A NEW LOOK INTO ENERGY-OPTIMIZED NEIGHBORHOODS WITH ENERGY-EFFICIENT DISTRICT ENERGY SYSTEMS

Abstract

This manuscript presents a new approach to designing energy-efficient supply systems for districts with low-energy and low-carbon buildings. By taking the case of two neighborhoods located in Boston, a heating dominated climate, and Mumbai, a cooling dominated climate, the study investigates alternative energy supply systems for these neighborhoods that meet the projected energy demands when buildings are designed to meet stringent performance standards.

The study shows that climatic conditions, performance of buildings, configuration of district system, availability of low-carbon energy sources, and cost of energy are critical factors for a successful realization of neighborhoods with low greenhouse gas (GHG) emissions and low-operation costs. Taking all factors into account, carbon emissions in Mumbai are found to be higher than emissions in Boston, for same neighborhoods with similar district energy systems. Furthermore, the preferred district systems for high performance neighborhoods in Boston and Mumbai are different for cost-saving and emission-reduction targets. In Mumbai, all gas is the best energy supply scenario in terms of low emissions when compared with baseline and all-electric district systems, but has the highest operational cost. On the other hand, in Boston, all gas has the highest emissions, but the lowest operation cost. The reverse is true for all electric ,where in Boston it has the lowest emissions with the highest operation cost, but in Mumbai it has the highest emissions with the lowest operation cost.

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Keywords

Energy-systems, low-energy buildings, low-carbon buildings

Introduction

There is a growing interest in Net-Zero and Passive House buildings among investors and building developers. Consultants that promote the design and construction of low-energy and low-carbon buildings are becoming leaders in setting new performance standards and benchmarks, both regionally, and internationally. Institutions with substantial, continuous building stocks—such as university campuses—are taking a new approach that implements innovative energy supply systems. Compared to previous years, a large number of residential and commercial buildings are setting goals to lower heating and cooling loads by relying on high performance building envelopes, efficient building systems, and onsite energy-production strategies. As a result, the overall energy profile of neighborhoods changes significantly and alters the way buildings draw energy from the main municipal grid system, or central energy facilities.

It is important to evaluate various possible thermal plant configurations, especially at initial design stages, to compare the operational energy use, annual energy costs and GHG associated with purchased grid utilities for different scenarios. In the United States, the most common inputs for district systems are grid electricity and natural gas. The combination of these energy inputs can vary considerably based on the selection, capacities, and efficiency of the thermal plant equipment, and it should be configured carefully after considering the load balance between project electricity and thermal energy requirements, and the relative emissions and costs associated with grid electricity and natural gas (Letellier-Duchesne, Nagpal, Kummert, & Reinhart, 2018).

Urban Building Energy Modeling (UBEM) is used to estimate energy loads in the neighborhood. The simulated building load curves are combined with energy supply models based on different energy inputs and central plant configurations. Previous researchers have developed a continuous design workflow by linking neighborhood-level building load calculations with detailed district-energy network analysis models (Letellier-Duchesne et al., 2018). This approach is instrumental for integrating supply- and demand-side management of district systems. As a proof of concept, the authors have analyzed neighborhoods in Boston and Montreal and the performance of different district systems are reported (Letellier-Duchesne et al., 2018). However, the impact of a growing number of energy-efficient buildings on the performance of district energy systems of neighborhoods has not been evaluated.

Districts in cities are at a point where they have to actively incorporate strategies to reduce building energy-associated greenhouse gas emissions. One way of achieving this goal is incorporating efficiency on the demand side to individual buildings—another way is improving the efficiency of energy supply systems. This paper compares these two and illustrates that the preference of district energy systems for energy-efficient neighborhoods relies on the types and size of energy demands, which are highly influenced by the performance of the buildings on site.

Methodology

A neighborhood is modeled in Rhinoceros, a 3-D CAD application, and energy performance simulations are performed using the Urban Modeling Interface (UMI) tool (Reinhart, 2014). UMI is a Rhino-based environmental performance analysis platform for cities and neighborhoods. The district systems are evaluated using the district system plug-in for UMI developed by Letellier-Duchesne and Nagpal at the Universite de Montreal and MIT (Letellier-Duchesne, Nagpal, Kummert, & Reinhart, 2018). The investigated neighborhood has mixed-use buildings with residences, offices, and retail spaces (Figure 1). In order to understand the impact of climate and local fuel mix on costs and environmental impact of the operational energy use of a neighborhood, the analysis is also studied in Mumbai. In both cities the neighborhood is evaluated for two different demand-side scenarios, and three different supply-side scenarios.

