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# EVALUATING THE IMPACT OF URBAN FORM EVOLUTION ON URBAN ENERGY PERFORMANCE AND RENEWABLE ENERGY POTENTIAL USING AGENT-BASED MODELING

Osama Mussawar[1], Elin Markarian[2], Ahmad Mayyas[1], and Elie Azar[2]

[1]Dept. of Mgmt. Science and Eng., Khalifa University of Science and Technology, Abu Dhabi, UAE
[2]Dept. of Civil and Environmental Eng., Carleton University, Ottawa, ON, CANADA

## ABSTRACT

This paper presents an agent-based modeling framework to quantify the impact of evolving urban forms on urban energy performance and renewable energy potential. The framework leverages energy modeling tools, large public datasets, and urban form classifications to assess urban performance along various techno-economic metrics (e.g., self-sufficiency and energy costs). A case study of the historical evolution of the urban form of the city of Toronto, Canada, is presented, focusing on the transition from large low-rise to open high-rise urban forms. Results show that increasing the proportion of open high-rise areas from 0 to 25% increased the net energy ratio from 22% to 72%, implying higher reliance on the grid to match demand. While a denser urban form challenges energy self-sufficiency and net-zero emissions goals, aggregating buildings' energy demand and supply at the community level has improved self-sufficiency levels, offering a promising avenue for future urban energy planning and policy efforts.

## 1 INTRODUCTION

### 1.1 Background

The building sector is a major contributor to global energy demand and greenhouse gas emissions, motivating the development of knowledge, technologies, and policies that promote sustainable and resilient built environments (IEA 2023). Canada, for example, through its Green Building strategy, aims to achieve net-zero emission and climate-resilient buildings sector by 2050, which would require significant investments in demand- and supply-side strategies (Government of Canada 2022). The energy demand and renewable energy production potential of urban areas are shaped by the built form (e.g., building physical features and attributes), function (e.g., building activities and land-use types), and environment (e.g., type of climate). The prospects of sustainability-oriented innovations in urban areas are influenced by the spatial patterns of their built environments (Castán Broto 2019). The urban context has an important influence on the attainment of performance goals such as energy self-sufficiency (Mussawar et al. 2023a). Urban studies have characterized urban areas in various ways, such as Local Climate Zone (LCZ) classification (Stewart and Oke 2012), for analytical purposes. LCZ taxonomy defines common urban built types (e.g., large low-rise, compact low-rise, open high-rise) based on attributes related to form (height and compactness of buildings), function (commercial or residential usage of land) and surface cover (Stewart and Oke 2012). It enables consideration of typical urban contexts in the study of urban-scale energy performance. However, urban form is not static and evolves over time. For example, (Demuzere et al. 2020) studied temporal changes in urban form and morphology in terms of proportions of various LCZ types across various cities in Canada over the 1986-2016 period and noted a shift in urban form from large low-rise to open high-rise in the city of Toronto; the large low-rise form comprises buildings of three or less floors and large surface area, while open high-rise covers openly spaced buildings of ten and above floors. However, the impact of such changes on urban energy demand and renewable energy potential was not assessed.

### 1.2 Relevant Literature and Knowledge Gaps

Earlier works studied the energy performance of building blocks and clusters through physics-based modeling and simulation (Ahmadian et al. 2021; Mirzabeigi and Razkenari 2022). In some cases, they also combined engineering simulation with methods from data science for energy-driven analysis and urban design (Nutkiewicz et al. 2018; Wang et al. 2022). However, their approaches often do not consider the functional heterogeneity of buildings and tend to be cumbersome at large scales (e.g., neighborhoods and districts) (Ferrari et al. 2019). The use of data-driven approaches for estimating and analyzing energy consumption on large urban scales has also grown (Bansal and Quan 2022; Zhang et al. 2023). However, they often lack high temporal resolution and overlook the role of building function in energy consumption. The energy supply side of the urban energy system is also seldom considered in urban energy analyses, which is needed for the planning and development of sustainable communities and districts (Pelorosso 2020; Charani Shandiz et al. 2021). The studies focused on urban-scale energy supply systems do not adequately represent contextual nuances of urban energy demand in their approaches (Kachirayil et al. 2022). The studies that covered energy demand and supply of building groups and their temporal interaction remained short of properly addressing urban built context and its influence on urban-scale energy performance towards sustainability goals (e.g., self-sufficiency) (Huang and Sun 2019; Volpe et al. 2022).

Recent studies presented scalable agent-based models that partially address the stated limitations by integrating energy demand, supply, and contextual factors, leveraging the LCZ classification to study urban energy performance conditioned by the urban-scale built form and function (Mussawar et al. 2023a; Mussawar et al. 2023b). They evaluated energy performance of urban areas represented by basic urban built types (e.g., compact high-rise and open low-rise), as defined by the LCZ classification. However, their modeling frameworks did not consider the representation of urban areas with mixed LCZs (e.g., areas comprising compact high-rise and compact low-rise zones). Consequently, they could not be used to study the evolving urban form of an actual area and the resulting consequences on urban energy dynamics and performance.

### 1.3 Research Objectives

This paper presents an agent-based modeling approach to evaluate urban energy performance and renewable energy potential while accounting for changes and differences in urban form. This work extends an agent-based urban energy system model presented in (Mussawar et al. 2023a; Mussawar et al. 2023b) by incorporating urban areas with mixed LCZs (e.g., areas with large low-rise and open high-rise built types) in the energy performance analysis. The added capabilities, coupled with a parametric variation scheme, enable quantifying the impact of evolving urban form on urban energy performance and sustainability (e.g., energy self-sufficiency, net-zero energy). The proposed approach is demonstrated and validated through a case study.

