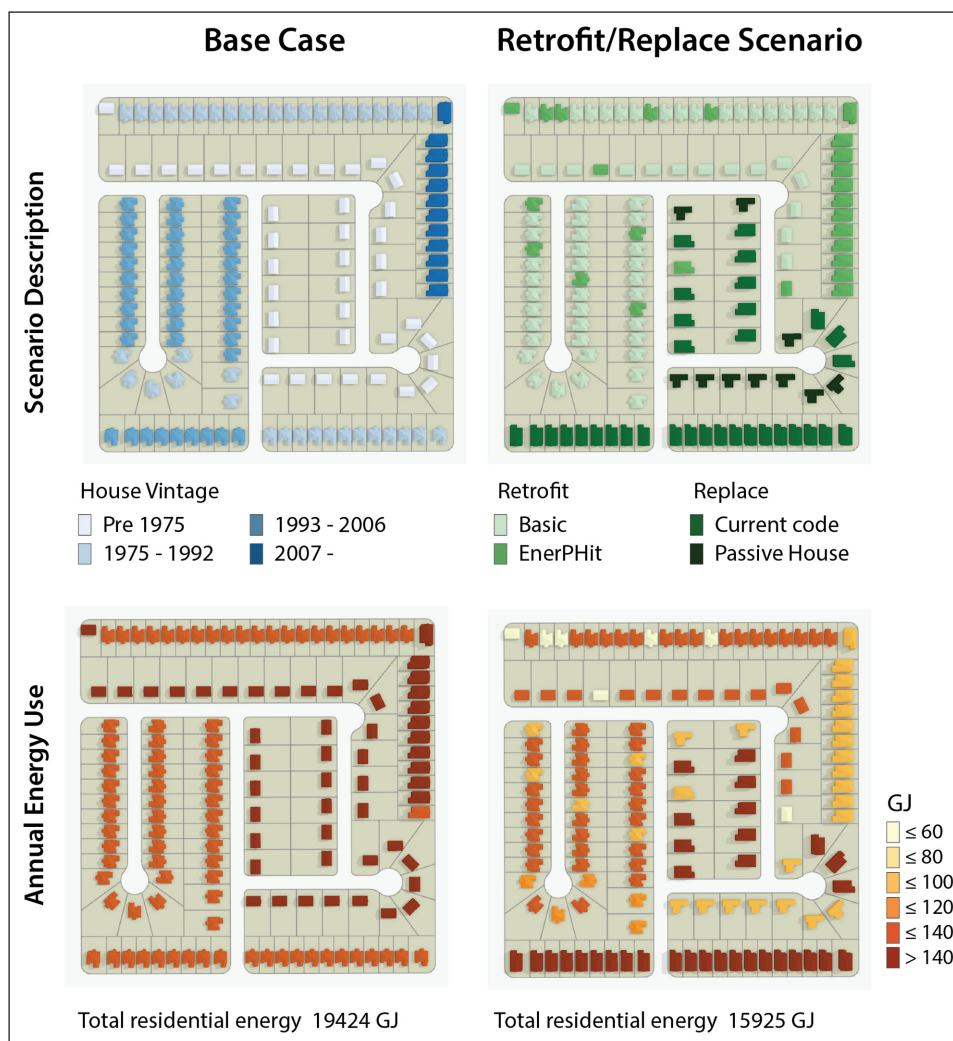


Figure 4: Annual building energy use for the 15–35 people per ha (pph) single-family loops: base case and retrofit scenarios.

and EnerPHit houses perform efficiently, the newer, larger homes built to the current code perform similarly to older, smaller and less efficient homes (Table 3). While the EU intensity of the current code house is significantly lower than the pre-1975 home, the floor area is significantly larger, resulting in only a small improvement in total EU.

2.3.2. Redevelopment scenario

The redevelopment scenario focused on an urban form-based energy pathway (Table 3). One contiguous area of five parcels was redeveloped from commercial to residential and mixed use, typical of intensification strategies used in BC. The new development reduced regular retail space by 3089 m², adds 3657 m² of food retail, 3610 m² of office and 24,022 m² of multi-family residential. This development significantly increased both the population and jobs, and simultaneously increased dwelling diversity (Figure 5). In this scenario, all new buildings were constructed to the current code, holding the HVAC system, fuel source, and behavior variables constant. Emissions were calculated from the building energy results using provincial emission factors (Canadian Ministry of Environment 2016).

This infill scenario revealed an increase in neighborhood energy demand and emissions given the significant increase in population (Figures 6 and 7). However, EU intensity, CO₂e intensity, EU per capita and tCO₂e per capita all decreased for residential buildings.

Table 3: Sample energy and CO₂e outputs for building models in the retrofit scenario shown in Figure 4 (not all buildings are represented).