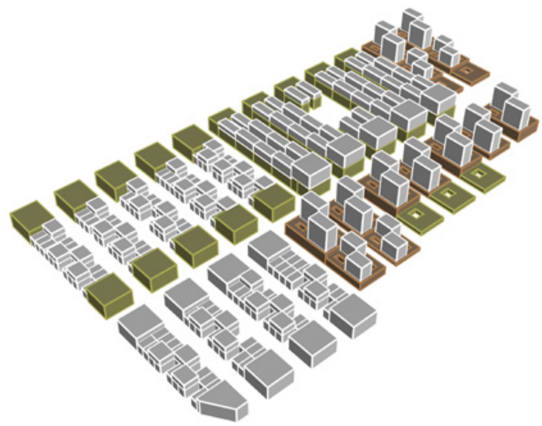

Figure 1: Mixed-use neighborhood with residences, offices, and retail buildings.

The neighborhood is evaluated for two different constructions and building internal-load scenarios. The base construction is assumed to represent the typical current construction and performance. Mechanical systems for heating, cooling, and ventilation are considered to be operational a majority of the time in the base case. In contrast, the improved construction has high-performance building envelopes, efficient lighting systems, and efficient equipment. Natural ventilation is used when outdoor conditions are within acceptable range; mechanical cooling and ventilation systems are used only when natural ventilation is not possible.

While Boston is located in ASHRAE zone CZ-5, a heating dominated climate, Mumbai is in climate zone CZ-0, a cooling dominated climate, based on the latest climate zone definitions provided in ANSI/ASHRAE Standard 169-2013 Climate Data for Building Design Standards. Typical meteorological year (TMY) weather files in EPW file format, both for Boston and Mumbai, are accessed from EnergyPlus database (US-DOE & NREL, 2018). Figure 2 shows annual temperature plots of the two cities with monthly average, and maximum and minimum for every hour in a day.

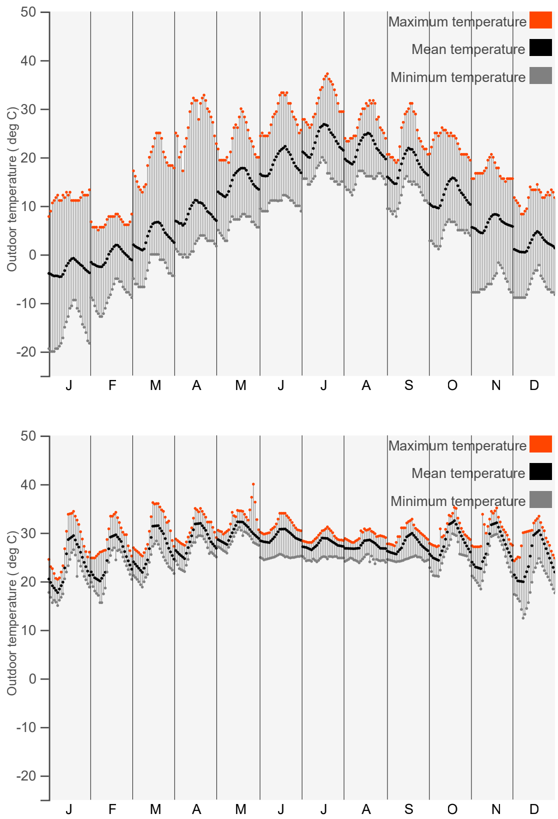

Figure 2: Annual temperature plots: Boston (top), Mumbai (bottom).

The average maximum temperature in Boston is about 33°C, while in Mumbai it goes above 35°C. On the other hand, the lowest average minimum temperature in Boston goes below -10°C in the winter months, while in Mumbai it only goes as low as 15°C. In Boston, the monthly average temperature is between -5°C and 25°C, and in Mumbai, it remains between 18°C and 32°C.

In comparison to Boston, the outdoor temperature in Mumbai remains within similar temperature range, and space heating is not required in winter. However, Mumbai has a humid climate with a monthly mean relative humidity above 70% between May and October, while Boston has dry winters and relatively humid summers—its monthly mean relative humidity is always below 70%.

	Base	Improved
Façade insulation thickness (m)	0.05 – 0.1	0.1 – 0.2
Window type	Double, air, clear	Double, argon, low-e coating
Infiltration (air change rate)	0.35	0.15
Equipment power density (W/m²)	4 – 8	3.4 – 6.8
Lighting power density (W/m²)	7 – 16	4.9 – 11.2
Dimming for lighting	Off	On

Table 1: Building performance parameters, Boston.