## 2 METHODOLOGY AND CASE STUDY

### 2.1 Model Description and General Process Overview

The methodology in this paper utilizes an agent-based model that computes building energy demand and renewable energy supply potential of an urban area based on its built form and function (and other factors such as climate) and simulates the interaction of energy supply and demand. The simulation outcomes are used for multi-dimensional performance evaluation through a set of metrics spanning energy and economic aspects. The modeling framework is applied to a case study that assesses the impact of changing urban form (from large low-rise to open high-rise built types) on urban energy performance in the city of Toronto, which will also help demonstrate the framework's capabilities.

The agent-based model of an urban energy system is illustrated in Figure 1. The agents in the model are prosumer buildings in an urban area connected to an electric grid. The buildings bear features of form and function (i.e., surface area, floors and use type), consume energy, and can also produce energy through rooftop solar photovoltaic systems. They import energy from the electric grid to meet their needs and may also export to it in case of surplus from their own energy generation. Such an energy exchange with the electric grid can occur individually (Figure 1a), or collectively in an aggregated fashion (Figure 1b), which represent two different modes of energy demand and supply matching. Building occupancy is not modeled as it is deemed out of scope in the current study but could be considered in future research. The agents' environment consists of an urban built context modeled by features of built form and function, the climate, a renewable resource, and economic parameters. The urban built context delineates the possible form and function of buildings in an urban area, such as an area with both large low-rise and open high-rise commercial buildings occupying certain proportions of land area.

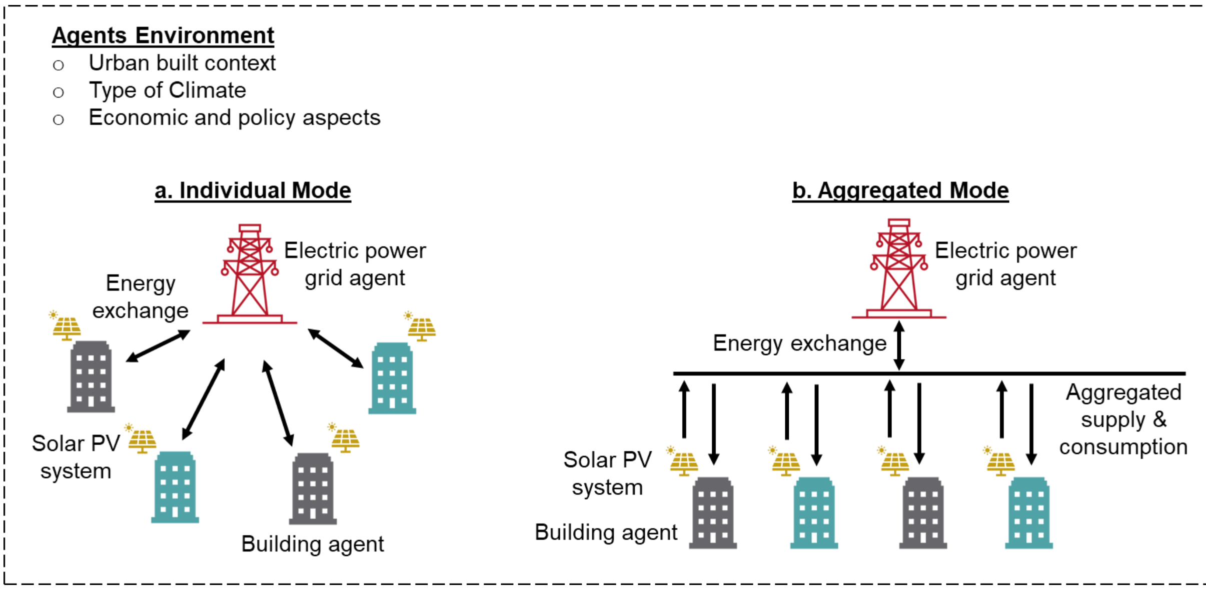


Figure 1: Urban energy system model illustration, considering two modes of energy demand and supply matching.

The analytical process is summarized in Figure 2, which consists of generating a representative instance of a given urban built context, computing and initializing the energy demand and supply of the generated set of individual buildings, matching the energy supply and demand of buildings both individually and as an aggregate (assuming a community configuration of buildings), and computing a set of energy and economic performance metrics based on the matching outcomes. Multiple instances of an urban built context (sets of prosumer buildings in an urban area) can be generated and analyzed through the agent-based model. Instance generation involves the use of empirically-informed sampling distributions for initializing building form parameters (e.g., land area occupied, number of floors). The model is implemented in Python programming language. The following sub-sections explain the constituent modules of the model along with the specifics of the case study for a better understanding of the methodology.

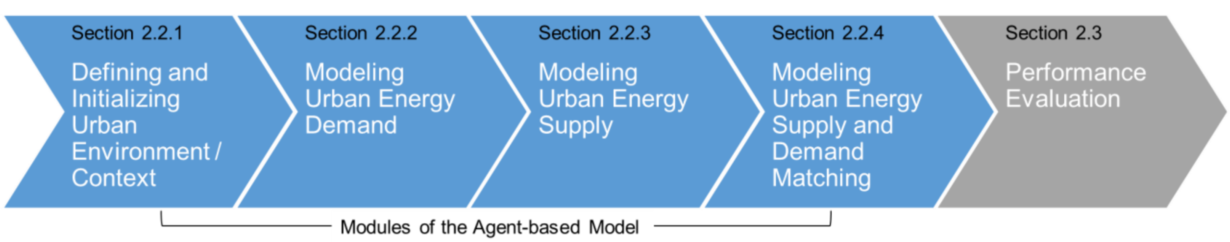


Figure 2: Methodology flowchart.

