The Mothership - A Mixed-Use High-Density Proposal To Combat Urban Sprawl

by

Wesley Bowley
B.Eng, University of Victoria, 2017

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

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We acknowledge with respect the Lekwungen peoples on whose traditional territory the university stands and the Songhees, Esquimalt and W̱SÁNEĆ peoples whose historical relationships with the land continue to this day.

Supervisory Committee

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Dr Ralph Evins, Department of Civil Engineering
Supervisor

Dr Christopher Kennedy, Department of Civil Engineering
Committee member

Abstract

The built environment is responsible for a large portion of total energy use and emissions. A large portion comes from the buildings themselves, but also the transportation system to move people around. As global populations grow, and more people migrate to cities, it is critically important that new city growth is done in the most sustainable manner possible. The typical North American pattern of urban growth is urban sprawl, characterized by single use type zoning, low density, transportation system dominated by personal vehicles, and poor public transit. Urban sprawl has numerous downsides, including poorer energy efficiency in buildings and infrastructure, more congestion and higher emission from vehicles, as well as many negative health effects.

This thesis presents the concept of a Mothership, a large, high-density mixed-use building designed to combat urban sprawl and minimize energy use and emissions of the built environment. A mothership is designed to provide all the amenities and housing of a typical suburb for 10,000 people. The analysis in this thesis employ building simulation tools to model various mothership designs and analyse the operational and embodied energy and carbon emissions for each design, and compare it to base cases of more traditional building use types such as single detached homes, and different types of apartment buildings. The effect of high-performance building envelopes and other building materials on operational and embodied energy and emissions are analysed. A multi objective optimization analysis is performed to determine which technologies and combinations of technologies provide the lowest cost solution to meet the mothership's energy demands while also minimizing emissions.

The mothership's effect on transportation emissions is also investigated. The building's mixed-use nature allows trips to be satisfied within walking distance in the building. The high concentration of people makes for a good anchor load for public transportation, so the emissions reductions of implementing a bus rapid transit system from the mothership to the central business district is estimated. To reduce transportation emissions further, the effect of an electric car share fleet for mothership residents use is also quantified.

The energy system of a mothership is optimized, along with base cases of single detached homes, under numerous scenarios. These scenarios are designed to explore how the energy system changes in an attempt to answer a series of research questions. Some of the measures explored are a high carbon tax, net metering, and emissions limits of net zero, and negative emissions with two different electrical grid carbon intensities.

Results showed that a highly insulated, timber framed mothership can achieve very high reductions in energy use and emissions. Overall it showed reductions of 71%, 73%, and 74% in operational energy, embodied energy and embodied carbon respectively, over a baseline case of single detached homes. It was estimated that transportation emissions could be reduced by 58% through the mixed-use development reducing the number of trips and electrically powered transportation vehicles and bus rapid transit. This gives a combined total emissions reduction of 61%. Energy system optimization showed that the mothership design in achieved far lower costs and emissions (4 and 8.7 times lower respectively) than the base case of single detached homes. Of the mothership cases examined, the most expensive case was the one which had a carbon tax, with an annualized cost of $4.3 million. The case with the lowest annualized cost was one with, among other factors, a net zero carbon emissions restriction (annualized cost of $3.08 million. Many of the cases had negative operating costs due to the sale of renewable energy or carbon credits. This illustrates that the integration of renewable energy technologies is not only beneficial for reducing emissions but can also act as an income pathway for energy systems.

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Author Contributions

This thesis consists of three peer reviewed conference publications and two journal article manuscripts that will be submitted to peer reviewed journals. The author contributions are clarified below.

Bowley W., Evins R. A Bottom Up Statistical Building Stock Model for the City of Victoria. *1st International Conference on New Horizons in Green Civil Engineering, 25-27 April 2018, Victoria, Canada*.

> W.B. developed the methodology, performed the analysis and wrote the manuscript. R.E. supervised the project, contributed to the methodology and revised the manuscript.

Bowley W., Westermann P., Evins R. Using Multiple Linear Regression to Estimate Building Retrofit Energy Reductions. *IBPSA-Canada's biennial conference themed Building simulation to support building sustainability (eSim), 10-11 May 2018, Montreal, Canada*.

> W.B. contributed to the methodology, consolidated the database in preparation for regression analysis, and wrote relevant manuscript sections. P.W. contributed to the methodology, performed the regression analysis and wrote the relevant manuscript sections. R.E. supervised the project, contributed to the methodology and revised the manuscript.

Bowley W,. Evins R. Energy Performance Comparison of a High-Density Mixed-Use Building To Traditional Building Types. *Proceedings of Building Simulation 2019, IBPSA, 4-6 September, Rome, Italy.*

> W.B. developed the methodology, performed the analysis and wrote the manuscript. R.E. supervised the project, contributed to the methodology and revised the manuscript.

Bowley W., Evins R. Assessing Energy and Emissions Savings for Space Heating and Transportation for a High-Density Mixed-Use Building. *Prepared for submission to the Journal of Building Performance Simulation.*

> W.B. developed the methodology, performed the analysis and wrote the manuscript. R.E. supervised the project, contributed to the methodology and revised the manuscript.

Bowley W., Evins R. Energy System Optimization of a High-Density Mixed Use Development. *Prepared for submission to Applied Energy journal.*

> W.B. developed the methodology, performed the analysis and wrote the manuscript. R.E. supervised the project, contributed to the methodology and revised the manuscript.

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Of course, I would like to thank my partner Kristen, and my family for their unconditional love, support and willingness to listen to my rants and ramblings throughout the course of my degrees.

1. Introduction

The world's population is growing at an unprecedented rate, and is expected to increase to 9.8 billion people by 2050 (United Nations 2018). This increase in population is putting more and more strain on the built and natural environments. Much of this growth happening in urban centers. Currently 55 % of people live in cities and urban environments (82% in North America), and this to is expected to increase to 68 % by 2050 (United Nations, 2014). As a result of this growth, cities either need to densify, or expend, or both in some cases.

Compounding this problem is climate change, which is expected to drastically change the earths climate in certain areas, potentially reducing the ability of urban areas to support high densities of people. With sea level rise threatening low lying settlements, this could cause further displacement of millions of people into other cities (Nicholls et al. 2011).

Therefore, it is critical that this new growth, or densification be carried out in the most environmentally friendly and sustainable manner possible, minimizing energy use and more importantly, carbon emissions.

In most cases of urban growth, especially in North America, there is little planning or control, and cities expand outwards into previously peri-urban areas and greenfield sites. This leads to a phenomenon called urban sprawl, which can be characterized by low density, single use type (typically single detached homes), with a dominance of personal vehicle transportation and poor public transportation (White et al. 1974).

There are many negatives to urban sprawl. There is increased energy use in buildings, due to larger surface area to volume ratio of single detached homes compared with more dense forms of housing, meaning more area for heat to transfer in and out of buildings which needs to be replaced or expelled by mechanical systems. The focus on personal vehicles and poor public transit systems increases congestion, resulting in higher emissions, particulate matter in the air, and more motor vehicle accident with associated health care costs (Ewing et al., 2016). The absence of neighbourhood walkability encourages a more sedentary lifestyle, which increases risk of diabetes, heart disease, and other illnesses (Ewing et al. 2014).

The main portion of this thesis deals with the concept called a "Mothership," which is a large mixed-use residential building that is more expansive than tall, build with mass timer construction with a high-performance building envelope and advanced energy systems. It is designed to house 10,000 residents, as well as contain all the amenities in a typical suburb, all co-located in one building. These include schools, retail and office spaces, medical and recreational facilities. Some advantages of building in this way include better energy efficiency due to lower building surface area, the mixed-use nature of the mothership means that trips can be satisfied by walking, which reduces car use. Further, the high density of people forms an anchor load for higher capacity modes of public transportation between the mothership and other urban centers which further reduces car trips.

Transportation is a critical part of the urban environment and must be considered when trying to reduce emissions of the built environment. As buildings and energy systems become more efficient and operational energy and emissions falls, embodied energy and transportation are left. Embodied emissions can be minimized relatively easily by new building materials such as mass timber construction used in place of concrete. Summing up the possible reductions, it becomes apparent that the problem of minimizing the emissions of the built environment comes down to transportation emissions. Therefore, designing a holistic solution that considers transportation as well as the buildings themselves is critical.

There are many studies that examine the benefits of mixed use and "smart growth" strategies. Each chapter, particularly Chapters 5 and 6 have literature reviews, so to reduce repetition a separate literature review chapter is not included in this thesis. There are also many examples of large mixed-use developments around the world. However, most of these focus on one area of problem, such as only the building and not considering transportation, or only the energy use of buildings and not the emissions produced during its lifecycle. Much of the literature and resources is more qualitative than quantitative, saying that there are benefits to be gained but no estimates as to how much. There is also a lack of holistic modeling, although this is changing, an example being the Urban Modeling Interface (UMI) ((Reinhart et al. 2013)) developed at MIT. Chapters 5 and 6 of thesis presents a methodology for holistically accounting for the operational and embodied energy and emissions of an urban area, including potential reductions to transportation emissions based on higher density mixed use developments. This methodology is applied to a mothership design and compared to base cases of single detached homes.

To summarize the sections of this thesis:

- Chapter 2 is a conference paper that was presented at the New Horizon in Green Civil Engineering (NHICE 2017) held at the University of Victoria. It forms an introduction to urban design and modeling by building a bottom up statistical building stock model of the City of Victoria to model building energy use and tie it to GIS database so that it can be visualized.
- Chapter 3 is a conference paper presented at the eSim conference in Montreal, the Canadian conference dedicated to building energy simulation. This work was an opportunity to apply bottom up urban modeling to a practical application of estimating the energy and emissions reductions for building retrofits for buildings in the City of Victoria.
- Chapter 4 is a conference paper that will be presented at the Building Simulation 2019 conference in Rome (4-6 September). This is the first real dive into urban building modeling and simulation with a preliminary exploration of the mothership concept and initial results. It focuses on modeling numerous typical building architypes and many different mothership designs, and comparing their operational and embodied energy and emissions. Different building shapes, heights, and materials were explored to examine how they effect energy use and emissions.
- Chapter 5 is a journal paper that is ready for submission to the Journal of Building Performance Simulation. It delves more in depth into the mothership concept, refining a potential design, modeling the energy emissions and how this changes in the future by using future climate projections. Additionally, a transportation

analysis is conducted to estimate the emissions reductions provided by the mixed-use nature of the mothership reducing vehicle trips, as well as the implementation of an electric car sharing fleet and an electric bus rapid transit line connecting the mothership to the downtown business district.

- Chapter 6 is another journal paper ready for submission to the Applied Energy journal. It focuses on the energy system of the mothership and applying the Energy Hub model to optimize the technologies and their capacities to minimize costs and carbon emissions. Numerous scenarios are run and compared to the base case of single detached homes.
- Conclusions are drawn that synthesise the findings in Chapter 7.

2. A Bottom Up Statistical Building Stock Model for the City of Victoria

W. Bowley[a*], R. Evins[b,]
1st International Conference on New Horizons in Green Civil Engineering,
25-27 April 2018, Victoria, Canada.
[a] Energy Systems and Sustainable Cities group, Department of Civil Engineering, University of Victoria,
3800 Finnerty Rd, Victoria, BC V8P 5C2.
* wesleyb@uvic.ca

2.1. Abstract:

Creating a useful model of any system requires high-quality information about the inputs and outputs of that system. In order to model and optimize energy systems, the demand for energy must be determined alongside possible sources of supply. A model of the building stock of the City of Victoria was created in order to generate a set of spatially accurate and representative energy demand data. This was done by combining existing datasets obtained from the City of Victoria, Statistics Canada (StatsCan), and Natural Resources Canada (NRCan), and mapping variables between these datasets. The City of Victoria provided high spatial resolution building data (building use type, footprint area, height and location). This data was mapped to neighbourhoods consisting of around two hundred buildings using the StatsCan dataset, which allowed us to add the correct age of construction and the number of households and occupants per building type. The resulting representation was then mapped to NRCan energy use data to get an estimate of the energy use of the building stock for the City of Victoria which is highly resolved both spatially and with regards to building characteristics. The final dataset therefore describes the energy use of the city in a way that can easily be disaggregated into different combinations of neighborhood, age and use type. This will form the basis for further studies regarding energy systems changes, building retrofit programmes and city planning decisions

Keywords:
Building stock, energy modeling, bottom up, statistical

2.2. Introduction

Residential and commercial buildings account for a significant portion of energy use. Therefore, municipalities are considering the building stock in their strategies for reducing emissions. Building stock modeling is a very useful tool for municipalities to get a sense of the kinds of buildings that exist in their area, as well as their energy use. This can then be used in determining where to target policies in order to meet their climate change mitigation goals.

There are two main methods of creating a building stock model: top down and bottom up [1,2]. Top down method involves using aggregated high-level data and statistics to draw conclusions about the building stock. They are beneficial in that they use aggregated data that is more easily available, and avoid detailed technology descriptions. The downside is that it is limited in its ability to assess individual changes to buildings, such as a change of heating system type. It is also not spatially resolved, or at least not at high resolution.

Bottom up models involve using data at an individual building level and compiling these for all the building types in the stock [3]. This has the advantage of being a higher resolution with the ability to look at targeted policy in certain specific areas. This can also be resolved spatially if that data is available. Naturally this requires detailed data for individual buildings to be available which is not always the case.

The method used for this building stock model is to some extents a hybrid of these two methods, referred to as “bottom up statistical” in [1]. It uses a bottom up design for the data that is available, and to get the spatial attributes, but uses high-level aggregated data when building level data is unavailable. Building use type, height, number of storeys, footprint areas, age, and GPS coordinates are all used for the bottom up design, with energy use values obtained using high-level aggregations due to data not being publicly available.

A bottom-up engineering model is another option that analyses energy use down to single building level. The challenge with this method is that detailed building data regarding the building envelope and systems is needed, but often not available. This results in many assumptions that need to be made, which reduces accuracy. In addition, this method does not implicitly include occupants influences on energy use. Statistical models have these factors included implicitly in their aggregated values.

One example of a bottom-up building stock model for Canada is by L. Swan et al. [4], which assembled a building stock representation that is statistically representative of Canada’s residential stock, with nearly 17,000 detailed building entries.

This method has the advantage of being building level and includes spatial elements, but does not require detailed building data, which is not currently available publicly, making it easier to develop and use. As more data becomes available, it can be integrated to improve the model.

The method used to construct the building stock model is appropriate because it makes use of the existing GIS database with the building use distributed how they appear in reality. This is inherently more accurate than assuming a statistically representative distribution of Canadas’s building stock, such as [4]. In situations where building use types are not known, then assuming a distribution is acceptable, however, that is not the case here.

2.3. Data Sources

Figure 1 shows the different databases that were used to make the building stock model and the flow of data from each.

The *City Database* was obtained from the City of Victoria and contains aerial LIDAR data consisting of building footprints, height, GPS coordinates, and elevation, as well as other building information that was available digitally.

The *Survey of Household Energy Use 2011* [5] is a survey performed by NRCan to determine the how much energy is being used in different kinds of residential buildings in Canada and for what purpose. It contains detailed information about energy use based on the building type, age and number of occupants, as well as a breakdown of what kinds of appliances or other plug load items dwellings typically have (computers, video games consoles, etc.). This was the most detailed and relevant residential energy use data available on which to base the energy portion of the stock model.

The energy per square meter values for each residential building type and age bracket is shown in Figure 2. Figure 3 shows the per square meter energy use for commercial and institutional buildings.

A few of the energy use values in Figure 2 go up for the more recent age brackets. This is counter intuitive, since usually building performance increases in newer buildings and hence energy use goes down. One potential reason for this increase, especially in the high-rise apartments is likely due to the higher proportion of glass in facades. Glass has a much lower insulating value than a typical wall does, so thermal losses are increased. It could also be due to contiguous balcony designs without thermal breaks. This also increases thermal losses by making the balconies behave like cooling fins on heat sinks

The *Comprehensive Energy Use Database* [6] contains energy use data for residential, commercial, institutional, and industrial building use types at the province level. This data is not as detailed for residential buildings as SHEU2011, however it is a useful source of data on commercial and institutional buildings

Statistics Canada census data is available at the level of Dissemination Area (DA) [7]. A DA is roughly equivalent to a neighbourhood of about 200 to 500 buildings. It contains a large amount of demographic information, but the parts use for this stock model are the land area, the distribution and number of building types, and the number of people living in each DA.