	Base	Improved
Façade insulation thickness (m)	0.025 – 0.05	0.5 – 0.1
Window type	Single, clear	Double, air, clear
Infiltration (air change rate)	0.35	0.15
Equipment power density (W/m2)	4 – 8	3.4 – 6.8
Lighting power density (W/m2)	7 – 16	4.9 – 11.2
Dimming for lighting	Off	On

Table 2: Building performance parameters, Mumbai.

Three major district energy system scenarios are adapted for this study (Figure 3). The Baseline district system scenario assumes buildings with natural gas-fired furnaces for heating and domestic hot water (DHW) and electricity supplied from the grid for everything else, including cooling demand in the neighborhood. An all-electric district system is the second scenario where all the required heating and DHW needs are provided by heat pumps that are powered by the grid. The third scenario is an all-gas district system where a centralized, combined heat and power (CHP) plant with a gas-fired backup boiler provides all heating and electricity demands in the neighborhood. In this all-gas scenario, the recovered waste heat from the plant goes to absorption chillers to meet the cooling demand and the remaining recovered energy is used to meet heating demand. When the energy recovered from the CHP plant cannot meet heating demand, gas-fired backup boilers are operated.

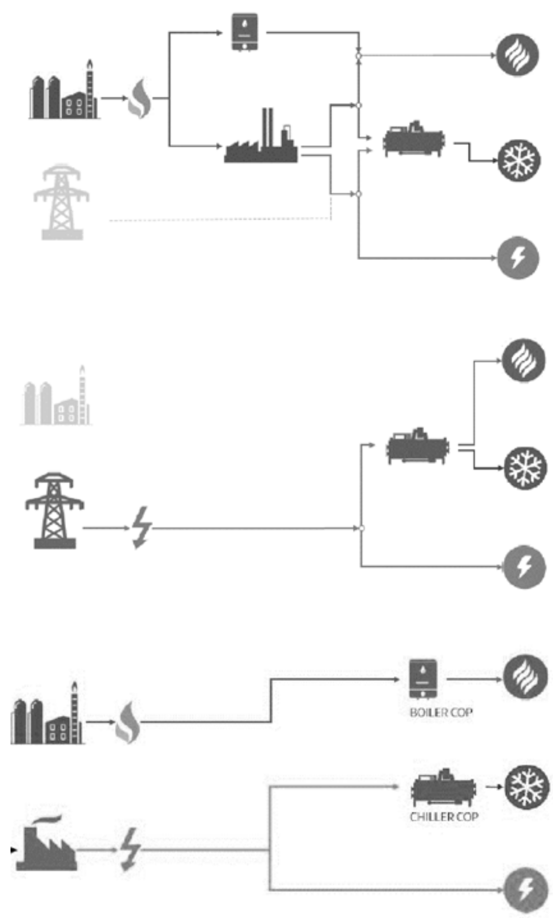

Figure 3: Three types of energy supply scenarios compared for the neighborhood.

The building performance parameters for Boston and Mumbai are given in Tables 1 and 2, and the efficiencies and performance coefficients that are considered for the three district energy system scenarios are given in Table 3.

Electric chiller	Cooling coefficient	4.4
Natural gas boiler	Heating efficiency	84%
Electric heat pump	Heating coefficient	3.2
Absorption chiller	Cooling coefficient	0.9
	Tracking mode	Electrical
Combined heat and power	Electrical efficiency	30
	Waste heat recovery	45

Table 3: Performances of district system components.

Results

This section includes figures comparing different parameters for *base* and *improved* constructions for Boston and Mumbai. The comparisons are shown by end use energy demand as well as by total purchased energy consumption.

The total energy demands by end use for Boston and Mumbai present contrasting patterns. In Boston, the heating demand of the neighborhood is larger than the cooling demand, in both *base* and *improved* neighborhoods. The largest end use energy is electricity load for lighting and equipment. In Mumbai's *base* construction on the other hand, the largest energy demand is for cooling, while in the *improved* construction the largest energy demand is for electricity. Heating demand is always the lowest and that is primarily to supply DHW.

Furthermore, in comparison to *base* construction in Mumbai, the cooling demand is reduced by about 70% in *improved* construction, where buildings have high performance envelopes and natural ventilation is used for fresh air supply and thermal comfort when outdoor conditions are within the acceptable range.

These variations in end use energy loads have direct implications on the total purchased energy of the site based on a given district system. The total energy consumption in Boston's *base* neighborhood is 6% larger than the total energy consumption in Mumbai's *base* construction. However, the total purchased energy for *all gas, base* construction in Boston is 12% lower than that in Mumbai. For *all gas, improved* construction the difference becomes lower than 1% between the two cities.