## 2.2 Model Structure and Modules

### 2.2.1 Module 1 – Defining and Initializing the Urban Environment/Context

The environment module of the agent-based model comprises an urban built context, climate conditions, renewable resource specifications, and economic parameters (i.e., supply system costs, energy prices, policies related to solar supply and an aggregated configuration of buildings). Several features of form and function define the urban built context of an area, which include urban land area ($la$), set of urban zone types ($ZT$) and a corresponding set of land fractions occupied by each zone type ($ZTW$), building surface fraction ($sf$) indicating buildings' compactness for a zone type, possible number of floors ($[fl_{min}, fl_{max}]$) indicating the height of buildings in a zone, and a set of building use-types ($UT$) with a corresponding set of proportions (fractions) of land area occupied ($UTW$) denoting the function of a zone. These parameters can be used to model a variety of urban built environments/contexts.

The case study, based in the city of Toronto, considers five cases of an urban land area of 0.6 km$^2$ representing different fractions of two types of urban zones: large low-rise (LLR) and open high-rise (OHR), as per LCZ classification. The cases reflect the noted change in urban form in the city of Toronto between 1986 and 2016, as documented in (Demuzere et al. 2020). Table 1 shows the five cases of urban form considered in the case study, which comprise different proportions of two urban zone types (LLR and OHR) in terms of land area occupied. The built form and function parameters of the two-zone types used in the case study are given in Table 2.

Table 1: Cases of urban context (built form) considered in the study.

| ***Cases*** | ***a*** | ***b*** | ***c*** | ***d*** | ***e*** |
|---|---|---|---|---|---|
| % of Large low-rise (LLR) | 100 | 75 | 50 | 25 | 0 |
| % of Open high-rise (OHR) | 0 | 25 | 50 | 75 | 100 |

Table 2: Parameters for the two types of urban zones.

| ***Zone type (ZT)*** | $sf$ | $fl_{min}, fl_{max}$ | $UT$ | $UTW$ |
|---|---|---|---|---|
| Large low-rise (LLR) | 0.4 | 1, 3 | Distribution center, Enclosed mall, Warehouse/Storage, Strip mall | 0.2, 0.2, 0.4, 0.2 |
| Open high-rise (OHR) | 0.3 | >9 | Hotel/Lodging, Multi-family housing, Office | 0.2, 0.4, 0.4 |

### 2.2.2 Module 2 – Modeling Urban Energy Demand

The modeled features of a building agent $i$ are land area occupied ($lsa_i$), number of floors ($fl_i$), type of activity ($ut_i$), temporal energy demand ($ed_t^i$) and temporal energy self-supply ($ss_t^i$). This module involves generating a set of buildings that constitute an instance of the urban built context defined in the previous module (2.2.1) and initializing the building energy demand. The energy demand ($ed_t^i$) of a building is given by equation (1). The energy use intensity of a building ($eui_i$), determined by its characteristics and surroundings, is a ratio of its annual energy consumption and total floor area ($fla_i$). The pattern of energy demand ($nd_t^i$), largely driven by the type of building activity and climate, is a normalized energy consumption profile of a building (with respect to its annual energy usage).

$$ed_i^t = eui_i \times fla_i \times nd_i^t \quad (1)$$

A two-step process is carried out to collect energy (electricity) use intensity (EUI) data and develop energy (electricity) profiles of hourly temporal resolution. In the first step, the EUI of buildings in the city of Toronto is obtained from two data sources: The Ontario data catalogue (Ontario Data Catalogue 2024) and the open database of buildings (ODB) (Government of Canada 2018). The Ontario Data Catalogue provides EUI for buildings exceeding 100,000 square feet, encompassing various building types such as commercial, multi-residential, warehousing, and light industrial. This data is provided by building owners or their agents. The ODB (Version 2.0) contains approximately 4.4 million records sourced from 65 government open datasets and aims to streamline access to a compilation of building data across Canada. The data from both sources is collected, filtered to only include buildings located in the city of Toronto, and combined, resulting in a dataset comprising EUI data of 2796 buildings. It is used in the case study to initialize $eui_i$ of buildings. The distribution of EUI data for various building types is exhibited in Figure 3, which indicates that strip malls and enclosed malls are the most energy-intensive commercial buildings, followed by the office and lodging buildings.