House type	Scenario	Treated floor area (m ²)	Energy use (GJ)	Energy use intensity (GJ/m ²)	Emissions (tCO ₂ e)	Carbon intensity (tCO ₂ e/m ²)
Pre-1975 SF	Base	150	170.30	1.14	5.52	0.037
Pre-1975 EnerPHit	1	150	45.50	0.30	1.05	0.007
Pre-1975 Basic	1	150	129.36	0.86	4.06	0.027
1975 SF	Base	180	134.07	0.74	3.99	0.022
1975 EnerPHit	1	180	57.48	0.32	1.28	0.007
1975 Basic	1	180	120.49	0.67	3.52	0.020
1992 SF	Base	360	137.77	0.38	3.37	0.009
1992 EnerPHit	1	360	84.33	0.23	1.49	0.004
1992 Basic	1	360	135.98	0.38	3.27	0.009
2006 SF	1	461	140.19	0.30	3.13	0.007
2006 EnerPHit	1	461	97.80	0.21	1.57	0.003
Current code	1	461	143.67	0.31	3.25	0.007
Passive House	1	361	85.22	0.24	1.48	0.004

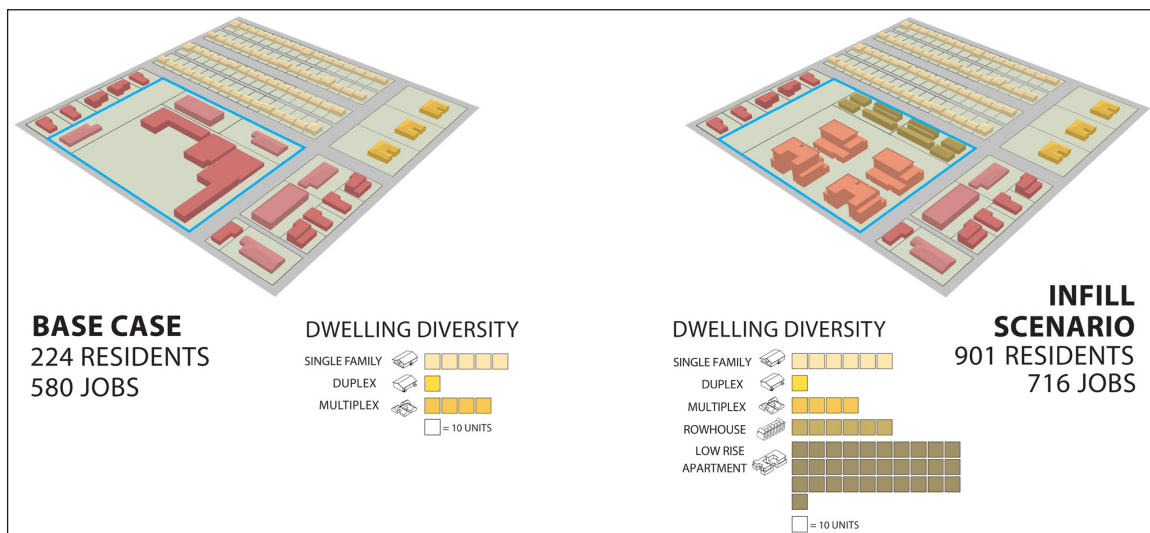


Figure 5: Pattern characteristics for the base and infill scenarios.