Comparing *base* to *improved* construction, *baseline* district system in Boston has the highest purchased energy reduction (50%), while *all gas* in Mumbai has the highest purchased energy reduction (47%). This observation indicates that the impact of low-energy neighborhood on different district systems is different for heating dominated and cooling dominated climates.

Figures 4 and 5 illustrate the different district energy sources that are implemented to meet end-use energy demand for the selected scenarios in Boston (Figure 3) and Mumbai (Figure 4). All figures are showing scenarios for *improved* constructions.

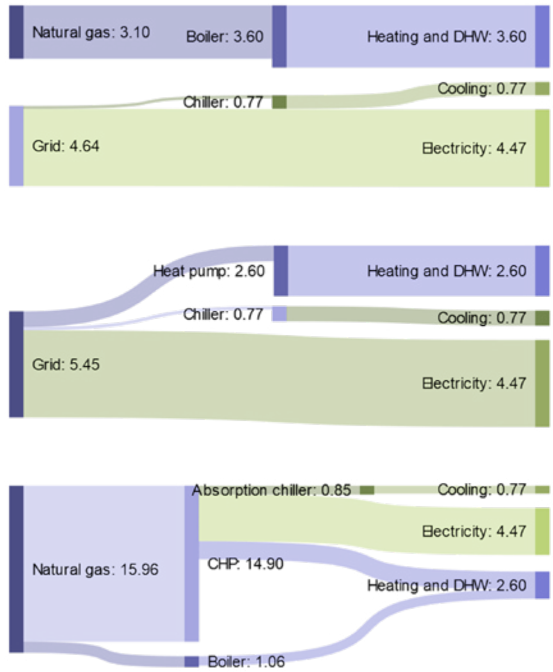

Figure 4: Comparison of the three district systems in Boston, for *improved* construction.

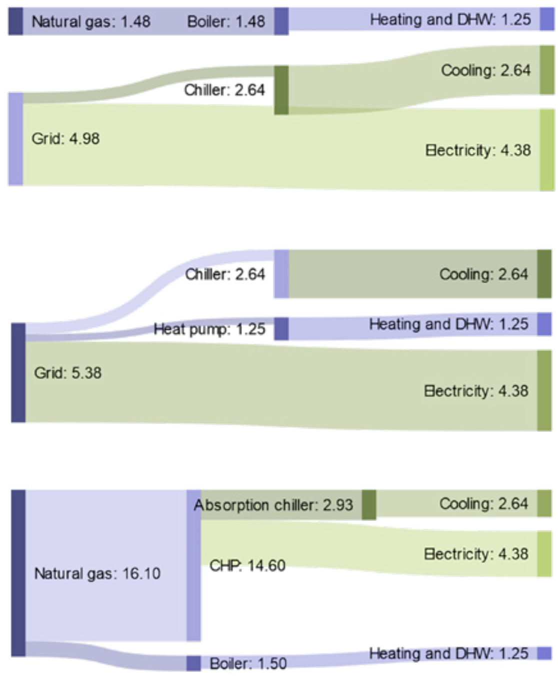

Figure 5: Comparison of the three district systems in Mumbai, for *improved* construction.

The diagrams illustrate the connection between purchased energy (at the left end) and end-use energy (at the right end), with all the district system processes shown in between. In the baseline scenarios, the proportion of natural gas and grid electricity consumption can be compared between Boston and Mumbai. Because Boston is heating dominated and Mumbai is cooling dominated, the proportion of natural gas consumed in Boston is larger than what is consumed in Mumbai. The Sankey diagrams in Figures 4 and 5 are created using a 3-D based online tool (Bogart, n.d.).

To demonstrate the effectiveness of the *baseline*, *all electric* and *all gas* district systems for the proposed neighborhood, the authors have compared carbon emissions and operational costs both for *base* and *improved* construction of the buildings in the site.

All gas has the lowest operational energy cost in Boston (Figure 5) with assumed gas and electricity prices of 0.04 US$/kWh and $0.20 US$/kWh, while *all electric* has the lowest annual carbon emissions. The emission rate of electricity generation in the geographical region of Boston is only about 50% of the national average emission rate (Power Profiler 2017). Close to 50% of electricity is being generated by renewable energy sources and nuclear power plants, with total associated greenhouse gas emissions of 0.275 $kgCO_2e/kWh$ (US-EPA, 2017). The emissions associated with natural gas in kCO_2e/kWh are about 65% of emissions from electricity, however due to lower efficiencies of gas-fired boilers, total source energy consumed in all gas is three times larger than that in *all electric*; the overall emissions of *all electric* system is the lowest.