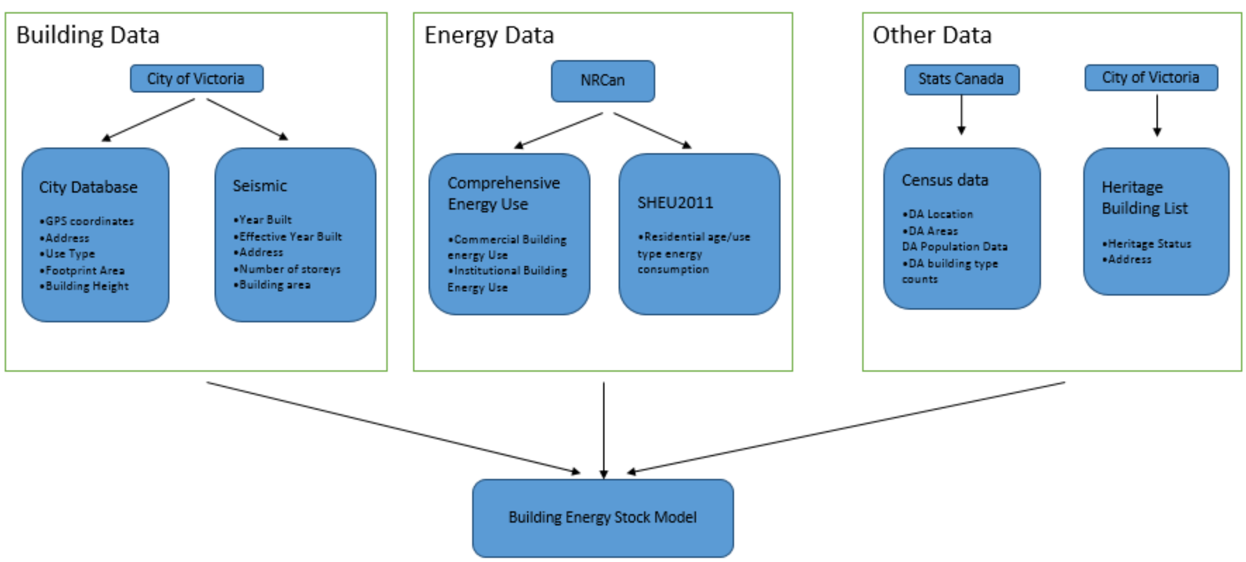

Figure 1: Flow chart of databases used, and which data components came from which source.

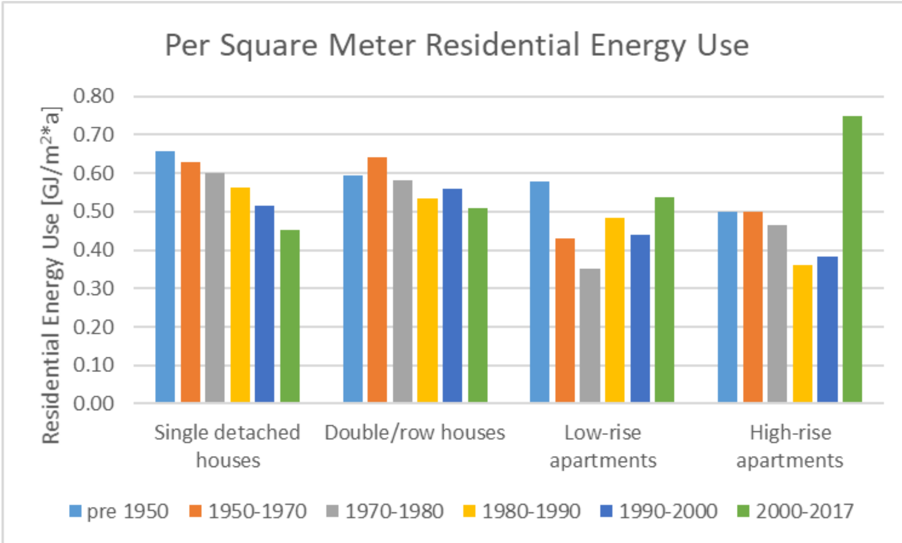

Figure 2: Per square meter residential energy use values from SHEU2011.

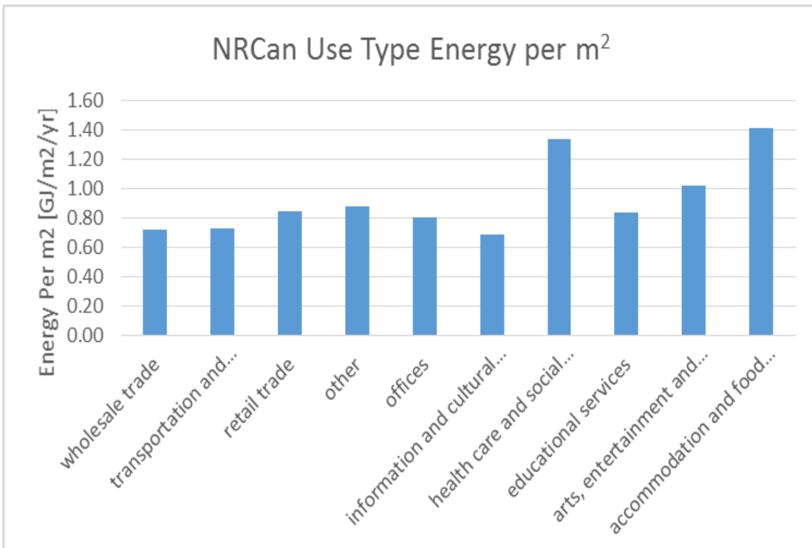

Figure 3: NRCan use type energy consumption per square meter for commercial and institutional buildings.

The *Heritage Building List* is a list of registered or designated heritage buildings in Victoria. This was used to add a heritage designation to building entries in the model. This is important because heritage buildings are restricted in some respects to the kinds of retrofits that can be performed on them that could affect their heritage attributes. This is mostly added with the expectation that it will be useful in future analysis to do with energy retrofits.

The *Seismic Database* was created as part of the Citywide Seismic Vulnerability Assessment of the City of Victoria produced by VC Structural Dynamics LTD, but was obtained through the City of Victoria.

2.4. Methodology

There were 72 use types in the City Database, which was reduced to three categories, residential, commercial and institution (C&I), and industrial (I). C&I and industrial buildings were then separated into ten categories each, however some of these were not present in the city.

Residential buildings were sorted into four categories: single detached houses, double/row houses, low-rise apartments, and high-rise apartments. These four categories were also broken down into 6 age categories that match the SHEU2011 categories: pre 1950, 1950-1969, 1970-1979, 1980-1989, 1990-1999, 2000-2011. The SHEU2011 dates from 2011 and so does not have information about buildings newer than 2011. As a result, buildings newer than 2011 were allocated energy data for the 2000-2011 period. C&I data do not have energy use based on age. Industrial building data on a per floor area basis is not available, only industry totals for the province. As a result, industrial buildings are not included in the stock model energy calculations, however they are still included in the database. The entries for industrial use types will still be present, however the energy use for those use types is not calculated.

In order to determine the number of storeys, sub-grade storeys and building ages, the Seismic Database was used. This database was partially created by VC Structural Dynamics and merged with the database maintained by BC Assessments. The buildings in the stock model were cross referenced to buildings in this database, based on address so that the final stock model would have all the information needed to estimate its energy consumption.

Statistical information for each DA gives the number of buildings, population demographics, land area as well as total numbers of residential housing types. The grouping of buildings in each DA are such that they could be useful in determining the feasibility of district energy systems or other systems where proximity is important. The DA polygons were plotted in GIS software along with the coordinates of all the buildings, which was used to determine which buildings were in which DA.

The heritage building database was also used to determine which buildings were designated as heritage buildings. This is important because it could limit the type and extent of energy retrofits or other development that could be implemented in order to preserve the historical significance of the building or neighbourhood.

The data on energy use comes from two different databases, the Survey of Household Energy Use 2011 (SHEU2011) and the Comprehensive Energy Use (CEU) database, both produced by Natural Resources Canada (NRCan). The SHEU2011 provides energy use per square meter floor area values for different building types and various age brackets. This dataset is only for residential buildings however, so for C&I buildings the CEU database was used, although age bracket data was not available. The relevant values are put into key value tables which are then used to look up the energy use for each building according to its use type and age.

The energy use of each building is calculated based on footprint area, number of storeys, and the relevant energy use per square meter value for the use type. These three numbers are multiplied together to get the total energy use per year for each building. This can then be summed or averaged for the dataset as a whole or by DA.

There was a significant amount of data cleaning that needed to be performed for the different datasets, particularly the city database. This included checking for and removing erroneous values and entries as well checking that the values were listed in the correct units. Some buildings had multiple listings, so the duplicates needed to be removed. Buildings labeled as strata had numerous problems including no differentiation between commercial and residential stratas, as well as many erroneous buildings that didn't exist or were actually vacant land. Properties with multiple buildings were listed as strata under use type, however most of these turned out to be detached garages. To prevent the entries from skewing the results they were removed and added as additional "garage" fields associated with the larger building on the property. After this the city database was cross referenced with the seismic database, and all entries that did not correctly cross reference were removed after spot checking confirmed that they were erroneous.

The bottom up statistical methodology employed here combined with the cross-referenced data from the different datasets tied to geographical coordinates allows for interesting analysis and visualizations to be obtained that could not be achieved using conventional analysis. One example is getting spatially resolved breakdowns of the energy use of the building stock across multiple dimensions such as age, use type, and location (neighbourhood/DA). Plots of these parameters can be overlaid onto maps of Victoria, so it can be clearly seen which areas have older buildings or greater energy demand. Additionally, since most of the data is building-level there is no need to assume certain distributions of parameters such as building age. This eliminates much of the guesswork needed in statistical models, and allows the model to be more accurate.

2.5. Results

This building stock model is useful for creating visualizations using GIS, since all building information is tied to geographic coordinates. As a result, building density, energy use and energy use per capita can be plotted using heat maps overlaid on the city map and DAs. This can be very useful for policy makers and city planners, because they can easily see areas of high energy use, allowing targeted policies to be developed. Figure 4 shows estimates of building energy use according to the building stock model. The lighter blue circles indicate lower energy use, and the darker blue indicate higher energy use. Due to the high number of lower energy use buildings (single detached houses) the colour scale is not linear but rather quantile, i.e. each category has the same number of buildings in it. This is necessary due to the high extremes of energy use of large towers or malls.

Figure 5 shows the same building energy plot as Figure 4 zoomed in to individual building level and showing the DA boundaries so that the variety of energy use in different DAs can be seen.

Figure 6 shows the effective age distribution of the building stock. Effective age is the age that is representative of the current state of the building. For example, a building could be built in 1950, however it was renovated in 1980, so its effective age is 1980 because it is assumed that things like increased insulation and structural improvements have been made. It can be seen that there are certain areas where there are more older buildings, and others more newer ones. Red dots indicate old buildings (pre-1900), blue dots indicate recent ones (post 2010), and light green and yellow indicate middle values (1960-1970).

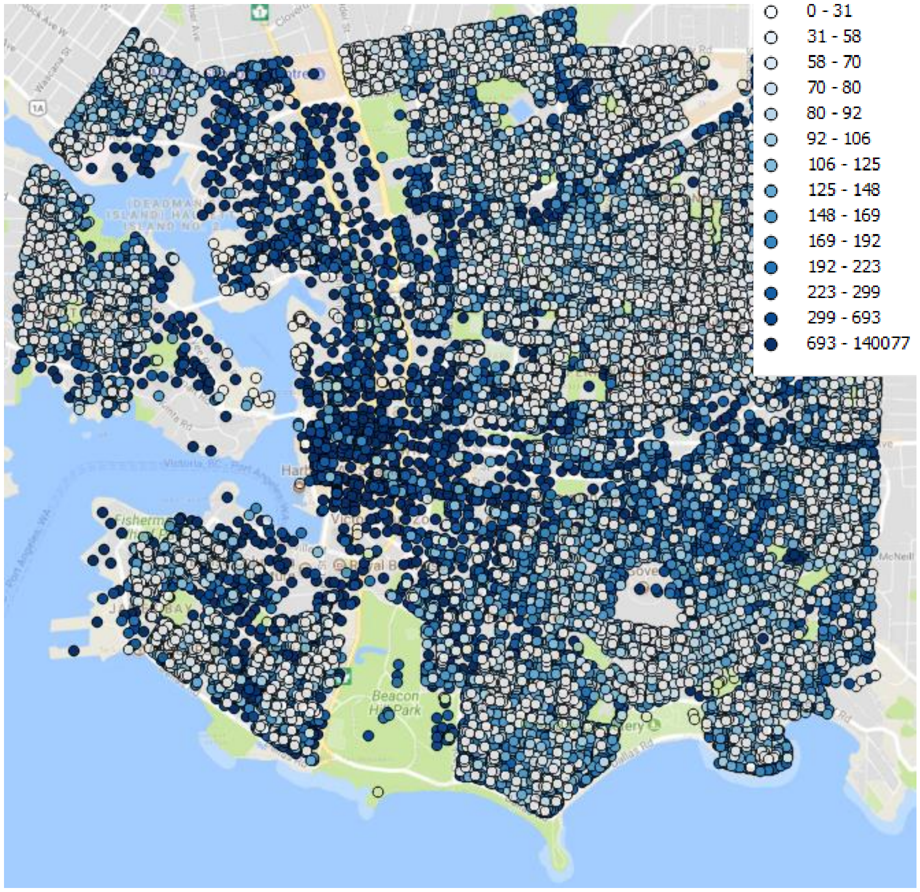

Figure 4: Map of building energy use of City of Victoria

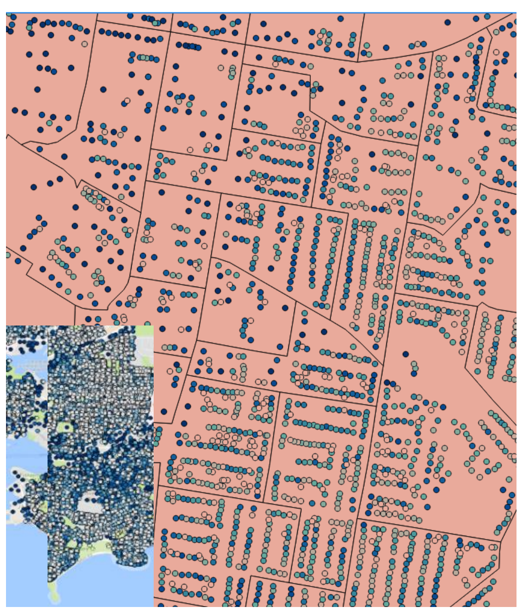

Figure 5: Zoomed in portion of Figure 4 plot, but with the DA layer turned on showing their boundaries

In this way the building stock model can help determine if policies and incentives should be targeted not only to certain spatial areas, but also building use types or ages.

Figure 7 shows the total energy use and per capita energy use for each DA. Some are much higher than others, typically indicating either a higher density or more commercial buildings with few residential buildings. It can be seen that per capita use tends to follow the total energy use, implying that density is the major determinant of energy use. However, there are some exceptions that have dramatically different total and per capita values. This could be a good indicator to examine these specific DAs in more detail to see if there are reasons for this.