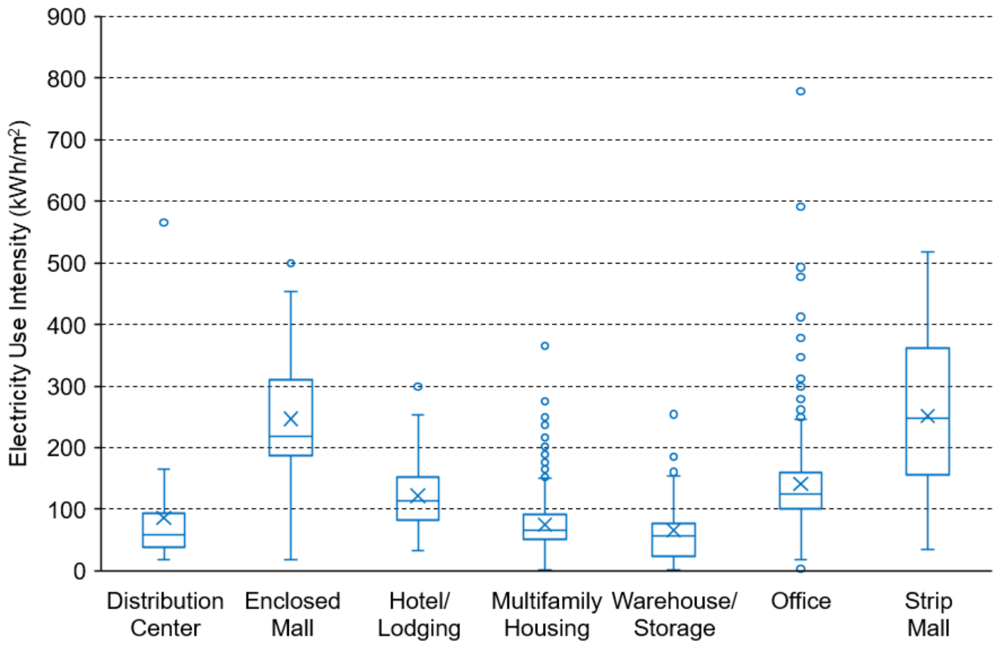


Figure 3: Energy (electricity) use intensity of actual buildings in Toronto.

In the subsequent step, hourly energy profiles are generated using the ANSI/ASHRAE/IES Standard 90.1 Prototype Building Models, used globally for applications such as evaluating new technologies, developing energy codes and standards, and informing design and operation strategies (Deru et al. 2011). Sixteen building prototypes of various types and sizes tailored for the 5A climate zone (cool-humid), similar to the climatic conditions of Toronto, are obtained from (Building Energy Codes Program 2022). The prototype buildings include “Small Office”, “Medium Office”, “Large Office”, “Full-Service Restaurant”, “Hospital”, “Small Hotel”, “Large Hotel”, “Midrise Apartment”, “Outpatient Health Care”, “Primary School”, “Secondary School”, “Quick Service Restaurant”, “Stand-alone Retail”, “Strip Mall”, “Supermarket”, and “Warehouse”. The Toronto weather file (CWEC) is downloaded from (Natural Resources Canada 2023) to simulate local weather conditions. EnergyPlus batch processing capability is used to streamline simulations. Overall, 16 hourly simulations are conducted using Toronto CWEC file to generate hourly energy (electricity) consumption profiles, which are normalized to obtain the hourly demand patterns ($nd_i^t$) of various types of buildings. The energy demand patterns obtained from simulations of four of those buildings are summarized in Figure 4, which shows the peaks and troughs of energy demand during a day and variations in them over a year. Mid-rise apartments, for example, experience large peaks in the evening unlike buildings with commercial activity.

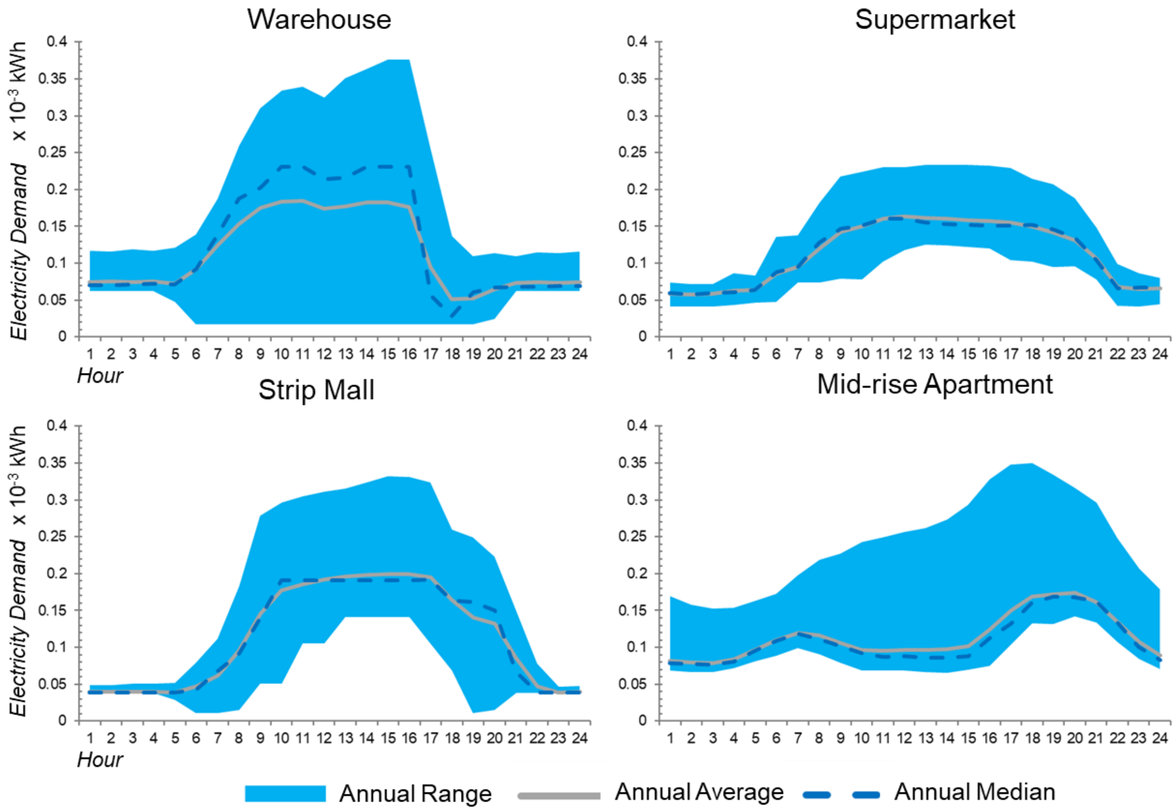


Figure 4: Energy (electricity) demand pattern (daily) for select building types in Toronto.