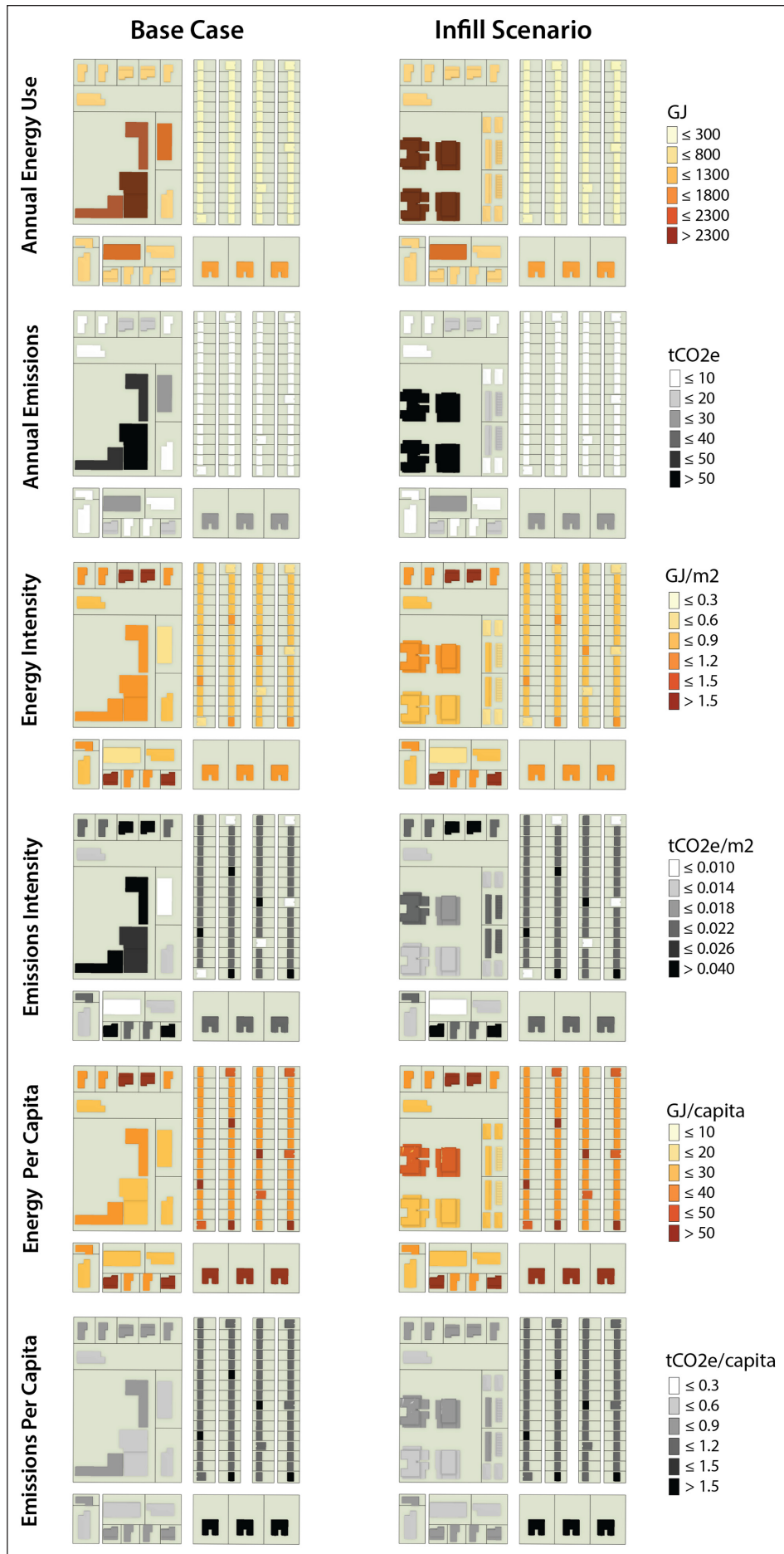


Figure 6: Energy and emissions maps for the commercial pattern base case and infill scenarios.

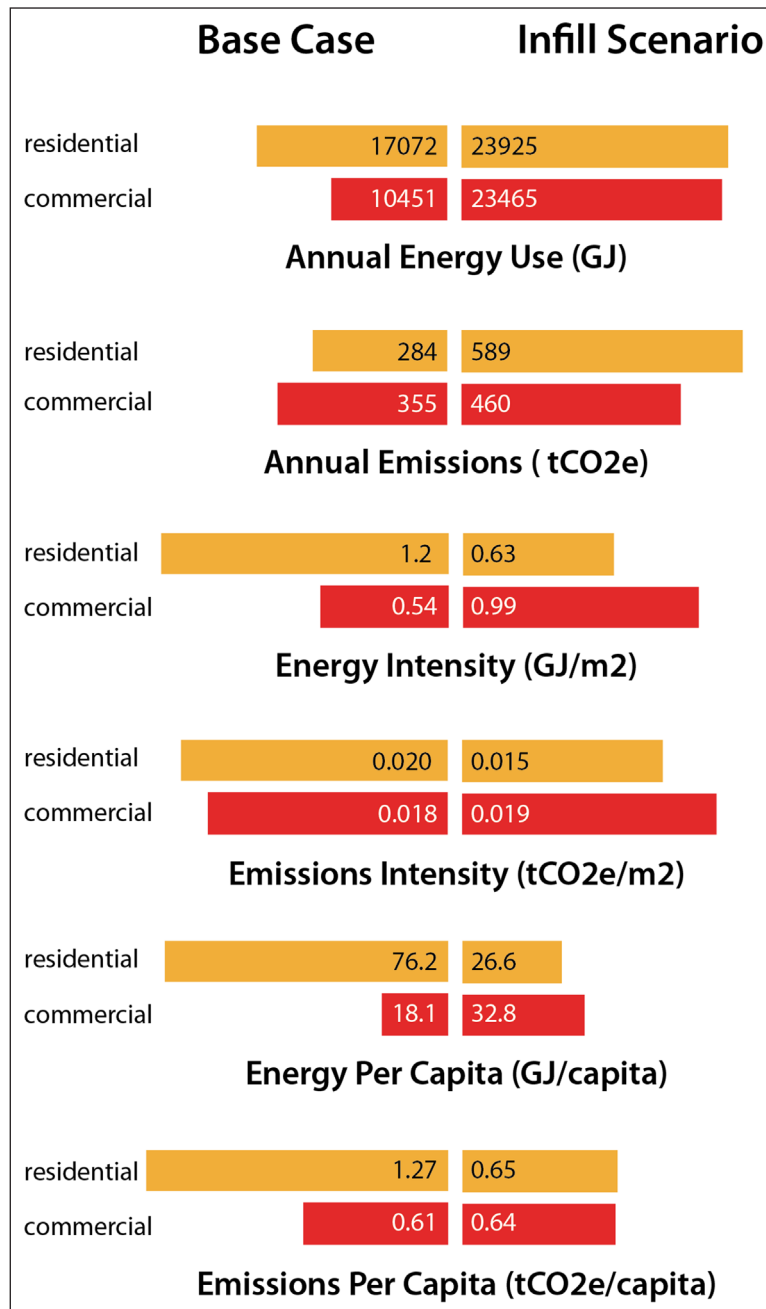


Figure 7: Energy and emissions metrics for the commercial pattern base case and infill scenario.