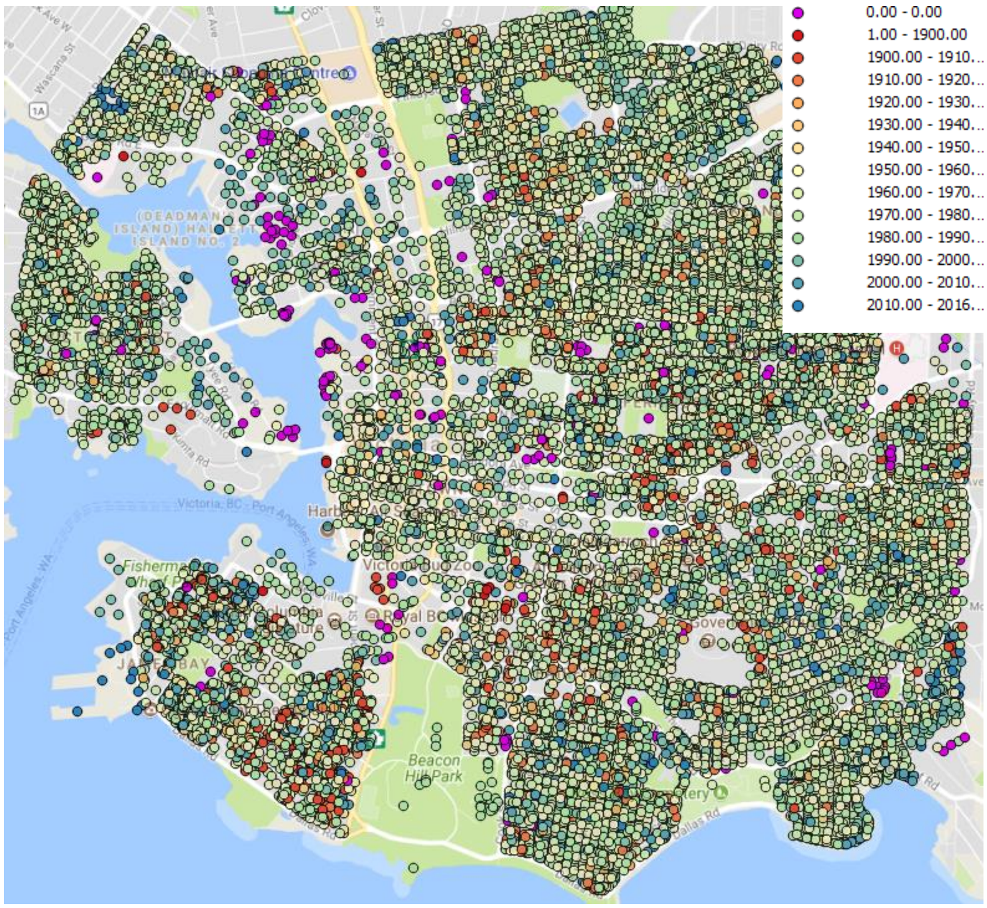

Figure 6: GIS plot of effective building age. Purple dots indicate buildings that do not have age values recorded

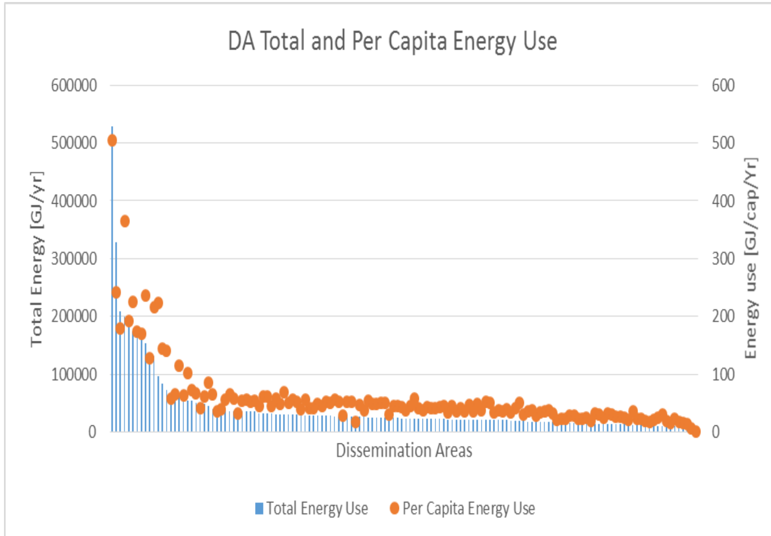

Figure 7: Plot of the total and per capita energy use for all dissemination areas

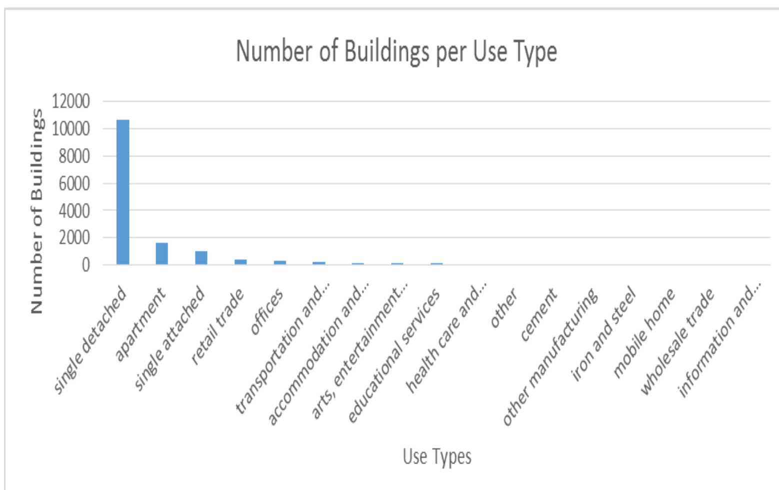

Figure 8: Plot showing the number of buildings for each building use type for the whole city

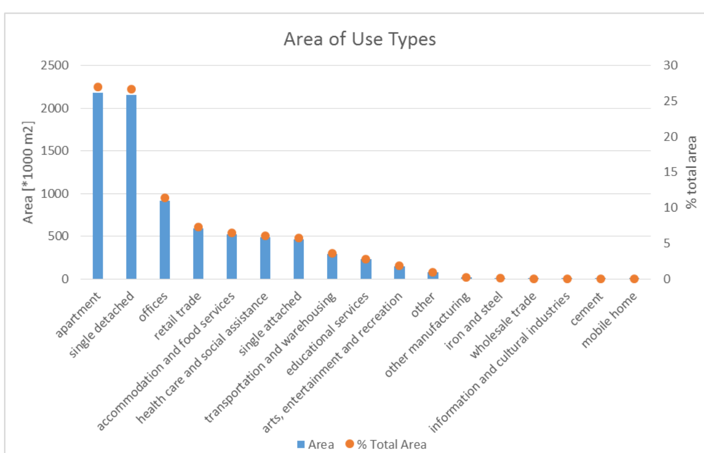

Figure 9: Plot showing the floor area for each building use type for the whole city.

Figure 8 and Figure 9 show some specific use type data for the whole city. Figure 8 clearly shows that single family homes make up the majority of the number of buildings. However, Figure 9 shows that in terms of floor area, apartments and single detached homes have almost the same amounts, at just over 26% of total floor area each.

Figure 10 shows the percentage of total energy used by each use type. Single detached homes and apartments consumed the most energy, followed by accommodation and food services, then offices.

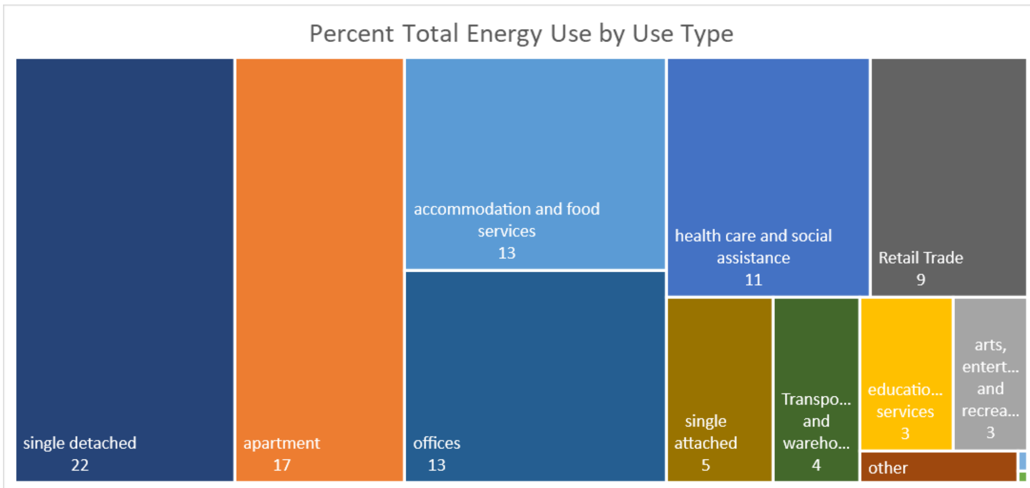

Figure 10: Percent of total energy used by each use type.

Figure 11 breaks down the total residential energy use into the three residential use types, as well as their effective age brackets. As can be seen there is a large proportion of the energy use in buildings with effective built ages of between 1960 and 1980.

2.6. Discussions

The results of a detailed analysis of the building stock model can have many implications for city planners and policy-makers. The usefulness to planners when developing policy to reduce the city's carbon emissions is significant. It allows policy makers to visually see certain areas or attributes that can be targeted to reduce emissions that may not otherwise be apparent. Certain areas may have a higher energy consumption then others, or perhaps buildings constructed in a certain decade may perform worse than expected and so should be targeted over those from other decades.

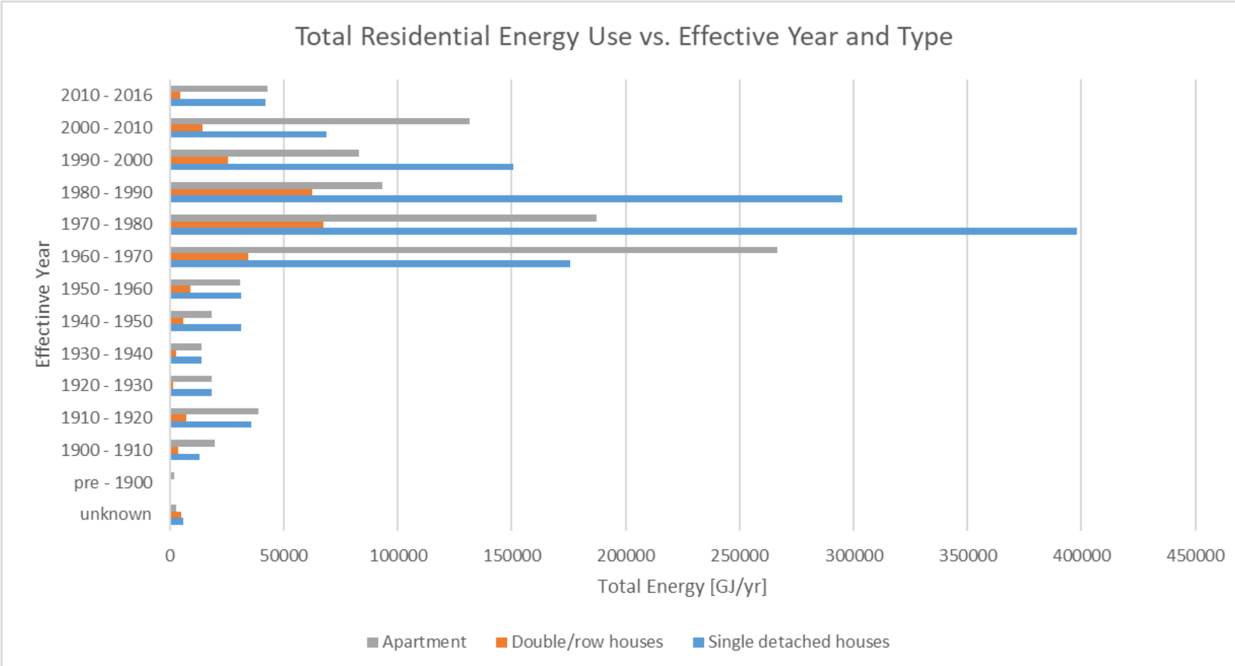

Figure 11: Total Residential Energy Use values for the City based on effective year and type.

The building stock model also serves as a platform on which to add more data as it becomes available. An obvious case would be more detailed building information such as heating system details, heating fuel type and other building envelope details. This would allow for the effects of energy retrofits to be assessed. Energy retrofit datasets exist, however they have often been anonymized to protect property owner's identities. However, if these could somehow be linked to spatial stock models like these then retrofit incentives could also be analyzed in greater detail.

The spatial aspect would also be useful in assessing the potential for district heating systems and electrical microgrids. Since the dataset is viewable in GIS, it is simple to look for areas of high demand density that could make district heating economically viable.

2.7. Conclusions and outlook

Building stock models are useful to municipalities in deciding how to develop policies to reach their climate change goals. A bottom up statistical building stock model was developed for the City of Victoria using data from a variety of data sources. The building entries include information such as use type, height, footprint area, number of storeys, and geographical coordinates. Energy use for each building was determined using per square meter energy use values from two NRCan sources.

This dataset can be used with GIS software to create spatially accurate assessments and to graphically show various parameters such as energy use density, building age and building use type. This is useful to quickly see certain areas where there may be problems or that may be performing well. With a building stock model, municipalities can develop policy that can be more targeted and hopefully more effective.

2.8. Next Steps

Some further investigation and analysis steps that could usefully be performed in the future include the following.

Updating building footprints, heights, and geographical coordinates using updated LIDAR data from May 2017 would reflect the increases in the number of buildings as well as other changes and replacements in the building stock.

Integrating more detailed building specific data (heating system type, envelope R values, window types, etc.) and energy retrofit information would allow a more in-depth study and higher accuracy modelling energy consumption and emissions information. It would also allow an exploration of retrofit options and incentives and estimating the energy and emissions reduction potential.

Using more specific energy data if or when it becomes available could also help improve the model accuracy. Most of the energy data used comes from NRCan studies that are aggregated at the provincial level. If energy use data for different building types and ages could be obtained at a smaller scale, such as for Vancouver Island, then more accurate estimates could be produced. The climate of the south west coast of British Columbia is very different from the rest of the province, so it is important to capture these variations.

Obtaining industrial energy use per square meter values for the major industries in Victoria so that they can be added into the model would better represent energy use in this sector.

More broadly, a move to time series data so that higher fidelity models could be made that look at hourly trends instead of annual averages. This would allow a much better analysis of renewable energy employment challenges, which revolve around the matching of demands and supplies.

Finally, the use of building energy simulation tools such as EnergyPlus has the potential to give highly detailed information on the energy use of specific buildings. A comparison between modelling typical buildings in EnergyPlus (a more engineering-based approach) and this statistical approach would be highly informative. This would provide time-series information, and would also allow the impact of specific interventions to be predicted more accurately. This could also be combined with an optimization algorithm as in [8] to explore the most cost-effective ways of improving the Victoria building stock.

2.9. Acknowledgements

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3. Using Multiple Linear Regression to Estimate Building Retrofit Energy Reductions

Wesley Bowley[1]*, Paul Westermann[1], Ralph Evins[1]
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[1] Department of Civil Engineering, University of Victoria, Victoria, Canada
*corresponding author

3.1. Abstract:

This work applies multiple linear regression to a building energy retrofit database of the City of Victoria in order to determine the energy reductions associated with different retrofit measures. The results of the regression are then used to construct marginal abatement cost curves for retrofit options. A comparison between continuous and binary variables is performed to examine their effect on accuracy. It was found that the accuracy is comparable (R^2 for binary: 0.81, R^2 for continuous: 0.76). The regression results estimated that building envelope retrofits could reduce energy use by 40%, and heating system retrofits can reduce energy use by up to 30%. Switching to electric heat pumps could reduce emissions by an estimated 80%.

Keywords: retrofit, building stock, multiple linear regression

3.2. Introduction

Retrofitting residential buildings has great potential to reduce carbon emissions through both improvements to the building envelope and by upgrading the heating systems. In British Columbia, the low carbon content of grid electricity makes converting to electrically-driven heating systems an excellent way to decarbonise the building stock. Retrofitting can also reduce energy bills for occupants. However, retrofitting measures incur significant up-front costs, which must be balanced against the possible benefits.

There are numerous ways to analyze the cost effectiveness of retrofit actions as well as how much each particular retrofit action reduces energy use. Physical modeling software can estimate the energy use of a building given many parameters and environmental conditions. However it is time consuming and impractical to model every building in a municipal building stock, and the required data is often not available.

One way around this is to collect data by surveying building characteristics as was done by Dall'O' et al. (2012). Another option is to use aggregate data from a national level and assume that this is representative of the local building stock as in Constantinos (2007), which may not be accurate.

Another option is to create building archetypes that are representative of the buildings in the stock, so that detailed simulation can be performed on a smaller number of archetypes rather than on all the buildings in the stock, while still being representative. Linear regression is sometimes combined with archetypal analysis as in Chidiac (2011), however this study only covered office buildings.

Martinez et al. (2018) use multivariate linear regression to assess the energy use reduction of retrofits that include and exclude building envelope upgrades. They found that upgrading building envelopes increase the energy savings. However, the dataset is somewhat limited in size, in addition to no consideration to specific components of the retrofits (eg. Insulation, windows, etc.).

Walter and Sohn Walter (2016) use a multivariate linear regression model to predict energy use intensity with variables representing building parameters such as climate zone, heating system type, etc. The model quantifies the contributions of each characteristic to the overall energy use, then the energy saving from modifying or retrofitting that particular characteristic is inferred. The analysis is limited however in that it uses only pre retrofit data and isn't validated using pre and post retrofit energy use data.