### 2.2.3 Module 3 – Modeling Urban Energy Supply

This module assumes that buildings harness their technical solar potential by installing rooftop solar photovoltaic systems. The model for energy self-supply ($ss_i^t$) of a building is given by equation (2), which comprises solar PV system DC power capacity ($pvcap_i$), a temporal distribution of PV system's unit power output ($ns_{pv}^t$), and a factor capturing the effect of buildings' compactness ($bfs_i$). Urban areas with compact buildings (with high building surface fraction) tend to receive less solar irradiation on building rooftops (Mohajeri et al. 2016). The potential capacity of a rooftop solar PV system ($pvcap_i$) for a building is given by equation (3), which depends on the roof area ($ra_i$), available fraction of roof ($rav_i$) and the solar PV module efficiency ($pvef$).

$$ss_i^t = ns_{pv}^t \times pvcap_i \times bfs_i \tag{2}$$
$$pvcap_i = ra_i \times rav_i \times pvef \times 1kW/m^2 \tag{3}$$

For the case study, a normalized solar energy profile ($ns_{pv}^t$ ) is obtained from simulation based on the TMY (Typical Meteorological Year) data of solar resource availability in Toronto using System Advisor Model (SAM) (NREL 2021). The capacity factor of solar PV systems is found to be 14.7% for Toronto. The values of built form compactness effect ($bfs_i$) for the LLR and OHR built types used in the study are 0.99 and 0.91, respectively. These values may further vary in the mixed types of urban built forms owing to inter-building shading effects, which can impact the solar energy supply of individual buildings. The case study, however, assumes constant values across scenarios. The module efficiency assumed is 16%. The $rav_i$ depends on the size of the roofs and is assumed to be 0.33, 0.53 and 0.68 for roof sizes 0-464, 465-2,323, and above 2,323 square meters respectively (Melius et al.2013).

### 2.2.4 Module 4 – Modeling Urban Energy Supply and Demand Matching

This module covers two modes of matching urban energy demand with supply. First is the individual mode in which energy self-consumption and energy exchange actions of each building agent are simulated to obtain urban-scale matching results. At each time instant (hour), a building agent acts to fulfill its energy demand from its self-supply, resulting in self-consumption ($sc_t$). It imports energy from the electric grid if self-supply is not enough or exports energy if there is a surplus resulting in energy exchange ($ee_t$) with the electric grid. The second one is the aggregated mode (or the community mode), in which the energy supply and demand of all building agents are aggregated, considering them as a single entity, and self-consumption and energy exchange actions of the urban area are simulated to obtain energy matching outcomes. The energy matching in the two modes is given by equations (4a) and (4b).

$$ed = \begin{cases} \sum_i ed_i & \text{Aggregated mode} \\ ed_i & \text{Individual mode} \end{cases} \quad , \quad ss = \begin{cases} \sum_i ss_i & \text{Aggregated mode} \\ ss_i & \text{Individual mode} \end{cases} \tag{4a}$$

$$sc_t = \begin{cases} ss_t & ed_t > ss_t \\ ed_t & ed_t \leq ss_t \end{cases} \quad , \quad ee_t = \begin{cases} ss_t - ed_t & ed > ss \quad \text{Import} \\ ss_t - ed_t & ed \leq ss \quad \text{Export} \end{cases} \tag{4b}$$

## 2.3 Performance Evaluation

The performance of chosen cases of the urban context is evaluated using a set of metrics, which include self-consumption, self-sufficiency, net energy, peak import reduction, and energy cost saving. Self-consumption is the portion of energy self-supply of an urban area or a building $i$, consumed to meet its demand, and is given by equation (5) for the aggregated and individual modes of energy matching.

$$scr = \begin{cases} \sum sc^t / \sum ss^t & \text{Aggregated mode} \\ \sum_i \sum_t sc_i^t / \sum_i \sum_t ss_i^t & \text{Individual mode} \end{cases} \tag{5}$$

Self-sufficiency is the share of energy demand of an urban area or a building $i$, fulfilled from its self-supply of energy, and is given by equation (6).

$$ssr = \begin{cases} \sum sc^t / \sum ed^t & \text{Aggregated mode} \\ \sum_i \sum_t sc_i^t / \sum_i \sum_t ed_i^t & \text{Individual mode} \end{cases} \tag{6}$$

Net energy is the proportion of net energy exchanges with the grid to the annual energy demand and is given by equation (7). It does not depend on the mode of energy supply-demand matching.

$$ner = \sum_i \sum_t ee_i^t / \sum_i \sum_t ed_i^t \tag{7}$$

Peak import reduction is the fraction of annual peak demand reduced due to self-consumption and is given by equation (8).

$$pir = \begin{cases} 1 - \max_t \, |(ee^t)^-| \,/\, \max_t \, (\sum_i ed_i^t) & \text{Aggregated mode} \\ 1 - \max_t \, (|\sum_i (ee_i^t)^-|) \,/\, \max_t \, (\sum_i ed_i^t) & \text{Individual mode} \end{cases} \tag{8}$$