2.4. Calibration and validation

The validation step was not intended to reconcile measured and simulated results but rather to demonstrate that UMI energy simulation results adequately represent the energy performance at the neighborhood scale in BC for the purposes of comparison. Validation is crucial to UBEM's development (Reinhart & Cerezo Davila 2016). However, it is not yet possible to validate the simulation results against high-quality energy-use data collected at a given neighborhood scale (Lomas *et al.* 1997). While UMI has been partially validated in other contexts (Cerezo Davila *et al.* 2016), it has not been validated for climatic conditions and construction methods in BC. UMI simulations used in the present paper covered four age categories ranging from 1940 to 2020, with three unique building geometries and four floor areas for residential buildings. UMI simulation results were validated against existing real-world energy data sets including Natural Resources Canada's (NRCAN) Office of Energy Efficiency (NRCAN 2009, 2011), BC Housing (2017), and the US DOE building database (US DOE 2011, 2012). NRCAN and BC Housing data are used to validate residential buildings, while the US DOE database is used for commercial buildings, including food retail, retail and office, respectively (OEE/NRCAN 2009, 2011).

For residential buildings, the authors modelled building stocks that matched the age categories and sizes of the reference data acquired from NRCAN/BC Housing due to the lack of energy performance data of buildings with

identical age, geometry and sizes used in the energy simulation. Specifically, each building size was simulated three times to reflect three unique building geometries used in the UMI simulation. EUs from three different geometries were averaged for correlation analysis against NRCAN and BC Housing data. Age category 3 (*i.e.* 1995–2005) was not included in the validation process because of missing reliable reference data. Commercial buildings were validated directly against the US DOE buildings database. Only buildings located in the same climate zone were selected.

Figure 8 shows the correlation between commercial energy simulation from UMI and the reference data from NRCAN and BC Housing. UMI-simulated EU results have a moderately strong correlation ($r = 0.86$) against the reference data. **Figures 8** and **9** indicate that overall UMI-simulated EU was strongly correlated with all commercial building types against the US DOE with correlation coefficients ranging from 0.88 to 0.98.

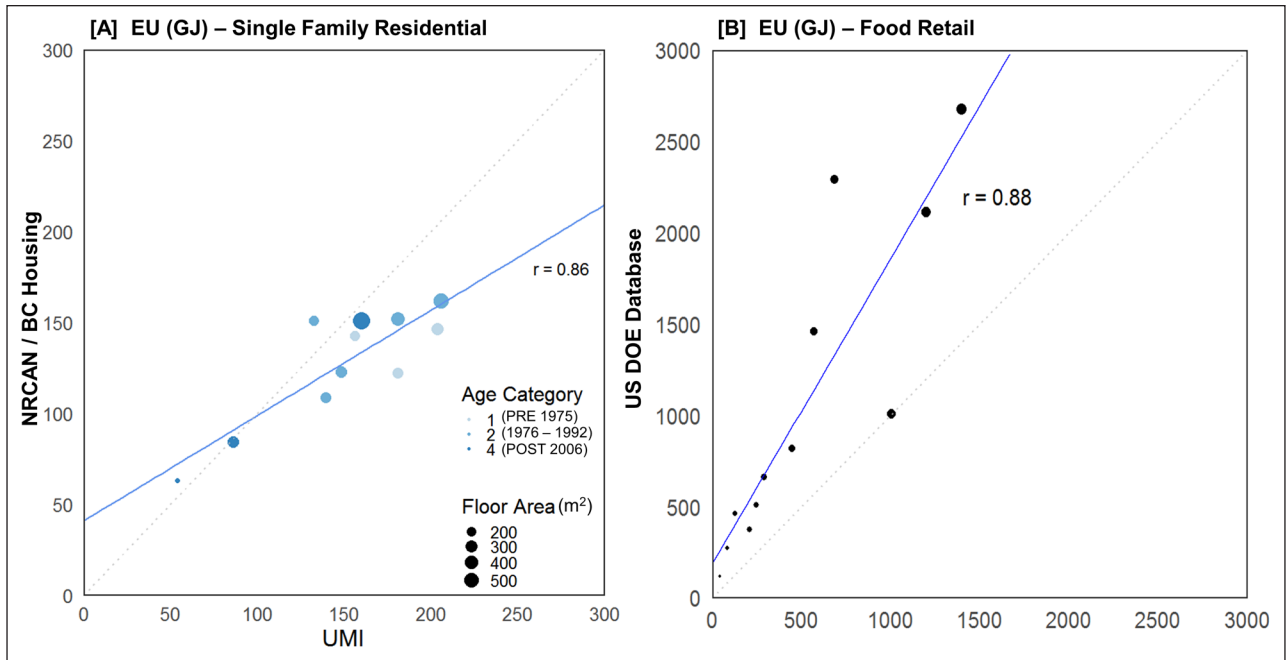


Figure 8: (a) Correlation between the Urban Modeling Interface (UMI) simulation results (*x*-axis) and reference data from Natural Resources Canada’s (NRCAN) and BC Housing (*y*-axis) for single-family residential; and (b) correlation between the UMI simulation results and the US Department of Energy (US DOE) for food retail.