This work aims to use multiple linear regression (MLR) to derive the statistical impact of each retrofit measure on the total percentage energy reduction. This has also been extended to carbon emissions and energy bills by making assumptions about the breakdown of energy use. Our method is similar to that used in Walter (2016) , however the key differences are that we performed the regression on the percentage energy reduction between the pre and post retrofit energy use as opposed to just on the pre retrofit energy use. The accuracy of the regression is discussed as well as potential ways to improve it.

The results of this analysis were then used to construct marginal abatement cost (MAC) curves, which quantify the cost and benefit of each possible retrofit measure. MAC curves provide a simple way of expressing this relationship. They are simplified representations of the underlying problem in that they rely on the assumption of linearity, i.e. that separate measures can be recombined in any manner, and that the total impact will be the linear sum of their individual impacts.

The study is based on a dataset of several thousand building retrofit evaluations in the City of Victoria compiled by National Resources Canada (NRCan). This gives the retrofit actions that were recommended and performed across 50 categories alongside the pre- and post-retrofit energy use as estimated using software called HOT2000.

3.3. Methodology

There are several steps to the analysis. First the available NRCan data on the energy use reduction of building retrofits has been cleaned and processed. The cost data associated with each measure has also been collated. Next a multiple linear regression process has been used to approximate the contribution of each individual measure to the total reduction. These coefficients are used to generate MAC curves, which are analysed and then scaled to the whole building stock. Please note that due to space constraints, we are limited in the amount of data that can be shown. This includes many building parameters such as pre and post retrofit heating system efficiency and retrofit measure costing.

3.3.1. Database analysis

The database is created from pre and post retrofit energy audits where parameters are recorded such as wall, foundation and ceiling insulation, number of energy star windows, and information about the heating system type (various types of gas or oil furnace, ASHP, electric base boards, etc.) and fuel type (oil, natural gas, electricity, wood). These parameters were used to create HOT2000 models of the buildings and the pre and post retrofit energy use was estimated. It is the difference between these values, i.e. the change in energy use, which is used for our calculations.

Ideally it would be better to obtain energy use from direct measurements or from simulation using a more advanced tool such as EnergyPlus. However, pre and post retrofit measurements are rarely available, nor are the many parameters needed for more detailed simulation. This paper describes a methodology that can be used on other building energy databases that could perhaps have direct energy use measurements, or are for different cities.

Before the dataset could be used, it was organized and cleaned. Building entries that did not perform post retrofit energy audits were removed since they provided no way of assessing improvements due to retrofits. Building entries were grouped based on different parameters, and erroneous values were removed.

3.3.2. Multiple linear regression analysis

Multiple linear regression models are an extension of the standard linear regression approach that can be used to quantify the impact of multiple inputs on one output. They are a class of statistical model that generate aggregated statistical insights from many individual observations. In this study it is used to analyse retrofit measures on city level using data on building level.

Multiple linear regression generates very useful results: unlike other methods, the fitted coefficients relate directly to the variables of interest, in our case the different retrofit measures. The weakness of the method is that it assumes all relationships between the inputs and the output to be linear and independent, i.e. that there are no non-linear relationships and no interactions between variables so that the total impact will be the linear sum of the individual impacts. Since this is also an assumption of the MAC curves that the outputs will be used to construct, this is not particularly detrimental.

In this study, we use linear regression methods to quantify the impact of different building retrofit measures (e.g. wall insulation improvement, replacement of heating system, etc.) on the reduction in the annual energy consumption, carbon emissions and energy costs of a building. The model is fitted using 7000 data entries relating to retrofitted buildings within the City of Victoria. The impact of each retrofit measure is captured by the regression coefficients p_i of the fitted model as shown by the mathematical formulation of the regression model:

$$\Delta E = p_{air}X_{air} + p_{window}X_{window} + p_{ASHP}X_{ASHP} + \ldots = \sum p_i X_i \,, \quad (1)$$

where $X_i \in [0,1]$, $p_i \in \mathbb{R}$, *i = measure index.*

The output variable ΔE represents the percentage reduction in energy consumption per unit floor area. Each coefficient p_i is multiplied by a binary variable X_i which indicates whether the respective retrofitting measure i was performed (X_i=1) or not (X_i=0). The method provides the values of p_i, which here can be interpreted as the percentage by which the energy consumption is lowered if each of the different retrofit options is implemented independently. The larger p_i, the larger the impact of retrofitting measure i. The output variable ΔE is the difference between the pre- and post-retrofit annual energy use as estimated in the HOT2000 simulation on building level divided by the building area, in units of GJ/m^2/a.

As an example, we consider a simple case where there are three possible measures: windows can be retrofitted, an air source heat pump can be installed, and wall insulation can be improved. Fitting the model to lots of different observations on buildings having conducted these measures will give the coefficients p_{window}, p_{ASHP} and p_{wall}, and the linear regression model estimates the reduction in energy consumption ΔE to be:

$$\Delta E = p_{window}X_{window} + p_{ASHP}X_{ASHP} + p_{wall}X_{wall} \quad (2)$$

For a specific building in which the windows and walls are upgraded but no heat pump is added, the percentage reduction in energy consumption is predicted to be:

$$\Delta E = p_{window} * 1 + p_{ASHP} * 0 + p_{wall} * 1 \quad (3)$$

i.e. the sum of the coefficients for the measures that were implemented. The full model is an extension of this to include all 17 measures, and hence has 17 coefficients.

3.3.3. Model fitting

The coefficients of the model are determined using ordinary least squares (OLS) methods. The model fitting and all related computations were programmed using the Python SKLearn Toolbox. To guarantee a statistically robust and accurate model, multiple steps were undertaken:

- The physics of the building heat balance show that the actual reduction due to building envelope and heating system retrofits are interlinked. For example, improving the insulation of a building with a low efficiency heating system is much more influential than of a building with a highly efficient heating system. To remove this link, the model was fitted to the percentage reduction in energy, emission or energy cost of a building. This modification eliminates the need to generate multiple models for each heating system type.

- The data set was scanned for outliers and 18 data points were removed.
- The coefficients resulting from the OLS fit were tested for statistical significance using the p-value score. All variables that are not statistically significant (i.e. whose p-value is larger than 0.005) are rejected from the model. The associated samples in which the associated measure is present are also removed, to reduce the variation in the remaining data.
- To verify the accuracy, the model was fitted to 90% of the data and its performance validated on the other 10% of the data. The samples for the validation set were chosen randomly.

3.4. MAC curves

Marginal abatement cost curves are used to compare the cost effectiveness of all retrofit measures in reducing carbon emissions. MAC curves integrate the previous findings on the impact of different retrofits on building energy consumption and the respective costs. The major advantage of MAC curves is the way they incorporate cost and emissions goals into one graph and display the most economical pathway of actions to reach a specific target.

First the energy consumption reductions must be converted in to carbon emissions reductions by multiplying the reduction by the carbon factor associated with that of the heating system and fuel type. The carbon factors for each fuel type was obtained from the BC Ministry of Environment (2016). Efficiencies of the heating systems were also accounted for.

MAC curves represent each retrofit measure according to the following metrics:

− *Annual kgCO_2 savings (per m^2 floor area), horizontal axis:* This number uses the coefficients of the multiple linear regression model as shown in the previous section. The percentage reduction value of each measure is multiplied by the total average pre-retrofit emissions in kgCO2/m^2.

− *Annual cost per kgCO_2 savings ($ per m^2 floor area), vertical axis:* The value above is divided by the cost of the measure. We compute the *equivalent annual cost* (EAC) to compare assets with different lifetimes, as determined for different building retrofit measures. EAC also considers the cost of capital by integrating current interest rates and inflation rates in Canada; a value of 1.16% was used Bank of Canada (2017).

MAC curves also have an advantage when paired with linear regression that they make the same assumptions regarding linearity and independence. This means that the assumptions of one method do not limit the ability or accuracy of the other method.

Energy consumption reductions are also converted into energy bill reductions by obtaining fuel cost data for Victoria, and then multiplying these factors by the energy reductions according to the fuel types (BC Hydro (2016), NRCAN (2015), FortisBC (2017)). All three metrics are examined in the results section.

*Table 1: Variables used in the multiple linear regression. R_{SI} insulation have units of m^2*K/W*

Variable	Description
thermostat	Addition of a thermostat
e2e	Upgrade of an electric heating system to a newer electric heating system.
E2G	Change from electric to gas fired heating system
E2O	Change from electric to oil fired heating system
G2E	Change from gas fired to electric heating system
G2G	Renewal of gas fired heating system
G2O	Change from gas to oil fired heating system
O2E	Change from oil fired to electric heating system
O2G	Change from oil to gas fired heating system
O2O	Renewal of oil fired heating system
GSHP	Change from any system to a ground source heat pump
e2ASHP	Change from electric furnace to air source heat pump
G2ASHP	Change from gas furnace to air source heat pump
O2ASHP	Change from oil furnace to air source heat pump
Upgrade	Renewal of air source heat pump
Air	Increasing air tightness of building, e.g. by fitting draft excluders
Window	Replacing windows
CRSI 0-4	Improving the ceiling insulation by an R_{SI} value between 0 and 4
CRSI 4+	Improving the ceiling insulation by an R_{SI} value of more than 4
FRSI 0-1	Improving the foundation insulation by an R_{SI} value between 0 and 1
FRSI 1-2	Improving the foundation insulation by an R_{SI} value of more than 1
WRSI 0-0.75	Improving the wall insulation by an R_{SI} value between 0 and 0.75
WRSI 0.75+	Improving the wall insulation by an R_{SI} value of more than 0.75

3.5. Results and discussion

In this section we first present the results of the model fitting, followed by an analysis of model accuracy, and finally the MAC curves derived from the model results.

3.5.1. Multiple linear regression results

The coefficients p_i of the multiple linear regression analysis give the average percentage reduction in energy use associated with each retrofit measure. The measure indexes i are given in Table 1. The results are shown in Figure 12; the numbers in brackets beside each retrofit option give the number of associated entries present in the data. The error bars display the standard error associated with each regression coefficient p_i. This is equivalent to the standard deviation of the model error, and therefore if the error is assumed to be normally distributed, then 68% of values will have an error less than or equal to the standard error.

3.5.2. Energy consumption

Energy consumption is lowered most effectively by installing more efficient heating systems, ideally an air source heat pump. The model suggests that a change from an electric furnace to an ASHP lowers the total energy consumption by 24%, a change from a gas furnace to an ASHP by 29% and a change from an oil boiler leads to a reduction of 37%. Installing new furnaces (especially gas or electric furnaces) leads to significant reductions in energy demand of between 10% and 17%. The reduction potential of ground source heat pumps is estimated to be 30%, but unfortunately since the dataset only features a very low number of samples (12), this value may not be accurate, and a detailed analysis of their impact is not possible.

Improving the building envelope also helps to lower energy consumption. Installing a highly effective wall insulation (R_{SI}-value > 0.75 m^2K/W) cuts energy consumption by 16%; major improvements in the floor insulation lower the energy consumption by around 10%. Improving the ceiling insulation, replacing the windows or increasing air tightness have a smaller impact. However, it should be highlighted that the building envelope retrofits can be combined, and accumulate such that they may have a similar impact to a heating system upgrade. If all possibly combinable building envelope improvements (Air tightness, window replacement, ceiling R_{SI}-Value > 4 m^2K/W, wall R_{SI}-value > 0.75 m^2K/W and foundation R_{SI}-Value > 1 m^2K/W.) are conducted a total energy consumption reduction of 41% is predicted.

The model results in negative coefficients (i.e. energy use is predicted to increase) for two of the retrofit measures: a change from electricity-driven heating to a gas-powered system, and adding a thermostat. The former is explained by the reduced efficiency from 100% (electric) to rather less for gas, and also possibly the reduced cost of heating leading to increased use. The small increase in energy consumption due to installation of a thermostat may be caused by the use of the thermostat to increase comfort rather than to decrease energy use.

Some retrofit measure options do not occur in the dataset: no samples feature electric furnace upgrades, electric to oil conversions or gas to oil conversions (unsurprisingly since running costs for an oil boiler are higher than gas). As a consequence, they have coefficients of zero, and we omit them in this study.

3.5.3. Reduction in carbon emissions

The model suggests that electrifying the heating system is the strongest driver to reduce carbon emission. It is found that replacing gas and oil furnaces by air source heat pumps helps to cut emission by almost 80% and even replacing them by standard electric heating systems lowers emissions by more than 60%. Other heating system upgrades like changing from oil to gas or from electric heaters to a heat pump still have significant reductions of 31% and 20% respectively. The reduction in emissions by building envelope improvements are similar to those for the reduction in energy demand. It is important to note however that the carbon factor if British Columbia's electricity grid is very low due to abundant hydro power, and these findings may not be the same for grids with a higher carbon factor.

3.5.4. Reduction in energy costs

The fundamental driver of energy costs are current fuel prices in Victoria as well as the effectiveness of the envelope and the efficiency of the heating system. Natural gas currently has the lowest cost and heating oil the highest cost per kWh; heat pumps have the highest efficiency of all heating systems. Based on this, the analysis of the results in the plot below are straight-forward. Changes from any system to a natural gas-fired system are estimated to reduce energy bills by at least 40% (electricity to gas) to 50% (oil to gas). The model suggests that installing a heat pump lowers bills by 24% (electric furnace to ASHP) to 38% (oil to ASHP). Two buildings which removed a gas system and installed an electric furnace instead suffered an increased energy bill of 61%. The reduction in bills by building envelope improvements are similar to the ones found for the reductions in energy demand.

3.5.5. Retrofit sequence effects

The order in which retrofits are applied to buildings can have an effect of the cost effectiveness of retrofits. The most obvious case is increasing envelope insulation and changing heating system type. If a building has poor insulation, it is going to require more heat through the year which will increase fuel and maintenance costs. If the heating system were to be upgraded, then the cost effectiveness will be high, since the use is high. If insulation were added first, it would decrease demand, and reduce the fuel costs, and lowering the cost effectiveness of a heating system upgrade.

The effect is more complex when emissions are considered. Switching from a fossil fuel heating system to an electric based one could be much more cost effective in terms of emissions than upgrading insulation or windows once electrifying the heating system has taken place. This is mainly due to the carbon factor of electricity being very low, so the reduction in emissions due to envelope upgrades after heating system electrification is almost negligible. Energy reductions obtained through envelope upgrades are still desirable however.

3.6. Model accuracy and prediction performance

The quality of the fitted model may be assessed by its ability to predict the energy reduction of the 10% of buildings that were not included in the fitting process (see Methodology section). The mean absolute error (MAE) and the standard deviation (SD) are given in Table 2. These indicate how much the model prediction of the annual reduction (in energy, emission or cost) deviates from the actual annual reduction. For example, for predicting the energy reduction we obtained a mean absolute error of 6.3% +/- 5.0%. Hence, in 68% of the cases (assuming normally distributed errors) the absolute prediction error is between 1.3% and 11.4%.

The prediction performance of the model was significantly improved over the course of this study, predominantly by converting the values to be estimated to percentage changes, adding further variables (e2ASHP, g2ASHP, o2ASHP) and eliminating outliers from the data.

The MAE and SD remain reasonably similar between the fitting data (90% of samples) and the testing data (10% of samples). This implies that the model is not 'over-fitted' to reproduce the fitting data as well as possible but then failing to accurately predict new testing data. The similarity implies that this is the limit of how well a linear model of this nature can represent the data available. Improving on this would either require more data (a greater number of samples), or better data (giving more details on the nature of the buildings or the actions performed). The latter is likely to give the best improvements, since the standard error values are reasonable.

Table 2: Model fitting results showing mean absolute error (MAE) and standard deviation (SD) for fitting and validation data for energy, emissions and cost models.