Energy cost saving, given by equation (9), is the fraction of annual energy expense lowered by the self-consumption of locally produced renewable energy while considering the capital ($cc$) and operational costs ($oc$) of the self-supply system. The case study assumes a net energy metering policy and tiered energy pricing ($p_t$) following the current situation in Toronto (Ontario Energy Board 2023). As per the policy, the surplus energy credits at year-end (from monthly net exports), if any, are nullified and not rolled over to the next year. Such leftover energy credits ($lec$) as a fraction of total energy demand expenses are given by equation (10). The energy prices used are 0.103 and 0.125 CAD/kWh for the first and second tiers respectively, with 750 kWh as the threshold for the first tier (Ontario Energy Board 2023). The costs of solar PV systems used in the study vary with system capacity and can be found in (Mussawar et al. 2023a).

$$ecs = \begin{cases} 1 - \frac{\sum_m(\sum_{t\in m}(|(ee^t)^-| - |(ee^t)^+|)\times p^t) + cc + oc}{\sum_i \sum_m(\sum_{t\in m} ed_t^i \times p^t)} & \text{Aggregated mode} \\ 1 - \frac{\sum_i(\sum_m(\sum_{t\in m}(|(ee_t^i)^-| - |(ee_t^i)^+|)\times p^t) + cc_i + oc_i)}{\sum_i \sum_m(\sum_{t\in m} ed_t^i \times p^t)} & \text{Individual mode} \end{cases} \quad (9)$$

$$lec = \begin{cases} -\frac{\min(\sum_m(\sum_{t\in m}(|(ee^t)^-| - |(ee^t)^+|)\times p^t),\ 0)}{\sum_i \sum_m(\sum_{t\in m} ed_t^i \times p^t)} & \text{Aggregated mode} \\ -\frac{\sum_i(\min(\sum_m(\sum_{t\in m}(|(ee_t^i)^-| - |(ee_t^i)^+|)\times p^t),\ 0))}{\sum_i \sum_m(\sum_{t\in m} ed_t^i \times p^t)} & \text{Individual mode} \end{cases} \quad (10)$$

The results from the simulation of 200 instances of an urban area for each of the five cases of urban context are presented and discussed in the following section (segregated into energy and economic performance). In each instance, the $lsa_i$ and $fl_i$ are assigned using empirically-guided sampling distributions, and the $eui_i$ is assigned randomly from the dataset filtered based on building features.

## 3 RESULTS AND DISCUSSION

### 3.1 Energy Performance

The energy performance of the simulated scenarios across the four metrics is displayed in Figure 5. Energy self-consumption of the urban area, shown in Figure 5(a), is higher in cases that are dominantly open high-rise compared to others under the individual mode of energy supply-demand matching. The cases with a mix of large low-rise and open high-rise zones, the energy self-consumption increased substantially under the aggregated mode of energy supply-demand matching. In those cases, surplus energy from large low-rise buildings is consumed by the high-rise buildings effecting a rise in self-consumption of the urban area. The increase in the proportion of open high-rise zones tends to benefit the urban area in self-consumption, which means less surplus energy to be handled by the electric grid.

Energy self-sufficiency of the urban area, shown in Figure 5(b), decreased to below 10% as the proportion of open high-rise zones (built types) increased under both modes of supply-demand matching. Certain cases with a mix of both types of zones (e.g., the case with 75% of urban area covered by large low-rise and 25% by open high-rise zones) have a larger difference in self-sufficiency compared to other cases. High self-consumption and low self-sufficiency of cases (e.g., the case with 75% of area occupied by large low-rise zones and 25% by open high-rise zones) indicate less room for improvement in self-sufficiency and strong dependency on the electric grid for demand fulfillment.

The net energy ratio of the urban area, shown in Figure 5(c), experienced a large jump from 22% to 72% as the proportion of the open high-rise zone increased from 0 to 25%, implying an increased reliance on the grid to match demand. This implies that a small proportion of high-rise buildings in a large low-rise area can substantially lower its chances of achieving net-zero energy goals. The urban area of only large low-rise built type can achieve self-sufficiency equal to its net energy ratio of 22% (average) by increasing its self-consumption to 100%. Furthermore, Figure 5(d) shows that the urban area experienced a lower percentage reduction in peak imports as the proportion of the open high-rise zone increased. Reduction in the cases with a mix of two types of zones is slightly more under the aggregate matching versus in the individual mode. However, the difference is not large between the two modes.

Overall, the results point out that the shift towards open high-rise buildings as seen in Toronto makes it harder for the city to realize energy self-sufficiency and net-zero emissions goals, which may require efforts beyond the urban boundaries amid competing land uses. For example, urban areas with open high-rise buildings can purchase clean energy credits (IESO 2023), which rely on generating renewable energy elsewhere, to account for their net-zero emissions goal. The model, enabled by its bottom-up building-scale approach, uniquely reveals that urban areas with a certain mix of large low-rise and open high-rise zones (e.g., a 3:1 ratio) can improve their self-consumption and self-sufficiency through an aggregated mode of energy supply-demand matching (e.g. by adopting energy community configuration). The results do not explore the impact of functional heterogeneity as the mix of building use types is kept constant in all cases.