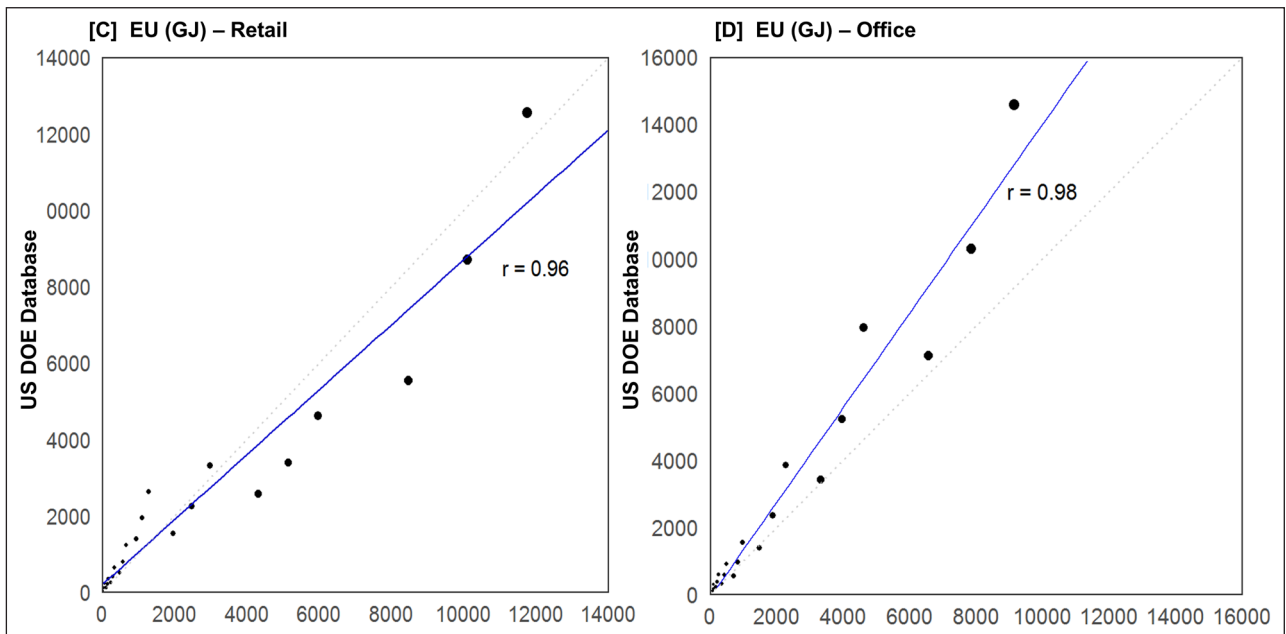


Figure 9: Correlation between the Urban Modeling Interface (UMI) simulation results (*x*-axis) and the US Department of Energy (DOE) (*y*-axis): (c) retail; and (d) office.

3 Discussion

This paper presents an approach to iteratively simulate the effect of potential energy and emissions-reducing policy interventions in urban-form patterns representative of BC municipalities, and to improve the understanding of interactions between and among urban form and retrofit technology policy. This framework incorporates technological and urban form factors, identifying urban context and building design (form) and building systems (technology) as categories of energy interactions in the built environment.

A strength of this approach is the use of emerging UBEMs to understand multiple 'what-if' scenarios for building emissions. These UBEM approaches make the assessment of integrated future scenarios at urban scales possible in ways that were not previously accessible (Swan & Urgusl 2009; Reinhart & Cerezo Davila 2016). In addition, a 'pattern-type' approach can expedite iterative and adaptive consideration of policy options across a diverse range of communities in different geographic contexts, including those that have neither the resources nor the data to undertake locally specific scenario modeling exercises. As these scenarios are spatial and visualised at a neighborhood scale, they also provide planners and decision-makers the opportunity to consider implications of urban form variations together with energy and emissions performance. For example, are retrofit and technology approaches associated with incremental infill and building-renewal policies distributed across a neighborhood more or less effective than densification and elevated building standards approaches associated with concentrated growth management policies? And which combinations of policy strategies yield better overall energy performances at a neighborhood scale?

To date, the project has been confined to building-related energy and emissions impacts of urban form. Extensive related research considers the impact of urban form on mobility-based energy demand and related emissions (Silva *et al.* 2017), which, in some BC communities, can exceed those of buildings. While effort is underway to bring building and transportation energy demand and emissions simulation together, the results are not yet available. Within the realm of building-scale energy demand, there are challenges of calibration with engineering models predicated on extensive, and sensitive data inputs. As the purpose of this research is not to accurately predict the energy performance of buildings at neighborhood scales, but rather to compare the relative magnitudes of different interventions, effective calibration and validation that are still critically important to that comparison. However, even with that caveat, behavior-related variables such as occupant schedules remain problematic, leading to significant variation in comparative results (Swan & Urgusl 2009; Nouvel *et al.* 2013, Reinhart & Cerezo Davila 2016). This aspect of the study can be tempered using validated statistical models of urban energy demand developed by others (*e.g.* Tooke, van der Laan, & Coops 2014; Zuehlke, Jaccard, & Murphy 2017), and avenues for validation beyond those discussed in section 2.4 are being explored.