	Energy reduction		Emissions reduction		Cost reduction	
	Fitting Data	Val. Data	Fitting Data	Val. Data	Fitting Data	Val. Data
MAE [% reduction]	6.13	6.34	6.61	6.45	6.34	6.13
SD of error [% reduction]	4.98	5.01	6.33	5.42	6.02	5.51

3.6.1. Linear vs continuous variables

The regression analysis was performed using binary variables as opposed to continuous variables for several reasons. Firstly, the retrofit measures that were recorded were a mix between continuous and binary with the majority being binary. For example, heating system upgrade was binary whereas insulation R value was continuous. The continuous values were separated into levels (e.g. wall R value increased by 0 to 2 m^2K/W, or 2 to 4 m^2K/W or by more than 4 m^2K/W); a binary variable was assigned to each level and the appropriate binary activated depending on the R value change that each entry performed

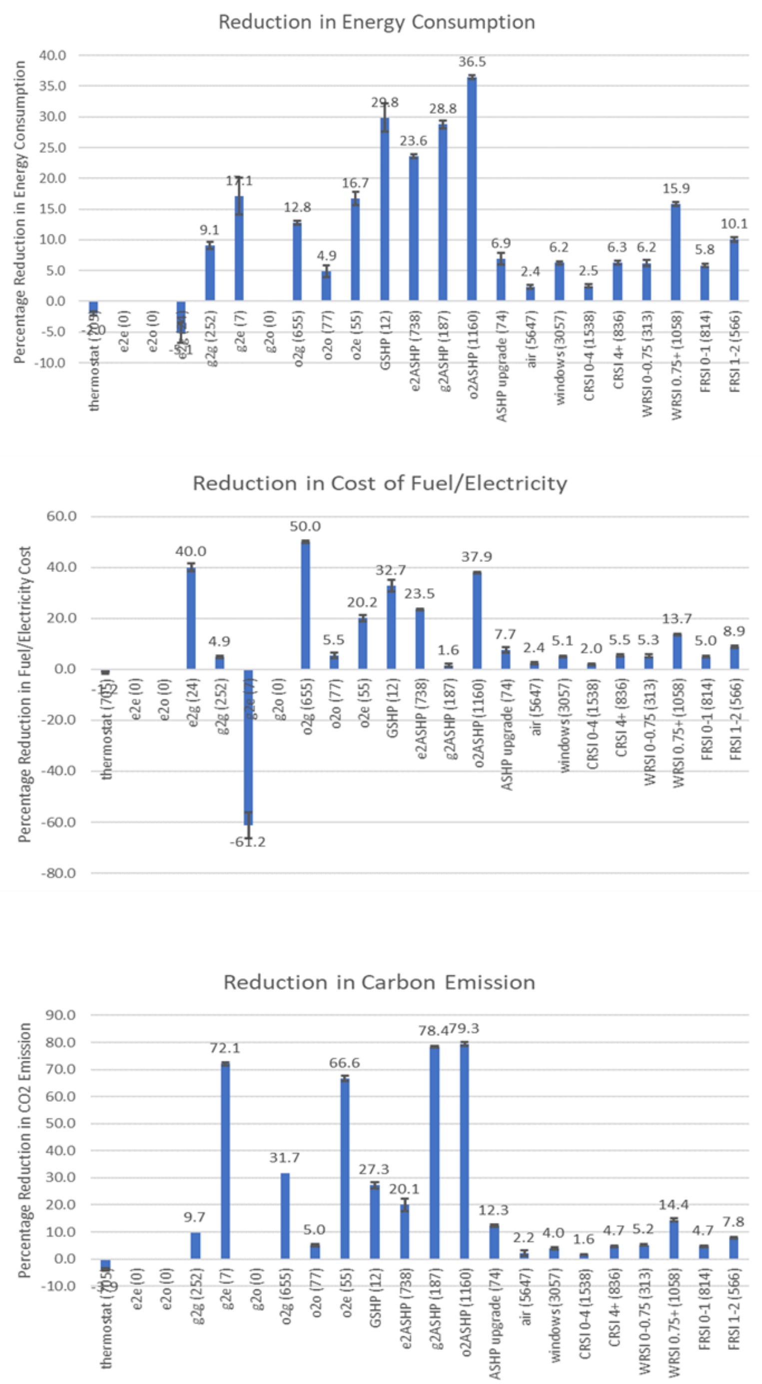

Figure 12: Results of the multiple linear regression for energy consumption, cost of fuel and carbon emissions. Each column shows the percentage reduction due to that variable. Variable descriptions are given in Table 1

Secondly having the different levels of binaries for continuous retrofit measures also made it easier to determine if there were diminishing returns associated with different levels of that variable, whereas it could be more difficult to determine that with continuous variables due to the p_i coefficient needing to be constant over the whole range. Effectively the use of binaries is capturing high-level non-linearities in the system at the expense of low-level precision.

Thirdly the binary values may more accurately represent retrofit measures as they would be performed in reality. Wall R-value would not typically increase by 1.37 for example, but rather would be increased in discrete intervals determined by the way the construction materials are sold and installed. The discrete levels could represent separate consecutive applications of spray foam or layers of fiberglass batting. This could have practical advantages in applying this method and its results to creating municipal policy for retrofit incentives as it is simpler to communicate the requirements to residents or contractors. Interpreting the discrete variables is as simple as reading the number from the plot, whereas with a continuous variable it is necessary to account for the units of the factors before multiplying them by the result.

A comparison between using continuous variables to represent the continuous data and binary variables, as opposed to entirely discrete variables was performed on the retrofit data, to determine its effect on accuracy. Continuous variables were used for insulation R values for foundations, walls and ceilings, as well as furnace efficiency, while the rest of the variables were left as binaries since the data only indicated if they were performed or not.

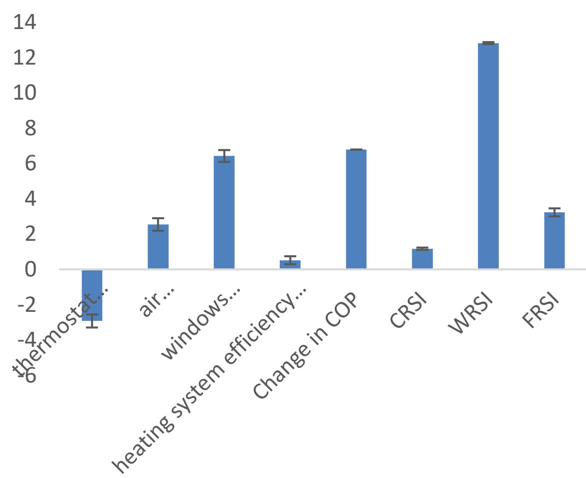

Figure 13: Regression coefficients of continuous variables.

Figure 13 gives the regression coefficients obtained for continuous variables. This gives a good example of the issue of units discussed above. The change in heating system efficiency appears to be small compared to the other variables, but this is due to the units being in percentage (usually between 70% and 100%) and the other variables having different units. This can be misleading to someone not familiar with linear regression.

A comparison of the binary and continuous fitting results showed that there was little change in the accuracy of the MLR, with the R^2 value decreasing slightly when continuous variables were used (0.81 for binary, 0.77 for continuous). One potential reason for the similar accuracy is that although we used binary variables, we had previously discretized continuous data into brackets that were each represented with a binary variable.

If a single binary was used to represent an entire continuous range of data, then this would likely give much poorer accuracy.

3.7. MAC curves

The results of the multiple linear regression have been combined with cost data and scaled by the city building stock to produce MAC curves, which we present in the following two sections.

3.7.1. Envelope and heating curves

First, we give separate results for building envelope retrofits and for HVAC retrofits. These are presented separately because the HVAC options are dependent on both the initial heating system type and on the preferences of the building owner (e.g. in prioritizing cost reductions over emissions savings).

Figure 14 shows that nearly all the retrofits that can be performed on the building envelope have negative annual cost over their lifetimes, meaning that they will pay back in energy bill savings over this period. Figure 15 shows the MAC curve for heating systems. It shows that switching oil furnaces to electric or ASHP are the most cost-effective carbon reduction options. The negative cost indicates that owners would save money by switching from oil to any other heating system. Likewise, switching from gas to electricity provides large carbon reductions, however due to the low price of gas there is a positive cost over the lifetime.

3.7.2. Whole building stock results

The MAC curves were then used to assess the cost effectiveness of different heating system retrofits applied to the City of Victoria residential building stock. This was done by estimating the proportions of residential buildings that had gas, oil and electric heating systems according to utility connection data, BC. Ministry of Environment (2012).

The retrofit measures were then applied in these proportions to the total residential stock area. It is assumed that all building envelope items that have a negative cost will be implemented. Regarding the heating system retrofit, two different approaches are studied:

1: *Green* approach: Based on the results above the most emissions can be avoided if gas and oil furnaces are replaced by energy efficient air source heat pumps (expected emissions reductions of 78% and 79%). This scenario represents the CO_2 emissions that can be avoided if all carbon-intensive furnaces in Victoria are replaced by air source heat pumps.

2: *Cost-effective approach*: In this scenario those heating system retrofits are considered which offer the lowest abatement cost per kg CO_2 while providing significant CO_2 reductions. All gas furnaces and electric furnaces are replaced by air source heat pumps, while oil furnaces are changed to low cost gas fired heating systems. Note, that the only difference between the green and cost-effective approach is the change of oil furnaces to ASHPs instead of a change to gas furnaces.

The results for these scenarios are given in Figure 16. Total carbon emissions, equivalent annual costs and the initial investments are shown. Equivalent costs include the annualized initial investment using the current Canadian interest and inflation rates over 20 years, as well as savings from the lowering of energy bills.

The initial investment in heating system upgrades is expected to be 72M$ for the *cost-effective* approach (gas furnaces and air source heat pumps) and 90M$ for the *green* approach. The building envelope upgrades have an initial investment cost of 166M$. However, it has to be noted that the building envelope cost can be reduced if fewer measures (e.g. only wall insulation and air tightness upgrades, no ceiling or foundation insulation upgrades) are conducted. This is not possible for heating system upgrades as a full system must be purchased. This gives total initial costs of between 238 and 256M$. The estimated total annual emissions savings when the building envelope upgrades are combined with the *green* option for heating system upgrade is around 49,000 t CO_2. The equivalent annual costs are all negative which indicates a long-term cost saving by performing the retrofit scenarios through reduced energy bills.

The CO_2 abatement cost calculated in this study was compared to other MAC curves from nearby studies. The abatement costs range from $-14 to $-250 CAD$/tCO_2 compared to our value of $-210 (Municipality of North Cowichan (2013), Canadian Association of Petroleum Producers (2015), City of Toronto (2017), McKinsey & Company (2007)). The negative values indicate that money is saved. It is worth noting that those studies are performed for different spatial scales and specific retrofit measures performed were not well defined.

3.8. Limitations and future work.

A limitation of this work is the assumption of linearity in retrofit measures and their effects. Namely that the effect of two retrofit measures together do not necessarily equal the sum of effects if they were implemented individually. We recognize that assuming linearity is not entirely accurate representation of reality. However, in the absence of detailed building dimensions for creating physical models, the only other option is to do more complex machine learning and non-linear modeling methods, which become more and more "black box" with complexity. We want to use a simple method that is as "white box" as possible so that it can be understood and adopted by municipalities as a tool for meeting their emissions targets.

Another limitation is that the database that was used calculates primary energy use based on the output of a HOT2000 simulation of a model with the recorded building parameters. A database that uses has directly measured energy use values pre and post retrofit would be ideal.

Future work could include moving to a non-linear model or machine learning algorithm to analyze the effects of retrofit measures, to get around the assumption of linearity that is made for this analysis. It would be interesting to then compare the results.

3.9. Conclusion

In this paper a novel methodology for estimating stock-level energy use reductions for building retrofits is applied to a dataset for residential buildings in the City of Victoria. The method uses multiple linear regression to estimate the amount of energy that each retrofit measure can save when applied to a building. The results of the MLR analysis are used to construct marginal abatement cost curves indicating the most cost effective and carbon saving measures. The MAC curves were then scaled by the residential building stock of Victoria to get an idea of the citywide potential for carbon reductions and the associated costs.

MLR is a relatively simple yet powerful tool that can be applied to datasets created from actual measurements from energy audits or simple simulations based on building surveys. The model was formulated using binary variables, with discrete intervals used to represent continuous data such as insulation R values. This resulted in a relatively quick set up and gives results that are simple to understand and use without post processing. A comparison was performed using the same dataset but with continuous variables where possible, and the results showed that there was little change in accuracy, and even a slight

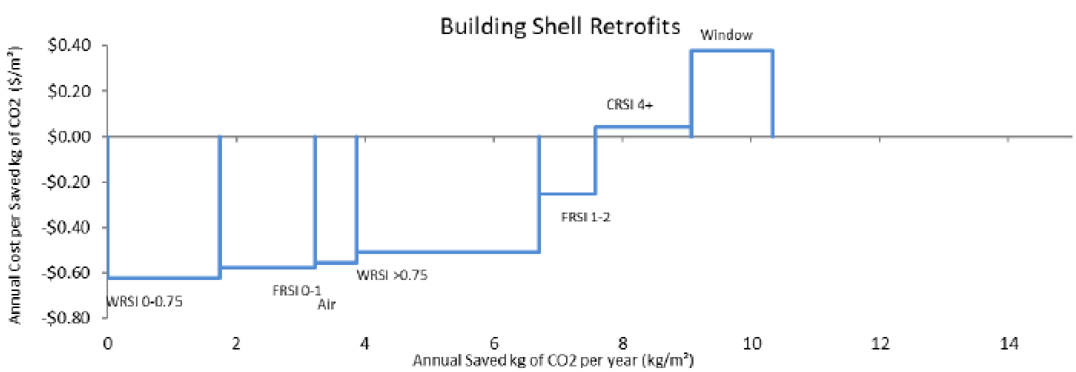

Figure 14: MAC curve for building envelope retrofits

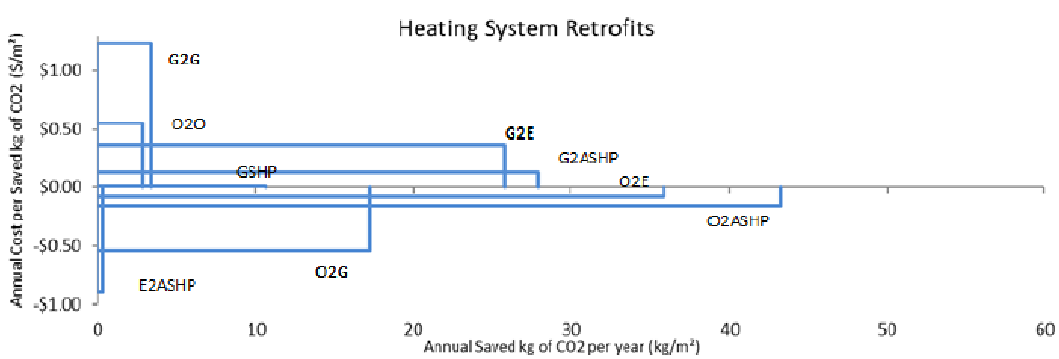

Figure 15: MAC curve for heating system retrofits. The different types overlap since only one can be performed at a time, so it is not a true MAC curve, but the comparison between options is still useful.

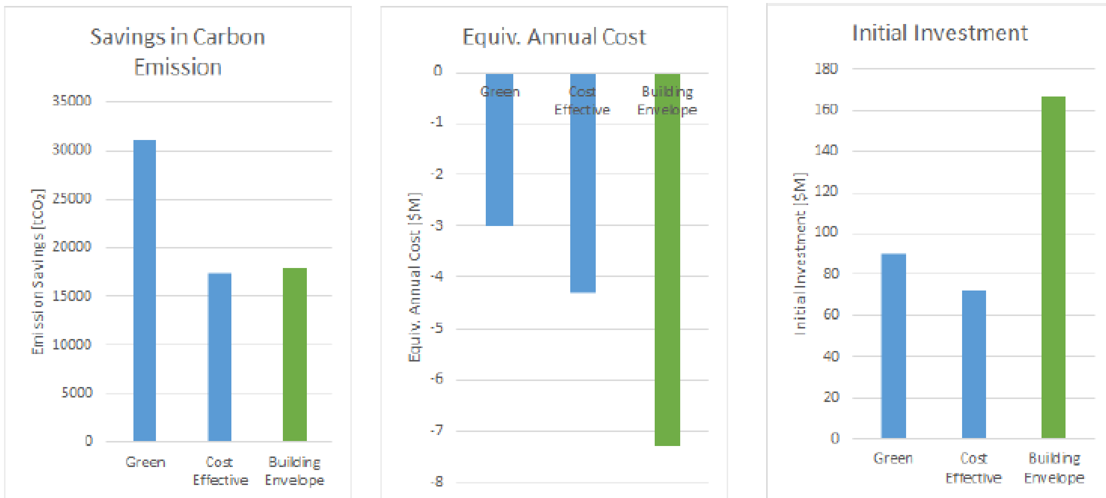

Figure 16: Equivalent annual cost, initial investment and carbon emissions savings of retrofit scenarios 1 and 2.

decrease for the analysis using continuous variables. The results of the MLR analysis are then used to create MAC curves, one for building envelope retrofits, and another for heating system upgrades. These are then scaled by the number of residential buildings in the City of Victoria to get an estimate of the magnitude of energy and emissions savings that could be achieved if these measures were applied. If all combinable building envelope retrofits are performed, energy use could be reduced by as much as 40%. Switching heating system types from oil and/or gas to electric, preferably with an ASHP, can give significant reductions in emissions. If all gas and oil heating systems were changed to ASHP then emissions could potentially be reduced by up to 80%. Part of this is due to the efficiency of ASHPs, but it is also due to the low carbon intensity of grid electricity in BC. Even if oil and gas were converted to electric resistance heating, reductions of up to 60% are estimated.