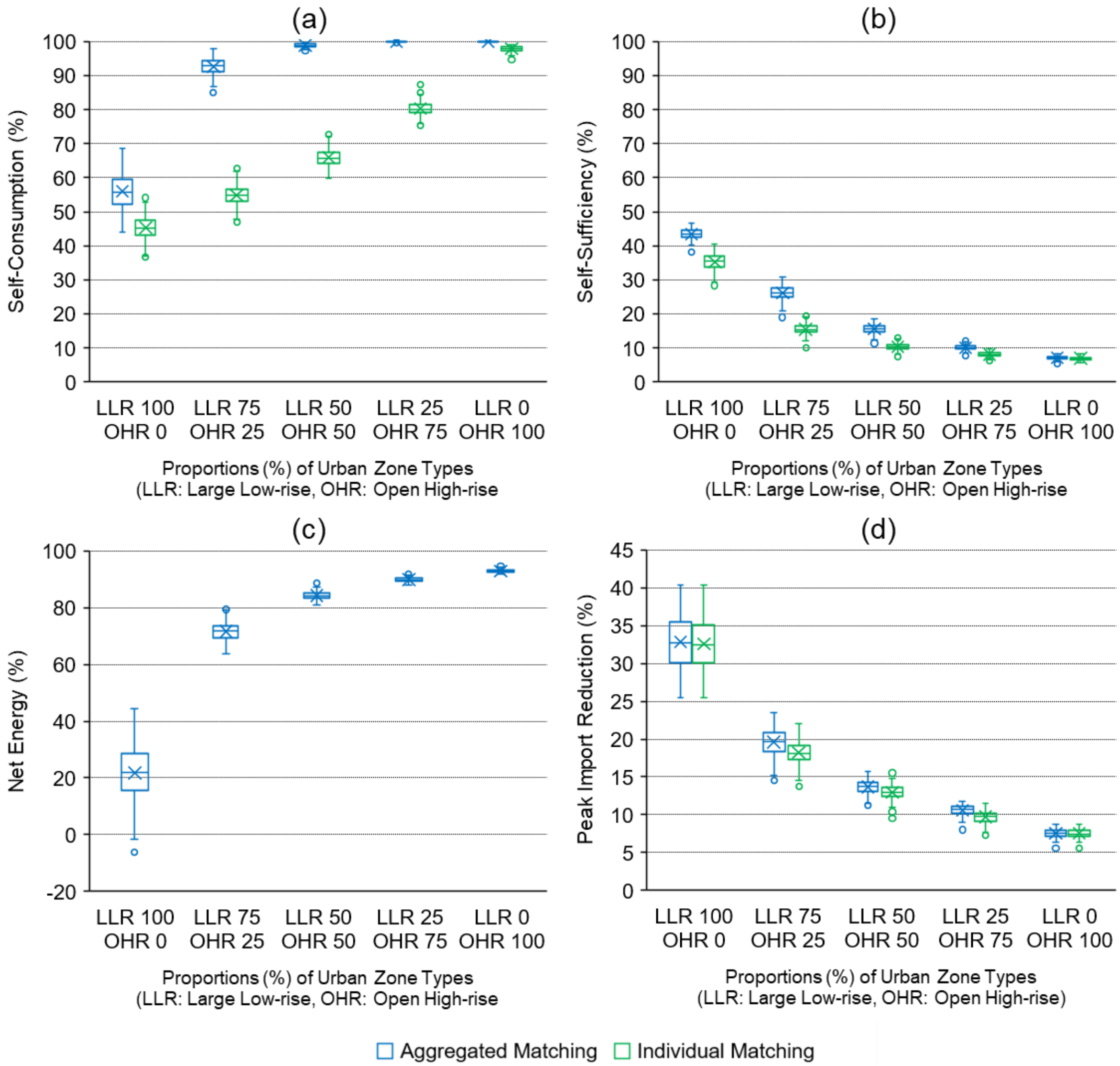


Figure 5: Energy performance of the urban area with urban form evolving from large low-rise (LLR) to open high-rise (OHR) types of zones.

## 3.2 Economic Performance

Energy cost savings of the urban area from local renewable energy production and consumption are presented in Figure 6 for the five cases. It is found that the urban area is unable to achieve savings in energy costs under the individual mode of energy supply-demand matching. The situation of the urban area comprising of large low-rise zone is worse than of the area with open high-rise zone. Buildings in the large low-rise zone experience large energy surplus due to their low energy self-consumption (shown in Figure 5(a)) and high solar energy generation. The net energy metering policy does not financially compensate for the surplus energy produced by the buildings or the urban area in a month beyond a year (Ontario Energy Board 2023). These two factors, besides relatively low electricity prices, contributed to the large negative savings (or increment) in annual energy expense of the urban area with large low-rise built type. However, the urban area consisting of mainly large low-rise zone achieved around 3% reduction in energy expense under the aggregated mode of energy supply-demand matching. The aggregated mode did not result in a large change in energy savings of urban area with the open high-rise zone since it had a very low margin of improvement in self-consumption and self-sufficiency (as Figures 5(a) and 5(b) indicate).

Figure 6(b) shows the financial credits obtained from surplus energy that are leftover at year-end and will be lost (unutilized) as per the net energy metering policy in Toronto. It is found that the large low-rise urban area is left with large percentage (20%) of surplus energy credits and the shift towards open high-rise urban form works well with the policy as the percentage of financial losses reduced. However, urban areas dominated by the large low-rise zone do not face the issue of unusable surplus energy credits under the aggregated mode of supply-demand matching. Overall, urban areas consisting of large low-rise type of urban form are more likely to improve their economic performance through the aggregated matching. The low levels of potential savings estimated for the city of Toronto are mainly due to the low capacity factor of solar systems, which inflated the unit cost of solar energy and the comparatively low electricity prices.