Energy and emissions implications are but one arena of considerations that shape the performance attributes of the built environment. Equally important are the broader social frames within which decisions about the planning, design and operation of the built environment are made. People, broadly speaking, do not make decisions about where, or how, to live based on energy or emissions information. They are far more likely to renovate their house for amenity and livability, rather than energy or emissions-related reasons (Wilson & Dowlatabadi 2007). Effective policy-relevant energy and emissions reducing solutions for the built environment will also need to consider these livability considerations in parallel. Current efforts in this research investigate linkages between spatial indicators of livability and energy and emissions intensity. Using the methods demonstrated, this paper is simulating future 'what-if' urban form development patterns using larger composites, and measuring both energy and emission against a set of spatial livability indicators.

4 Conclusions

A simplified urban building energy model (UBEM) method was developed for seven common urban neighborhood patterns (400 × 400 m). Practical urban policy strategies were then applied to a spatial modeling approach. This allows municipalities to consider future energy and emissions policy options iteratively from individual buildings to the neighborhood scale in a proxy context similar to their own. Validation using real-world data suggests that the simulated energy consumption was accurate in neighborhoods with relevant building types, ages and climate conditions.

It was found that retrofitting and replacing existing buildings achieved only moderate energy and emission reductions due to the 'rebound effect', where the improved energy efficiency and new homes were counteracted by growing house sizes. On the other hand, the infill redevelopment scenario decreased both energy and emissions per capita in residential buildings. Behavior factors and issues of neighborhood livability are undoubtedly important in terms of public acceptance and uptake, but outside the scope of this study. Additionally, mobility-based energy demand and emissions are clearly important in the energy and emission context, but not considered in this study because of the spatial scale of the current model (400 × 400 m).

As demonstrated in the illustrative simulations presented in section 2.3, this work enables iterative and valid simulations of specific energy policy consequences of building retrofit and land-use changes. In response to many municipalities' mandates regarding energy and emissions reducing policies in their community planning, the methods developed in this paper and the preliminary results offer a flexible yet consistent, realistic and accessible approach to test different municipal policy options for cities of differing sizes, geographic and climatic contexts.

Acknowledgements

The authors thank the anonymous reviewers for their constructive comments and critiques.

Competing interests

The authors have no competing interests to declare.

Funding

The authors thank the Pacific Institute for Climate Solutions (PICS) for funding this research (grant number PICS 36170–50280). They thank the Environmental Systems Research Institute (ESRI) Canada and the Natural Sciences and Engineering Research Council (NSERC) for funding portions of the tool development and related research.

References

- Baker, N., & Steemers, K.** (2000). *Energy and environment in architecture*. London: E&FN Spon.
- Batty, M.** (2013). *The new science of cities*. Boston: MIT Press. DOI: <https://doi.org/10.7551/mitpress/9399.001.0001>
- BC Assessment.** (2017). *Inventory information*. Retrieved from <https://www.bcassessment.ca/Property/AssessmentSearch>
- BC Building Code.** (2012). *British Columbia Building Code*. Province of British Columbia. Retrieved from <http://www.bccodes.ca/building-code.html>
- BC Housing.** (2017). *Energy step code building beyond the standard, 2017 metrics research full report*. Retrieved from <https://www.bchousing.org/research-centre/library/residential-design-construction/energy-step-code-2017-full-report&sortType=sortByDate>
- Calthorpe, P.** (2011). *Urbanism in the age of climate change*. Washington, DC: Island. DOI: <https://doi.org/10.5822/978-1-61091-005-7>
- Canadian Ministry of Environment.** (2016). 2016 B.C. best practices methodology for quantifying greenhouse gas emissions including guidance for public sector organizations, local governments and community emission. Retrieved from <https://www2.gov.bc.ca/assets/gov/environment/climate-change/cng/methodology/2016-17-pso-methodology.pdf>
- Cerezo Davila, C., Reinhart, C., & Bemis, J.** (2016). Modeling Boston: A workflow for the generation of complete urban building energy demand models from existing urban geospatial datasets. *Energy*, 117, 237–250. DOI: <https://doi.org/10.1016/j.energy.2016.10.057>
- City of New York.** (2014). *One city built to last*. New York: City of New York.
- City of Toronto.** (2017). *TransformTO: Climate action for a healthy, equitable and prosperous Toronto, Report #2—The pathway to a low carbon future*. Toronto: City of Toronto.
- City of Vancouver.** (2015). *Greenest city: 2020 Action Plan*. Vancouver: City of Vancouver.
- Clifton, K., Ewing, R., Knaap, G.-J., & Song, Y.** (2008). Quantitative analysis of urban form: A multidisciplinary review. *Journal of Urban Institute of Research and Urban Sustainability*, 1, 17–45. DOI: <https://doi.org/10.1080/17549170801903496>
- Denis, G. S., & Parker, P.** (2009). Community energy planning in Canada: The role of renewable energy. *Renewable and Sustainable Energy Reviews*, 13, 2088–2095. DOI: <https://doi.org/10.1016/j.rser.2008.09.030>
- Dixon, T., & Eames, M.** (2013). Scaling up: the challenges of urban retrofit. *Building Research & Information*, 41, 499–503. DOI: <https://doi.org/10.1080/09613218.2013.812432>
- Dogan, T., & Reinhart, C.** (2013). Automated conversion of architectural massing models into thermal ‘shoebox’ models. In *Proceedings of the 13th Conference of the International Building Performance and Simulation Association*, 3745–3752.
- Doxiadis, C.** (1968). *Ekistics*. New York: Oxford University Press.
- Evans, S., Liddiard, R., & Steadman, P.** (2017). 3Dstock: A new kind of three-dimensional model of the building stock of England and Wales, for use in energy analysis. *Environment and Planning B: Urban Analytics and City Science*, 44(2), 227–255. DOI: <https://doi.org/10.1177/0265813516652898>
- Ewing, R., & Rong, F.** (2008). The impact of urban form on U.S. residential energy use. *Housing Policy Debate*, 19, 1–30. DOI: <https://doi.org/10.1080/10511482.2008.9521624>
- Frank, L. D., Schmid, T. L., Sallis, J. F., Chapman, J., & Saelens, B. E.** (2005). Linking objectively measured physical activity with objectively measured urban form: Findings from SMARTRAQ. *American Journal of Preventive Medicine*, 28(2), 117–125. DOI: <https://doi.org/10.1016/j.amepre.2004.11.001>
- Güneralp, B., Zhou, Y., Ürge-Vorsatz, D., Gupta, M., Yu, S., Patel, P. L., & Seto, K. C.** (2017). Global scenarios of urban density and its impacts on building energy use through 2050. *Proceedings of the National Academy of Sciences, USA*, 114(34), 8945–8950. DOI: <https://doi.org/10.1073/pnas.1606035114>
- Kellett, R.** (2009). *Sustainability indicators for computer-based tools in community design*. Ottawa: Canada Mortgage and Housing Corporation.
- Kropf, K.** (2009). Aspects of urban form. *Urban morphology*, 13(2), 105.
- Larivière, I., & Lafrance, G.** (1999). Modelling the electricity consumption of cities: Effect of urban density. *Energy Economics*, 21(1), 53–66. DOI: [https://doi.org/10.1016/S0140-9883\(98\)00007-3](https://doi.org/10.1016/S0140-9883(98)00007-3)
- Lomas, K. J., Eppel, H., Martin, C. J., & Bloomfield, D. P.** (1997). Empirical validation of building energy simulation programs. *Energy and Buildings*, 26(3), 253–275. DOI: [https://doi.org/10.1016/S0378-7788\(97\)00007-8](https://doi.org/10.1016/S0378-7788(97)00007-8)