This paper has demonstrated that multiple linear regression using binary variables is a powerful tool. It is relatively simple to use and produces results which are easy to interpret. It can be combined with MAC curves since both methods have the same assumptions. These methods can be very useful for practical applications such as municipal policy and planning.

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4. Energy Performance Comparison of a High-Density Mixed-Use Building To Traditional Building Types

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Wesley Bowley[1], Ralph Evins[1]
[1]University of Victoria

4.1. Abstract

This paper applies an urban simulation tool to explore the impact of density on operational and embodied energy and carbon using parametrically-generated models. The models were created using Grasshopper and Rhinoceros 5, and the simulations were performed by the Urban Modelling Interface (UMI). A high-density mixed-use building housing 10,000 residents is compared to base cases of traditional building use types housing the same population. The retail and office space of the mixed-use building s also compared to typical local retail and office building types. Building shape, insulation levels and structural materials were also varied to analyse their affect. Results showed that of the base cases, highly insulated low-rise apartments had the best performance at 67% and 50% reductions over to-code insulated single detached homes. Of the large mixed-use building cases, they all had similar energy reductions to low rise apartments but due to utilizing concrete, their embodied energy and carbon were much higher. The timber framed versions of the mixed-use cases achieved better energy performance and cut their embodied energy and carbon by over 70%. Important results were that as buildings become much more energy efficient, the proportion of energy and emissions embodied in the materials becomes significant. Overall building form, as well as the construction material must be considered to minimize energy use and emissions.

4.2. Introduction

The global population is expected to increase to 9.8 billion by 2050 according to United Nations (2015), requiring ever increasing amounts of housing and other amenities. Studies have also shown that an increasing percentage of the population is living in urban areas (United Nations, 2018).

As a result, it is of critical importance that as cities either expand or densify, that they do so in the most sustainable manner possible, while also providing high quality of life. However, growth is often uncontrolled, without a holistic development plan and this can result in urban sprawl. Urban sprawl can be defined as a "particular type of suburban development characterized by very low-density settlements, both residential and non-residential; dominance of movement by use of private automobiles, unlimited outward expansion of new subdivisions and leapfrog development of these subdivisions; and segregation of land uses by activity" (White et al. 1974). Neighbourhoods are typically not as walkable with poor public transit.

Urban sprawl has many negative impacts, including increased congestion and emissions that result from increased personal vehicle use and idling. Additionally, human health is typically negatively affected by urban sprawl (Ewing et al. 2014; Ewing et al. 2016; Zhao and Kaestner, 2010). Neighbourhoods not being walkable leaves fewer alternatives to driving, whereas when amenities are within walking distance, residents can walk or bike to destinations which increases physical health.

A less obvious consequence of urban sprawl is efficiency, both in terms of energy and materials. Having lower density housing means that the buildings are spread out over larger areas. This increases the cost of infrastructure that is needed to provide basic services. Lower density housing also increases the building envelope surface area, as more buildings are needed to house the same number of people. This increases the heat losses through the building envelope, increasing energy use.

There have been studies that examine urban sprawl and evaluate different potential solutions that can be implemented to avoid or correct it. One solution that shows promise is "smart growth" using carefully planned higher density mixed use developments (Alexander and Tomalty, 2002; Daniels, 2001; Geller, 2003; Barbour and Deakin, 2012; Steemers, 2003; Jabareen, 2006; Ko, 2013). These combine denser housing in the form of apartments or townhouses with retail and office space. This has numerous advantages; higher density housing means less heat loss through building envelopes, and lower costs to provide services due to a more concentrated population.

This paper explores an extreme version of this approach called the "Mothership". A mothership is a high-density mixed-use development that is designed to provide all the amenities and housing of an entire suburb in one large building or cluster of connected buildings. The mothership is an attempt at combining the above topics of high density, mixed use, high efficiency energy systems, and transportation hub into a holistic solution to urban sprawl. It must be stressed that each of these components by themselves has been done before, and some combined together in the form of industrial and institutional campuses, the Apple Park being an example (Dezeen, 2019). However, there are few, if any studies which attempt to quantify the performance of a mothership style building and compare it to the performance of traditional building use types for the same number of residents.

The analysis performed in this paper attempts to quantify these differences in energy and emissions metrics, by parametric analysis of building dimensions, construction standards, and materials. Transportation analysis as well as energy system analysis and optimization are beyond the scope of this paper but are considered for future work.

4.3. Method

The overarching methodology for this project is to quantify and compare the benefits and disadvantages of high density mid-rise single mixed-use buildings with the typical building archetype base cases. This is executed through creating parametric models of different traditional building use types to create scenarios in which performance will be compared to the mothership. Each scenario will house the same number of people (10,000). In each of the scenarios, the number of buildings modelled will be the number required to house this population, using the average residents per housing unit values in Canada for each building type (Natural Resources Canada, 2014).

The building geometry was created in the 3D CAD environment Rhinoceros 5 (Rhino), using the Grasshopper plugin. Grasshopper is a visual programming language that allows designers to create parametric models using numerical sliders as inputs. The sliders can be used to change the input values and see the resulting geometry changes in Rhino in real time. Parametric models creating the building geometry were created with parameters such as width, length, and the number of floors of the different use types.

The building simulation is performed using another Rhino plugin, the Urban Modelling Interface (UMI) (Reinhart et al. 2013), developed by the Sustainable Design Lab at MIT. UMI specializes in urban scale environmental performance of neighbourhoods and cities using several metrics such as energy use, daylighting potential, walkability, and embodied energy and carbon. Building specifications such as materials, constructions, schedules and climate can be assigned to each building geometry in Rhino.

The energy simulation is performed using EnergyPlus (US-DOE, 2019) through UMI. The advantage of using UMI is that it is much faster at simulating all the buildings in an urban area than using EnergyPlus to simulate them individually. It accomplishes this using the shoeboxer (Dogan and Reinhart, 2017), an algorithm that goes through the building and determines the most significant zones to model, and then interpolates between them for the rest of the zones. This process does sacrifice accuracy for speed, however when only estimates are needed in a preliminary design phase with many potential designs, it is a very powerful tool for honing in on the higher performing options. This is the reason that it was chosen for this analysis.

The metrics that will be used to assess the performance of the different cases are operational energy use (OE) (kWh/person), embodied energy (EE) (kWh/person), and embodied carbon (EC) (kg CO_2/person). These are calculated for a building life cycle of 60 years. The metrics are intensities per person, as opposed to per unit floor area, due to the different floor areas in the residential base cases (e.g. it takes more floor area to house the same number of people in typical single detached homes than typical apartments). The number of residents does not change between the scenarios; therefore, the values were normalized by number of residents.

4.3.1. Base Cases

The use types that will be examined are:

- single detached homes
- single detached duplexes
- low-rise apartments (5 storeys)
- medium-rise apartments (10 storeys)
- high-rise apartments (42 storeys)

The building envelope constructions were modelled at different levels. The first is typical to-code building practices for the east coast of North America’s climate (UMI defaults). The second is super insulated, with wall and roof u-value of 0.022 W/(m^2*K) (R40) and a floor u-value of 0.17 W/(m^2*K) (R45). Another variation is the main structural materials, namely concrete/masonry or timber frame. Due to building codes, buildings above a certain height are required to be built using reinforced concrete. The height that this occurs, for our local building code (British Columbia Building Code or BCBC) is six storeys (BC Housing, 2009). As a result, mid-rise and high-rise apartment buildings are made using concrete, while the others are built using timber frame. The building parameters were left as the program defaults, with the exception of insulation. Table 3 summarizes the important default parameters, and what the insulation levels were changed to for the PH cases.

Table 3: Important modelling parameters for the default and passive house (PH) cases

Parameter	**Default**	**PH Case**
Wall Insulation [U-Value]	0.072	0.022
Roof Insulation [U-Value]	0.066	0.022
Floor Insulation [U-value]	0.08	0.17
Window U-Value	0.5	0.22
Infiltration Rate [ACH]	0.35	0.35
Ventilation Rate [ACH]	0.6	0.6
Heating Set Point [degrees C]	20	20
Cooling Set Point [degrees C]	24	24
Heating COP	0.9	0.9
Cooling COP	3	3

Since the motherships are mixed use and include some retail and office (RO) space as well as the residential space, base case buildings of these use types were also modelled. There are four RO archetypes, numbered one through four, and for each archetype there are six building templates applied. The scenarios are named according to their space use type, whether they are super insulated ("PH" suffix) and whether they are built with wood frame construction ("WF" suffix) instead of concrete as the main structural material. The floor areas for the RO space base cases are the same as in the mothership's (50,000 m2 each). The shapes chosen were meant to explore the effects of different building massing, from large sprawling single level warehouse or mall typologies, to more compact four storey office buildings. A summary of the base case scenario parameters is shown in Table 3.

Table 4: Dimensions, number and total area of buildings for each base case.

Use Type	**X Dimension [m]**	**Y Dimension [m]**	**Height [m]**	**Number of Resi Floors**	**Number of Ret/off Floors**	**Number of Buildings**	**Total Building Area [m^2]**
Single Detached	10	10	6	2	-	4,160	832,000
Duplex	13	13	6	2	-	2,304	778,752
Low Rise	26	26	15	5	-	160	540,800
Medium-Rise	26	26	30	10	-	64	432,640
High-Rise	23	24	126	42	-	29	672,336
RO 1	224	224	5	-	1	1	50,000
RO 2	50	50	12	-	4	5	50,000
RO 3	91	91	18	-	6	1	50,000
RO 4	25	25	60	-	20	4	50,000

4.3.2. Motherships

The different mothership scenarios try to explore various ideas. The first, MS1, consists of simple rectangular structures arranged in a rectangle enclosing a large quadrangle, and MS3 uses the same design but with longer buildings arranged into two parallel lines of 5 buildings each. The second concept was to terrace the MS3 design by shifting each successive floor back from the face of the floor beneath it. This was done to increase daylighting and create private outdoor space. This had the trade-off of increasing the surface area and increasing energy use. Additionally, it creates a large open space in the interior of the building that would likely need to be lit with artificial lighting, further increasing energy use.

The third major design scenario was a ring shape, that was further explored in three different cases. The first case MS10 is 10 storeys, with an inner diameter of 137 m, and a floor width of 50m. MS11 increases the number of floors to twelve, while keeping the overall floor area the same, thereby decreasing the radius. In the third case, MS12, the building width was decreased, to increase the daylight levels near the interior of the buildings. This causes the radius to increase to maintain the same floor area.

MS8 explores a dome shape, with each floor being terraced back from the one below it. This produces an interesting aesthetic, but poses some design challenges, the biggest of which is that the floor area on each level decreases substantially with each successive floor. This means that the radius needs to start larger or have multiple buildings. This also creates a large amount of space in the interior that would be relatively difficult to provide natural daylighting to.

Table 5: Dimensions, number and total area of buildings for each mothership case.

Use Type	X Dimension [m]	Y Dimension [m]	Height [m]	Inner Radius [m]	Outer Radius [m]	Number Resi Floors	Number Retail Floors	Number Off Floors	Number of Buildings	Total Area [m^2]	Residential Extension [m]	Terrace Width [m]	Terrace Offset [m]
MS1	50	50	30	n/a	n/a	8	1	1	20	500,000	n/a	n/a	n/a
MS3	100	63	30	n/a	n/a	8	1	1	10	500,000	n/a	25	5
MS4	100	50	30	n/a	n/a	8	1	1	10	500,000	n/a	n/a	n/a
MS8P	n/a	n/a	21	n/a	140	5	1	1	5	508,285	n/a	30	6
MS10	n/a	n/a	30	137	187	8	1	1	1	505,873	n/a	n/a	n/a
MS11	n/a	n/a	39	90	140	11	1.5	1.5	1	502,354	n/a	n/a	n/a
MS12	n/a	n/a	36	180	220	10	1	1	1	499,966	n/a	n/a	n/a
MS4 WF	100	50	18	n/a	n/a	4	1	1	10	500,000	66.66	n/a	n/a
MS10 WF	n/a	n/a	18	137	187	4	1	1	1	506,940	27	n/a	n/a

Typically, the first floor of the mothership is retail, the second floor is office space, and the ones above are residential. Some of the more complicated shapes are configured differently but the floor areas remain the same. As with the base case models, the construction materials were also varied. All mothership scenarios are super insulated, to the same extent as the other PH scenarios. Table 5 gives the list of parameters used for each of the mothership cases.

For designs that were over 6 storeys it was necessary to use concrete. However, others were built to six storeys using mass timber. The last two scenarios that were explored use mass timber for the main building material as opposed to using concrete. The reasons for this are mainly the reduced embodied energy and embodied carbon of the building material when compared to concrete. However, there are other benefits of mass timber, some of which are outlined in Sorenson (2016), Kremer and Symmons (2015), Naturally:Wood (2016a), Naturally:Wood (2016b), and WoodWorks (2019). The main downside of building with mass timber currently is the limit to six storeys according to local building code, when the mothership design is built to 10 storeys. This height limit means that the floor area of 4 residential floors need to be made up by increasing the building footprint. This increases the surface area and heat transfer losses through the building envelope. For this reason, wood frame versions of MS4 and MS10 were simulated, to see if this increased surface area had an impact and to compare the reductions in EE and EC to the other cases that used concrete.

4.3.3. Assumptions

UMI has components that should make it possible to run parametrically and automatically in grasshopper, but currently these are not functional at this time. As a result, the parametric models must have parameters modified manually using a limited range of values for the sliders. Ideally it would be possible to assign a larger range of values to each of the sliders and have a component that creates and runs models with all the permutations of these parameters. With this component it could potentially be able to use one of the built in Grasshopper optimizers to optimize the building geometry. However, this is not currently possible. An automatic way of varying the parameters and running the simulations is a topic for future work.

The values that UMI simulations output are estimates only and are not taken to be exact values. It is simply a good tool for quickly working through a design space, and once the best performing design is determined, dedicated specialized software should then be used.

4.4. Results and Discussion

We first address the residential cases, comparing the solutions offered by the mothership to traditional built forms in terms of operational and embodied energy and embodied carbon. We then examine the retail and office use types in the same way, and finally the combination of all use types, which is the overall purpose of the mothership concept.

4.4.1. Residential

The energy and embodied carbon results for the residential base cases, and the residential components of the mothership cases are shown in Figure 17 and Figure 18. Each of the scenarios is compared as a percentage reduction in energy use and emissions relative to the single detached home base case. One trend that can be seen is the decrease of energy use with increasing density. An exception to this is the high-rise buildings, due to energy use increasing as building height increases (Godoy-Shimizu et. al. 2018). The embodied carbon for each case also decreases with increasing density until the buildings are made with concrete where it sharply increases due to it being much more carbon and energy intensive to produce than wood.

Of the base cases, low rise apartments had the largest reductions in energy use and embodied carbon, 58% and 51% respectively. The PH cases with higher insulation levels had significant energy reductions at the cost of increased embodied carbon, except for low-rise apartments which saw a reduction. The residential components of the motherships saw high energy reductions, again at the cost of increased embodied carbon. The wood framed motherships saw slightly higher energy savings than the other motherships, as well as high reductions in embodied carbon of 82%.