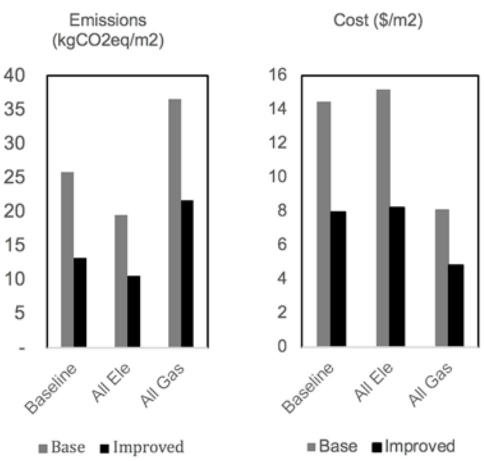

Figure 6a: District emissions and total energy cost, comparison of *base* and *improved* neighborhoods in Boston.

When investment decisions have to be made concerning improvements on the performance of buildings and district systems, with the goal of reducing emissions and operation costs, various alternatives can be drawn. As shown in Figure 5, emissions from *all electric*, *base* construction is only 1% lower than emissions from *all gas*, *improved* construction. On the other hand, operation cost of *all electric*, *base* construction is more than three times that of *all gas*, *improved* construction. Furthermore, the operation cost of all *electric*, *improved* construction is only 1% higher than that of *all gas*, *base* construction, while emissions is more than three times larger.

In Mumbai, *all electric* has the lowest operational energy cost both for *base* and *improved* construction with assumed gas and electricity prices of 0.056 US$/kWh and $0.09 US$/kWh (Numbeo, 2018), while *all gas* has the lowest annual carbon emissions when compared across similar construction. The emission rate of electricity generation in the geographical region of Mumbai is more than five times the emission rate of natural gas (Shailesh, 2013).

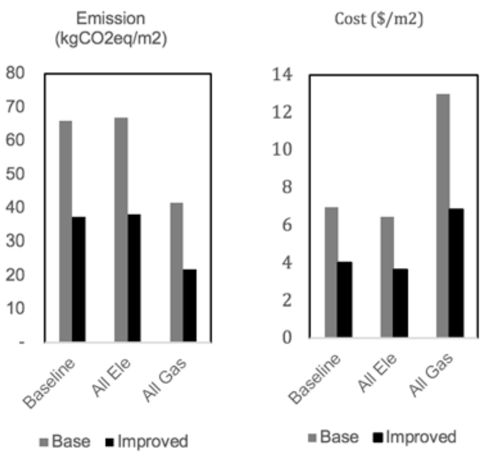

Figure 6b: District emissions and total energy cost, comparison of *base* and *improved* neighborhoods in Mumbai.

All electric, *improved* construction has 14% lower emissions than *all gas*, *base* construction (Figures 6a and 6b). In addition, the operation cost is three times smaller. On the other hand, *all electric*, *improved* construction is 42% of the operation cost of *all gas*, *improved* construction, whereas emissions are 70% larger. *Improved* construction is the best option in terms of operation cost for *all electric* district system, and it is the best option in terms of emissions for all gas district systems. In contrast to district systems in Boston where all electric is the most preferred, *baseline* and *all electric* have similar emissions in Mumbai.

Conclusion

With the current growing interest in district systems that play a great role in reducing emissions and operation costs, it is important to evaluate energy-efficient neighborhoods. In comparison to baseline constructions, improved performance of buildings helps reduce heating, cooling and electricity demands. This intern calls for a new way of designing and implementing district systems based on neighborhoods' energy profiles.

This analysis shows that fuel costs vary locally and can pose an impediment to sustainable development. In Boston *all gas* has the lowest operation cost and the highest emission, while in Mumbai it has the highest operation cost and the lowest emission. Electricity costs more in Boston than in Mumbai; it is also a cleaner energy source in Boston with about 50% generated from renewable sources, while in Mumbai about 65% of electricity is generated from coal. *All electric* is the most environmentally friendly in Boston.

Ultimately, carbon pricing will have to be employed as an effective tool for overcoming such conflicts between economic and environmental goals. In the case of Boston and Mumbai, the carbon price for selecting the best environmental solution are 58 US$/ton CO_2 and 20 US$/ton CO_2, respectively.

Furthermore, the commitments by district energy facilities to shift to cleaner energy play a great role in the decisions made at the neighborhood scale, and this paper discusses plausible scenarios that promote holistically designed, energy-efficient neighborhoods. A projection into the future under climate change, where conditions present new challenges with increased temperatures, shall be considered in future work, as the increasing number of buildings continue to adopt high-performance goals.

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