- Murray, B., & Rivers, N.** (2015). British Columbia's revenue-neutral carbon tax: A review of the latest 'grand experiment' in environmental policy. *Energy Policy*, 86, 674–683. DOI: <https://doi.org/10.1016/j.enpol.2015.08.011>
- Nouvel, R., Schulte, C., Eicker, U., Pietruschka, D., & Coors, V.** (2013). *CityGML-based 3D city model for energy diagnostics and urban energy policy support*. Retrieved from http://www.ibpsa.org/proceedings/BS2013/p_989.pdf
- NRCAN.** (2009). *Survey of commercial and institutional energy use: Detailed statistical report*. Ottawa: Natural Resources Canada (NRCAN).
- NRCAN.** (2011). *Survey of household energy use: Detailed statistical report*. Ottawa: Natural Resources Canada (NRCAN).
- OEE/NRCAN.** (2009). *Survey of Commercial and Institutional Energy Use Buildings*. Ottawa: Office of Energy Efficiency (OEE), Natural Resources Canada (NRCAN). Retrieved from <http://oee.nrcan.gc.ca/publications/statistics/scieu/2009/pdf/scieu2009.pdf>
- OEE/NRCAN.** (2011). *Survey of Household Energy Use*. Ottawa: Office of Energy Efficiency (OEE), Natural Resources Canada (NRCAN). Retrieved from <http://oee.nrcan.gc.ca/publications/statistics/sheu/2011/pdf/sheu2011.pdf>
- PHI.** (2016). *Criteria for the Passive House EnerPHit and PHI low energy building standard*. Darmstadt: Passive House Institute (PHI).
- Province of British Columbia, Climate Action Secretariat.** (2012). *Community energy and emissions inventory reports*. Victoria: Climate Action Secretariat.
- Ratti, C., Baker, N., & Steemers, K.** (2005). Energy consumption and urban texture. *Energy and Building*, 37, 762–776. DOI: <https://doi.org/10.1016/j.enbuild.2004.10.010>
- Reinhart, C. F., & Cerezo Davila, C.** (2016). Urban building energy modeling—A review of a nascent field. *Building and Environment*, 97, 196–202. DOI: <https://doi.org/10.1016/j.buildenv.2015.12.001>
- Rode, P., Keim, C., Robazza, G., Viejo, P., & Schofield, J.** (2014). Cities and energy: Urban morphology and residential heat-energy demand. *Environment and Planning B: Planning and Design*, 41(1), 138–162. DOI: <https://doi.org/10.1068/b39065>
- Rueda, S.** (2017). *Ecosystemic urbanism for the design of new urban developments and the regeneration of existing ones*. Barcelona: Urban Ecology Agency of Barcelona.
- Salat, S.** (2009). Energy loads, CO₂ emissions and building stocks: morphologies, typologies, energy systems and behaviour. *Building Research & Information*, 37, 598–609. DOI: <https://doi.org/10.1080/09613210903162126>
- Salat, S.** (2011). *Cities and forms: On sustainable urbanism*. Paris: CSTB Urban Morphology Lab.
- Schreurs, M. A.** (2008). From the bottom up: Local and subnational climate change politics. *Journal of Environment and Development*, 17, 343–355. DOI: <https://doi.org/10.1177/1070496508326432>
- Senbel, M., Girling, C., Kellett, R., & White, J.** (2011). Evaluating a web based urban design reference tool. *Conference Proceedings of the Council for Education and Landscape Architecture*, 197–216.
- Senbel, M., van der Laan, M., Kellett, R., Girling, C., & Stuart, J.** (2013). Can form-based code help reduce municipal greenhouse gas emissions in small towns? The case of Revelstoke, British Columbia. *Canadian Journal of Urban Research*, 22(1), 72–92.
- Silva, M., Oliveira, V., & Leal, V.** (2017). Urban form and energy demand: A review of energy-relevant urban attributes. *Journal of Planning Literature*, 32, 346–365. DOI: <https://doi.org/10.1177/0885412217706900>
- Sokol, J., Cerezo Davila, C., & Reinhart, C. F.** (2017). Validation of a Bayesian-based method for defining residential patterns in urban building energy models. *Energy and Buildings*, 134, 11–24. DOI: <https://doi.org/10.1016/j.enbuild.2016.10.050>
- Song, Y., & Knaap, G.-J.** (2004). Measuring urban form: Is Portland winning the war on sprawl? *Journal of the American Planning Association*, 70, 210–225. DOI: <https://doi.org/10.1080/01944360408976371>
- Song, Y., & Knaap, G. J.** (2007). Quantitative classification of neighbourhoods: The neighbourhoods of new single-family homes in the Portland Metropolitan Area. *Journal of Urban Design*, 12, 1–24. DOI: <https://doi.org/10.1080/13574800601072640>
- Steadman, P., Hamilton, I., & Evans, S.** (2014). Energy and urban built form: An empirical and statistical approach. *Building Research & Information*, 42, 17–31. DOI: <https://doi.org/10.1080/09613218.2013.808140>
- Stevens, M., & Senbel, M.** (2012). Examining municipal response to a provincial climate action planning mandate in British Columbia, Canada. *Local Environment*, 17, 837–861. DOI: <https://doi.org/10.1080/13549839.2012.714752>
- Swan, L. G., & Ugursal, V. I.** (2009). Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews*, 13, 1819–1835. DOI: <https://doi.org/10.1016/j.rser.2008.09.033>
- Tooke, T. R., van der Laan, M., & Coops, N. C.** (2014). Mapping demand for residential building thermal energy services using airborne LiDAR. *Applied Energy*, 127, 125–134. DOI: <https://doi.org/10.1016/j.apenergy.2014.03.035>
- United Nations.** (2014). *World urbanization prospects: Highlights*. New York: United Nations Department of Economic and Social Affairs, Population Division. DOI: <https://doi.org/10.18356/527e5125-en>
- US DOE.** (2011). *Commercial reference buildings: Washington State*. Washington, DC: US Department of Energy (DOE).
- US DOE.** (2012). *Residential prototype building models: Washington State*. Washington, DC: US Department of Energy (DOE).