The results also indicate that although significant reductions in energy use can be gained by super insulating buildings (even accounting for the higher embodied energy and carbon associated with the higher performance building envelopes), there are still further significant gains that can be achieved through higher density. Especially when that increased density is built with less embodied energy and carbon intensive building materials

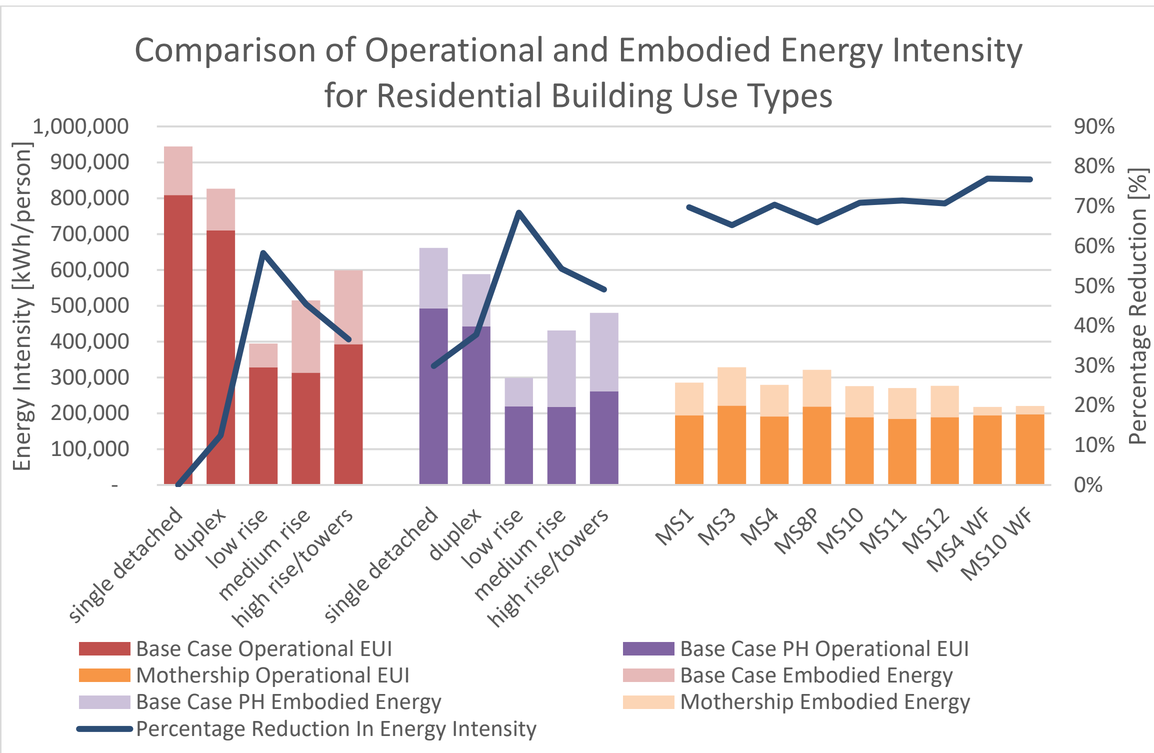

Figure 17: Comparison of operational and embodied energy and percent reduction relative to the single detached home base case. Low rise apartments perform best of the base cases, with the PH variant performing similarly to the mothership cases. The wood framed motherships performed better than the concrete motherships as a result of lower embodied energy.

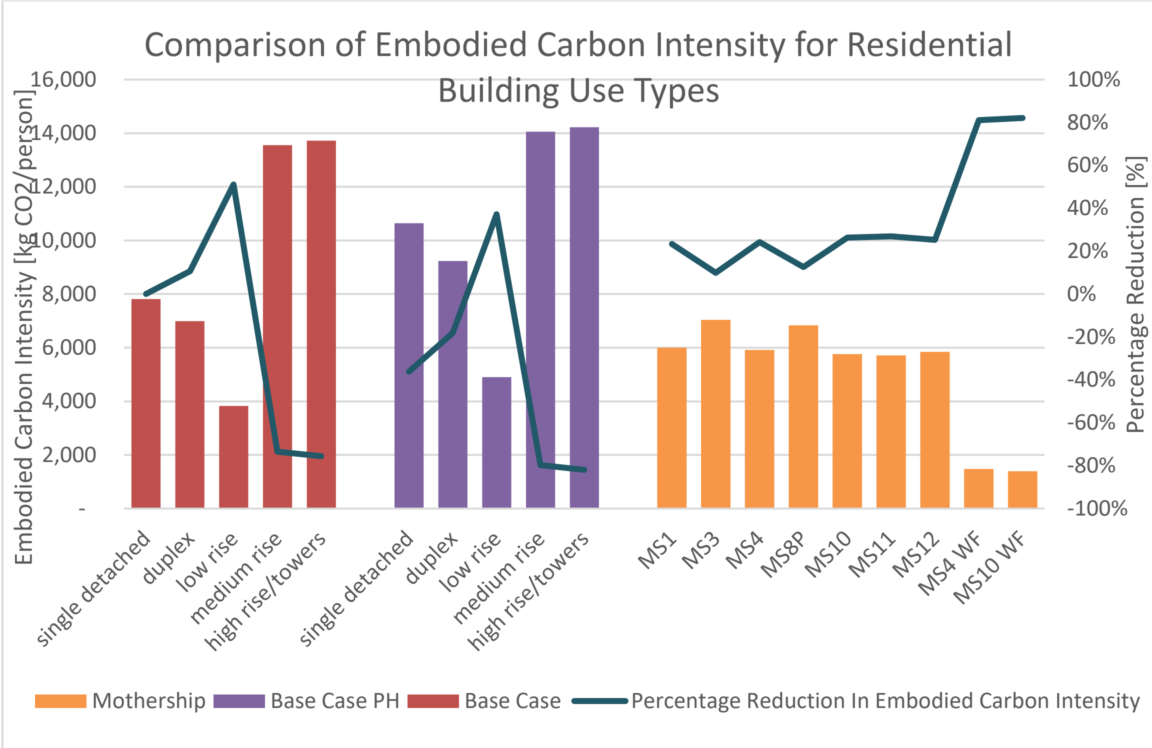

Figure 18: Comparison of embodied carbon and percentage reduction relative to the single detached home base case. Due to the carbon intensity of concrete, even the low-rise apartment base case has higher reductions than concrete motherships. Timber frame motherships far out perform concrete motherships and the base case.

4.4.2. Retail and Office

The energy intensity and embodied carbon results for the RO scenarios are shown in Figure 19 and Figure 20 respectively. Some of the building shapes such as expansive single storey spaces like RO 1 are not usually seen as office spaces. Likewise, in the local context, there are very few retail spaces that are multi-storey. However, for consistency, all the use type cases were modelled with each building type, even though they may not be realistic. Each building use type is compared to the base case for that use type using a percentage difference. For example, the RO 3 office PH WF is compared to the RO 3 office base case, and RO 1 retail PH is compared to RO 1 retail. The retail and office components of the motherships are compared to the best performing retail and office base cases, that is, RO 1 retail for mothership retail spaces, and RC 3 office for mothership office spaces.

In each of the scenarios, the super insulated PH cases saw significant energy reductions. The PH WF scenarios saw similar energy reductions for RO spaces in addition to significant reductions in embodied carbon (80% average)

The best performing retail scenario was RO3 PH WF at 33,891 kWh/person (34% reduction) over the building's lifecycle. The operational energy use reduction is nearly identical to the PH case, however it substantially (85% reduction) out performs concrete in terms of embodied energy and emissions. The best performing office scenario was RO3 PH WF at 29,766 kWh/person (39% reduction) over the building's lifecycle and a 83% reduction in embodied carbon.

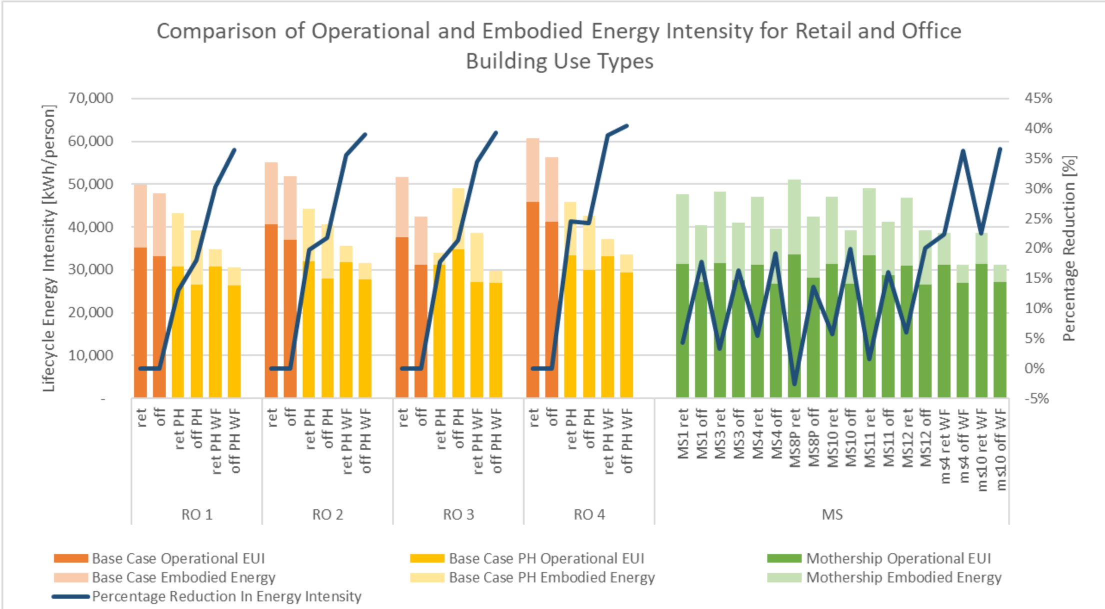

Figure 19: Comparison of operational and embodied energy of each of the retail and office scenarios and the motherships. The percentage reduction for each base case is calculated relative to the retail or office case of that building type. The mothership cases were compared against the best performing retail and office base cases, RO1 and RO13 respectively.

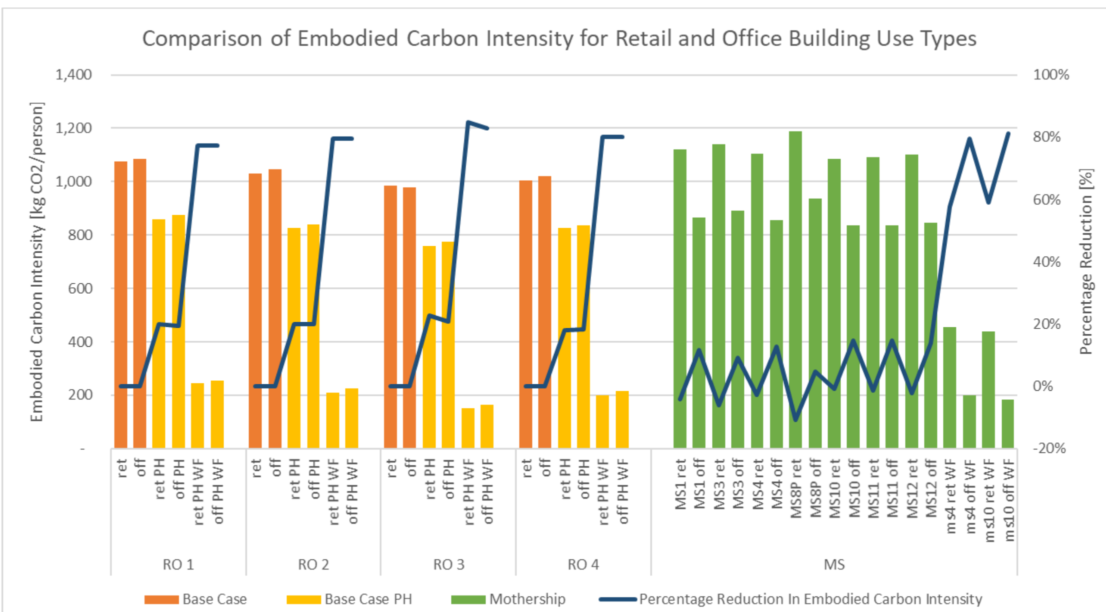

Figure 20: A comparison of embodied carbon of each of the retail and office scenarios and the motherships. The percentage reduction for each base case is calculated relative to the retail or office case of that building type. The mothership cases were compared against the best performing retail and office base cases, RO1 and RO3 respectively.

4.4.3. Combined Residential, Retail, and Office Comparison

The results for the residential and RO spaces were combined to come up with total energy use intensities and embodied carbon intensities for all the cases. These results can be seen in *Figure 21* and Figure 22 for energy and carbon respectively. The plots show the operational energy use, embodied energy, and embodied carbon, as well as the percentage reduction relative to the single detached home use type combined with the best performing RO cases with to-code building envelopes. There are four main categories consisting of: base case with to-code RO, base case PH with RO PH, base case PH with RO PH WF, and mothership cases. The base case consists of the residential base cases, combined with the highest performing to-code retail and office space cases. Likewise, the base case PH consists of the residential base case PH combined with the best performing RO PH cases. The base case PH WF consists of residential base case PH combined with the best performing RO PH WF cases. Finally, the mothership cases are simply their combined individual residential spaces and retail and office space values.

In all the non-mothership cases, low rise apartments perform best due to their higher density, and their lower height enabling timber construction to save on embodied energy and carbon. They achieve energy reductions of 53% and 64% for the to-code case and the PH cases respectively and 50% and 35% reductions in carbon for base case and base case PH respectively. The low-rise PH case with timber frame RO structures achieved a 48% reduction in embodied carbon.

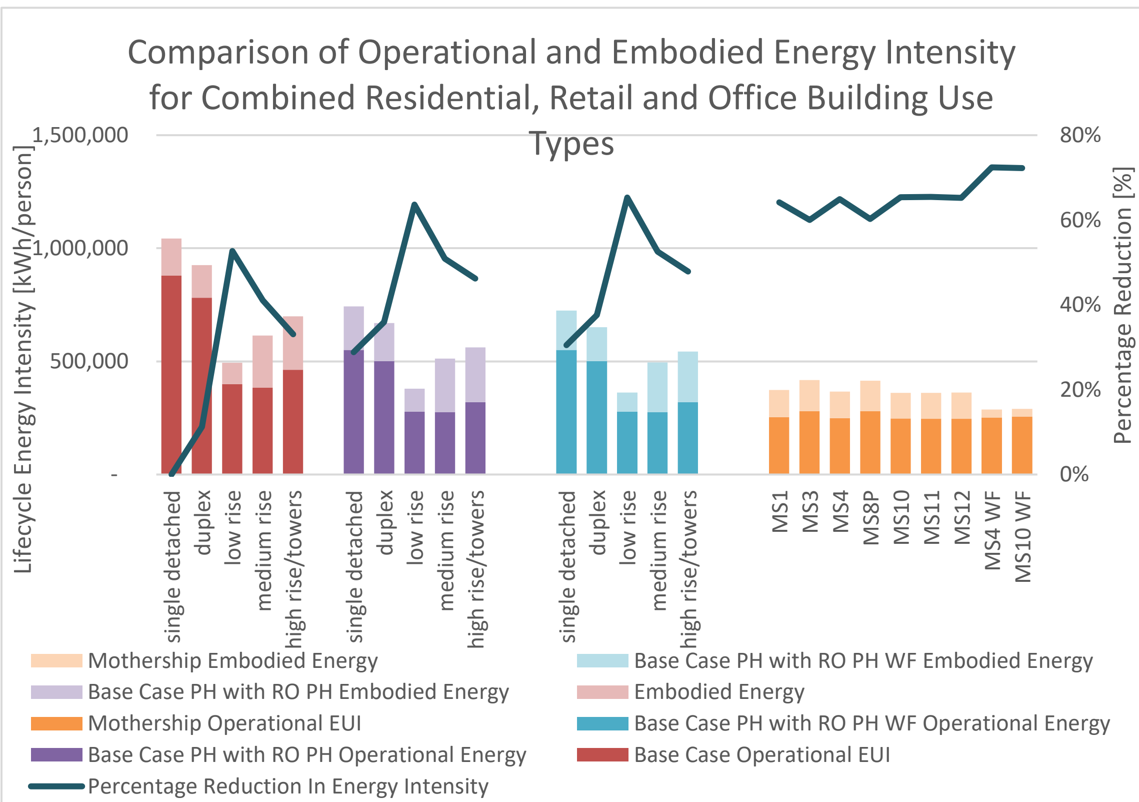

Figure 21: Compares operational and embodied energy of each scenario to the combined results for single detached home with the highest performing to-code retail and office cases. Significant savings can be made by high levels of insulation, especially with low rise apartments. Timber framed motherships have similar operational energy use but much lower embodied energy due to not using concrete.