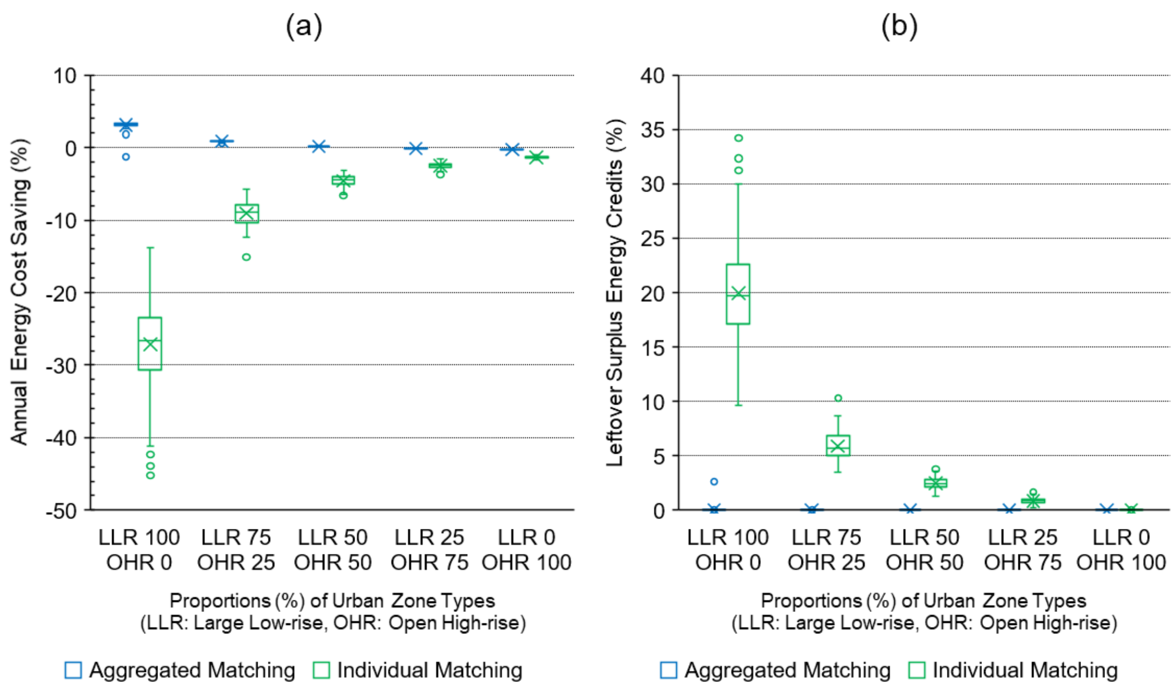


Figure 6: (a) Savings in annual energy costs of the urban area (b) Surplus energy credits leftover at year-end with urban form evolving from large low-rise (LLR) to open high-rise (OHR) zone types.

## 4 CONCLUSION

Efforts to achieve energy self-sufficiency and net zero emission goals need to consider the urban features of the built environment. Previous studies that incorporated urban built form and function in the analysis of urban energy performance did not consider urban contexts comprising multiple/mixed types of urban built form (e.g., areas with low-rise and high-rise buildings), which may exist as the urban form of cities evolves. This work extended an agent-based modeling framework to allow for the representation and analysis of urban areas occupied by multiple types of zones (urban built types) as per LCZ classification. The model simulates the energy supply-demand matching under the individual and aggregated modes and computes the performance outcomes through five metrics addressing energy and economic aspects. The model is applied to a case study based in Toronto that evaluates the impact of evolving urban form on urban-scale energy performance. It considered five cases of an urban area that differed in the land area-wise proportions of large low-rise and open high-rise zones. The shift from large low-rise to open high-rise urban forms is found to lower the potential of urban areas for self-sufficiency and net zero energy. Urban areas with a mix of both types of urban forms (large low-rise and open high-rise) can improve their self-consumption and energy cost savings through the aggregated mode of supply-demand matching as energy surpluses from large low-rise buildings can be utilized by the high-rise buildings. In addition to the nuanced insights from this work on the impact of urban form evolution, the model could be easily applied to other geographical urban contexts or developed into a support tool to inform energy policy-makers and planners. Future work could also incorporate the effect of mixed types of urban form on the urban solar energy supply potential.

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## AUTHOR BIOGRAPHIES

**OSAMA MUSSAWAR** is a Ph.D. candidate in the Engineering Systems and Management Program at Khalifa University, United Arab Emirates. His doctoral research focuses on the pursuit of sustainable cities and energy infrastructure, and develops novel computational and data-driven approaches for context-aware analysis, planning, economics, and policy. His email address is osama.mussawar@ku.ac.ae.

**ELIN MARKARIAN** is a Ph.D. student in the Building Engineering Program at Carleton University. Her research explores the use (and combination) of physics-based and data-driven models to provide fast and reliable building performance predictions. Her email address is elinmarkarian@cmail.carleton.ca.

**AHMAD MAYYAS** is an Assistant Professor of Management Science and Engineering at Khalifa University, Abu Dhabi, UAE. He joined Khalifa University in the fall of 2019. Before that, Dr. Mayyas worked as a clean energy systems analyst at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. He is currently involved in R&D activities of renewable energy systems, design, and manufacturing of fuel cells, water electrolyzers, and Li-ion batteries. His email address is ahmad.mayyas@ku.ac.ae and his website is https://www.ku.ac.ae/college-people/ahmad-mayyas.

**ELIE AZAR** is a Canada Research Chair and Associate Professor in the Department of Civil and Environmental Engineering at Carleton University in Ottawa, Canada. His research interests include human-centered building design and operation, occupant behavior modeling, building performance simulation, agent-based modeling, and data-driven predictive models. He has authored numerous scientific research articles in his field and edited books focused on sustainability, smart cities, artificial intelligence, and carbon neutrality. His email address is elie.azar@carleton.ca and his website is https://carleton.ca/cee/profile/elie-azar/.