- Van der Laan, M., Kellet, R., Girling, C., Senbel, M., & Su, T.** (2013, April). A collaborative multi-touch, multi-display, urban futures tool. In *Proceedings of the Symposium on Simulation for Architecture & Urban Design* (pp. 1–4).
- Wate, P., & Coors, V.** (2015). 3D data models for urban energy simulation. In *Energy Procedia, 6th International Building Physics Conference, International Building Physics Conference (IBPC), 2015*, 78, 3372–3377. DOI: <https://doi.org/10.1016/j.egypro.2015.11.753>
- Wilson, C., & Dowlatabadi, H.** (2007). Models of decision making and residential energy use. *Annual Review of Environment and Resources*, 32, 169–203. DOI: <https://doi.org/10.1146/annurev.energy.32.053006.141137>
- Yi, H., & Feiock, R. C.** (2015). Climate action plan adoptions in the US states. *International Journal of Climate Change and Strategic Management*, 7, 375–393. DOI: <https://doi.org/10.1108/IJCCSM-02-2014-0019>
- Zuehlke, B., Jaccard, M., & Murphy, R.** (2017). *Can cities really make a difference? Case study of Vancouver's Renewable City Strategy* (Report). Vancouver: Pacific Institute for Climate Solutions (PICS).

How to cite this article: Salter, J., Lu, Y., Kim, J. C., Kellett, R., Girling, C., Inomata, F., & Krahn, A. (2020). Iterative 'what-if' neighborhood simulation: energy and emissions impacts. *Buildings and Cities*, 1(1), pp. 293–307. DOI: <https://doi.org/10.5334/bc.51>

Submitted: 07 February 2020 **Accepted:** 23 May 2020 **Published:** 06 July 2020

Copyright: © 2020 The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC-BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. See <http://creativecommons.org/licenses/by/4.0/>.