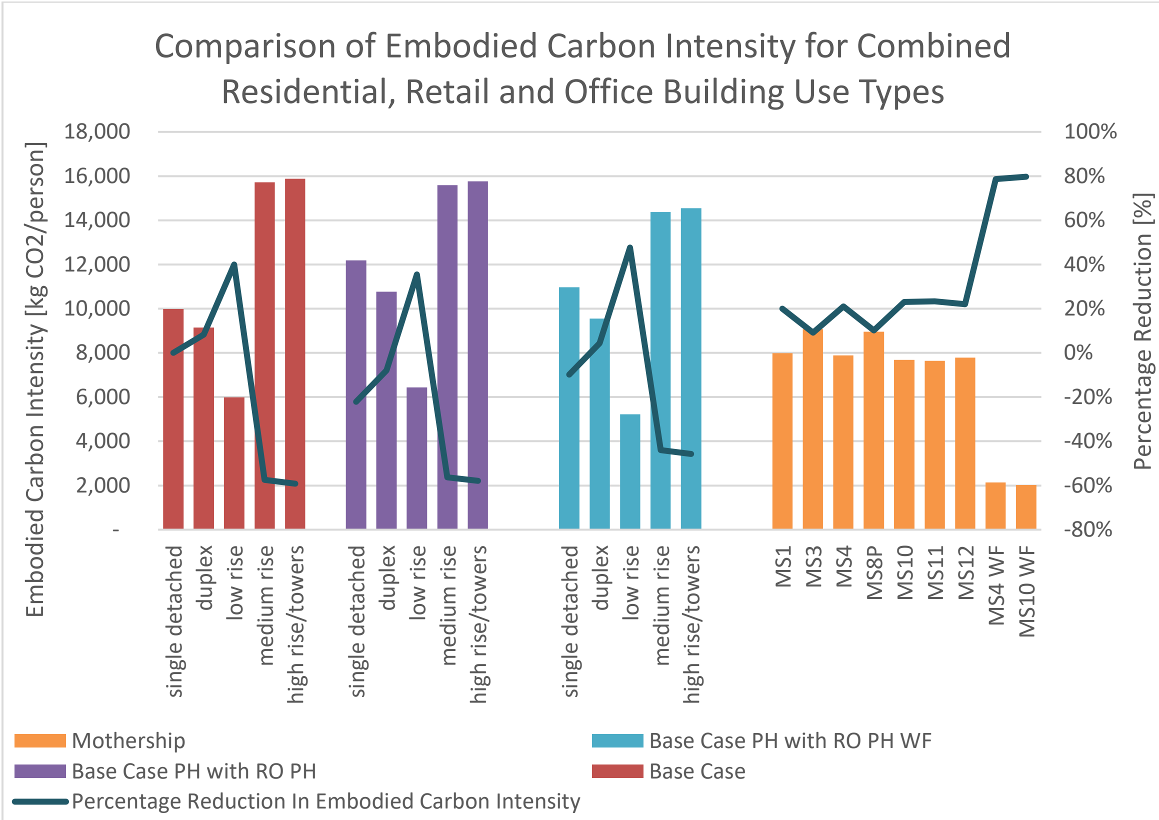

Figure 22: Comparison of embodied carbon to the combined results for single detached home with the highest performing to-code retail and office cases. Low rise apartments achieved higher reductions to concrete motherships, but still much lower than timber framed motherships.

Medium-rise apartments show a similar, although lower energy reduction than low rise apartments, however building with concrete makes their embodied energy and carbon much higher. High-rise apartments do not perform as well as lower density apartments in terms of energy use or embodied carbon. The timber framed mothership cases appeared to be the best cases. Their energy use being similar to the other mothership cases, but very large improvements in embodied energy and carbon, totalling 20% and 74% respectively, when compared to the same mothership cases built with concrete. Compared to the single detached house base case these reductions are 72% and 80% for energy and embodied carbon respectively.

An interesting comparison is that of the mothership performance to low-rise apartments. The motherships outperform all the base cases in terms of energy use, and the WF motherships outperformed in both energy and carbon. However, low-rise PH and PH WF apartments perform similarly to wood frame motherships, although less so in terms of embodied carbon, they still outperform all the concrete motherships.

Conceptually speaking there isn't many obvious things that can be done to further reduce the energy use and emissions of a group of buildings as cost effectively as making density higher and reducing surface area, and super insulating it as much as is realistically possible, without sacrificing other aspects such as natural light. A building could be designed with an even smaller surface area to volume ratio, but at some point, the natural light availability inside the structure will suffer, and increasing glazing to compensate often introduces other problems such as increased losses and overheating in summer.

This leads to the mixed-use aspect of the mothership design. It is an aspect that does not increase building costs by a large factor, but it can have a large effect in terms of overall energy use and emissions of the residents by reducing the number of personal vehicle trips. The effect could be compounded by having a transportation hub that would reduce the vehicle trips of the surrounding neighbourhood as well as the mothership residents.

Another advantage is having an advanced district energy system. Not only are these systems efficient and allow for different types of renewable generation and storage technologies to be used, it can also be optimized to share energy between the retail and office spaces, and the residential areas (Entchev et al. 2013). One example could be the extracted heat from cooling a server bank could be used to heat hot water for the residents.

4.5. Future Work

As mentioned in the method section, a major limitation of this work was not being able to have an automatic way of running the UMI simulations in grasshopper. Future work will include potentially developing a work around for this. The advantage of being able to run simulations automatically is that there are optimizer components in grasshopper that will vary the parameters based on their algorithms to optimize the design geometry for some parameter, the obvious one being energy use, but it could be any other calculated value.

It is important that a potential solution such as the Mothership will be able to perform well in different locations and climates. Therefore, a climate analysis will be performed, using different locations and climates to examine the effect on energy demand. Additionally, a climate change resilience study will be performed using weather files for future climate projections for these locations. This will show whether a Mothership style design is more resilient to a changing climate than traditional building types.

According to Natural Resources Canada (2018b) and Natural Resources Canada (2018a), approximately 16% of total energy use and 14% of produced emissions are associated with residential and commercial building space heating in Canada. Transportation accounts for 30% of total energy use, and 38% of emissions. Energy use of buildings can be reduced drastically through high performance building envelopes and using renewable sources of energy to provide the required heating and hot water through heat pumps. As this occurs, the proportion of emissions and energy use due to transportation becomes more significant than it already is. As a result, the conscious design of the built environment to minimize the need for personal vehicle trips and providing emissions free public transportation has the potential to yield huge reductions. Future work will attempt to quantify the effect of reducing the number of personal vehicle trips and using public transit that the higher density mixed use of the mothership can provide.

Opportunities for energy sharing between the different use types exist and deserve to be explored. To do this, an energy system optimization tool called the Energy Hub (EHub) (Evins et al. 2014) will be used.

4.6. Conclusion

A potential holistic solution to urban sprawl called the Mothership was modelled and compared to more traditional building archetypes. Building operational energy use as well as the embodied energy and emissions were the metrics used in the comparison. The motherships as well as super insulated versions of the base cases were compared to the single detached houses base case. Of all the mothership cases examined, the timber framed cases performed best, with similar energy use reductions to other motherships, but much lower embodied energy and carbon than the other mothership cases. Timber framed motherships showed reductions of 71%, 79%, and 80% of operational energy, embodied energy and embodied carbon respectively compared to the single detached base case with to-code insulation. The super insulated low-rise apartment case also performed similarly to the timber framed motherships, however they wouldn't necessarily benefit from the effects of mixed use as the mothership does. It is also important to note that the energy reductions associated with higher density taper off with increased height, as the higher the building is the more energy it uses. In the end, building energy use and emissions are but a part of the overall consumption of the built environment, and it is important to consider transportation and proximity of amenities in addition to buildings since they become more significant as building effects are reduced.

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5. Assessing Energy and Emissions Savings for Space Heating and Transportation for a High-Density Mixed-Use Building

Prepared for submission to the Journal of Building Performance Simulation.

Wesley Bowley[1], Ralph Evins[1]
[1]University of Victoria

5.1. Abstract

This paper introduces a combined framework for the analysis of building-related and transport-related emissions, to allow the comparison of a new high-density mixed-use development concept with traditional urban development patterns. The framework accounts for the energy and emissions arising from the operational of the building, the materials needed to build it, and the transportation of the residents. This provides a novel means to compare the impact of urban form on both building-related and transport-related emissions simultaneously. The building analysis performs detailed building energy simulations and embodied energy calculations. The transportation analysis estimates emissions reductions from eliminating personal vehicle trips through the mixed-use nature of the building, provision of an electric vehicle car sharing fleet, and a public transit hub with a rapid transit line.

The framework is used to assess the new concept, referred to as a ‘Mothership’, which provides a potential holistic solution to urban sprawl through high-density mixed-use development that meets the needs of 10,000 people. It includes a high-performance building envelope, advanced energy systems, a public transportation hub and electric car sharing fleet. The analysis compares this method of development to the ‘urban sprawl’ that has characterized new development in North America. The comparison is performed for two case studies in British Columbia, Canada.

Results show that the Mothership could reduce operational and embodied emissions by 73% and transportation emissions by 58% compared to low-density suburban development. A key takeaway is that as operational emissions decrease due to high performance building design and clean electricity for space conditioning, transportation and embodied emissions become much more significant. Therefore, it is critical that new development patterns account for these alongside building-related emissions.

5.2. Introduction

The United Nations expects that the global population will increase to 9.8 billion people by 2050 (United Nations, 2015), with an increasing percentage of people living in urban areas (United Nations, 2018). As a result, cities must inevitably either expand or densify or both. It is critically important that this new growth is done in the most sustainable, efficient and livable manner, that accounts for the whole urban area. Buildings account for 35-40% of national CO2 emissions according to the OECD (urge-Vorsatz et al. 2011). However, growth is often uncontrolled, without a holistic development plan, and this can result in urban sprawl.

Urban sprawl can be defined as development characterized by low built density, private automobile transportation, unlimited expansion of new subdivisions, and segregated land use by activity. (White et al. 1974). There are many negative impacts of urban sprawl, both in terms if energy and emissions, but also on human health. The increased distance between residences and amenities, as well as lack of effective public transportation necessitates personal vehicle use. This increase in vehicle use can lead to more congestion and idling, increasing emissions and pollution. Additionally, the dominant building archetypes characteristic of urban sprawl, single detached homes, are less energy and materials efficient than other higher density forms of housing such as low-rise apartments. This is due to the increased number of buildings required to house the same population, which increases building surface area and thus heat loss. Urban sprawl is also associated with negative health impacts of residents (Ewing et al. 2014; Ewing et al. 2016; Zhao and Kaestner, 2010). This is typically due to poor walkability, with few alternatives to driving in order to fulfill daily needs. Urban areas with amenities within walking distance of residences allows trips to be made via active means such as walking or cycling which positively impact physical health.

One promising way to prevent urban sprawl is termed "smart growth," which uses carefully planned higher density mixed use developments. Mixed use development combines residential apartments or town houses with retail, offices and other amenities within walking distance, often in the same building. Some advantages of this archetype are that the higher residential density decreases surface area and increases energy efficiency, and reduces costs associated with infrastructure because the end uses are concentrated, leading to smaller pipe and wire networks. Locating amenities near residences also allows trips to be satisfied by active means, eliminating many car trips and reducing the associated emissions and congestion.

This paper explores a version of smart growth on a large scale termed the "Mothership" - a highly insulated, large building or cluster of connected buildings, with high density and mixed-use, housing 10,000 people. It is designed to provide all the residences and amenities of a typical "suburb" (grocery stores, restaurants, retail, schools, health and recreation services, etc.) with advanced energy systems that are integrated together with building functions. We introduced the term in Bowley et al. (2019) [chapter 4 of this thesis], where we analyse and compare the operation and embodied energy use and emissions of various mothership and traditional building archetypes. This paper extends that work by modeling the mothership in future climate scenarios to assess the effect of climate change on building performance. A transportation emissions analysis is also performed to estimate the potential reductions to emissions resulting from the elimination of vehicle trips due to the building's mixed use, public transportation links, and electric vehicle car sharing fleet.

The role of buildings in preventing climate change is very significant. Buildings account for significant portions of global greenhouse gas emissions, as much as 35% (Nakićenović et al., 2000) and 40% (urge-Vorsatz et al., 2011). However, there is also great potential for reductions, with air tight, highly insulated building envelopes like those employed by Passive House can reduce operational energy use by 70%-90% (Passive House Canada, 2019) with only a small increase in building cost. The energy and emissions embodied in the building materials that go into the urban environment are also very significant (Sartori et al., 2007) often between 10-20% for typical buildings (Ramesh et al., 2010). Concrete production accounts for nearly 5% of global anthropogenic emissions (World Business Council for Sustainable Development, 2002), so using alternative building materials that have a lower carbon footprint such as mass timber construction can result in significant reductions.

Vehicle emissions in general, but especially in urban areas, is a significant portion of the total emissions of many regions. According to Natural Resources Canada (2018a, b), transportation accounts for 30% of total energy use and 38% of emissions in Canada, whereas approximately 16% of total energy use and 14% of emissions are associated with residential and commercial building space heating. Transportation emissions are more significant in areas where clean renewable energy makes up the bulk of the electrical generation, such as hydro electricity in British Columbia and Quebec. Using clean electricity to provide space and water heating increases the proportion of emissions caused by vehicles. Therefore, it is critical that any development plan not only tries to minimize building-related emissions, but also tries to minimize transportation emissions as well. We need holistic solutions which address both issues, while still maintaining desirability and livability.

The novel analysis framework presented here combines operational emissions from heating, cooling and electricity use, embodied energy and emissions of the materials used to construct the building, and transportation of the building occupants. The inclusion of embodied energy and transport emissions alongside the common focus of building operation is important, as there are now many means of reducing the latter, making the former relatively more impactful. As the energy grid is transitioning to clean forms of electricity, operational emissions fall, and embodied emissions become much more significant. Transportation emissions are also significantly impacted by the mixed-use aspect of mothership design and through enabling higher capacity modes of public transportation due to the anchor load provided by a higher concentration of people. Through the proposed framework, total carbon emissions and energy use are assessed in detail, highlighting how this can be reduced through the proposed mothership concept. Finally, climate resilience is also compared across the proposed building architypes through the use of future climate projections.

The framework summarised above is applied to case studies spanning two very different climates, both located in British Columbia, Canada (Victoria in the south and Fort Nelson in the north) for present as well as future climate scenarios.

5.3. Literature review

Mixed use development is not a new concept, but it has usually been a more organic process than something that was designed for. Shop keepers and business owners simply lived above or near their businesses. However, recently with the proliferation of urban sprawl, mixed use development is seen as mitigation measure and in some cases a solution. Alexander and Tomalty (2002) examines urban density and 13 indicators of community sustainability and find that it is associated with infrastructure efficiency and reduced automobile dependency and the associated benefits. Barbour and Deakin, (2012) analyse how smart growth principles can be applied as part of a climate protection framework. Geller (2003) describes how smart growth is not just about transportation, but also a means to promote heath and well being of residents. Similarly, Daniels (2001) examines the State of Maryland's approach to smart growth developments and how it linked land use planning, transportation to people's quality of life. Jabareen (2006) provides a good summary of design concepts and how they are applied to different urban forms to create a metric that can help assess the sustainability of different urban forms. Ko (2013) reviews how urban form affects residential energy use, and examines different climate responsive design principles.

Building energy modeling is a tool that can be used to estimate the energy use of individual buildings based on design parameters and expected climate. This can be expanded to multiple buildings or urban areas, however typically the computation requirements dramatically increase as more buildings are modeled. A new software tool developed by Sustainable Design Lab at MIT called the Urban Modeling Interface (UMI) (Reinhart et al. 2013) uses an innovative approach called the Shoeboxer (Dogan and Reinhart, 2017) to increase the speed of building energy calculations for urban areas. The Shoeboxer clusters floor area based on the building's incident solar radiation into multiple sections, then creates small EnergyPlus (Crawley et al. 2001) models for each, runs simulations, and then extrapolates the results to the whole building. This method drastically improves computation time and is useful for preliminary planning energy analysis.

Ewing et al. (2008) shows that there is a decease in building energy with increased density, with larger homes using more energy than smaller ones, even for equivalent households and lifestyles. Steemers (2003) breaks down energy use into that used by building, and that by transportation in an urban area and how these ties in with density. Ewing et al. (2011) examines the effect of mixed-use developments on generated traffic in six different regions. Estiri's (2016) uses path analysis to show that on average suburban households use more energy than their equivalent city dwellers. Increased urban density and reducing sprawl can also have health benefits. Ewing et al. (2014) examine the relationships between urban sprawl and decreased physical activity, increased obesity and morbidity. Zhao and Kaestner (2010) also examine the link between urban sprawl and obesity.

Litman (2018) examines how land use factors affect travel behavior and how policy can achieve planning goals such as energy and emissions reductions. It provides a good overview of some typical reduction values for personal vehicle trips for different planning measures. Additionally, there is a summary of numerous transportation modeling tools that have been developed. Tong and Wong (1997) describes how despite having a linear urban form, an area of Hong Kong island is able to develop a viable transportation network with high accessibility for resident with little reliance on personal vehicles.

Embodied emissions are those associated with the extraction of raw materials, processing and transport of the building materials used in a project. Typically, they only represent about 10-20% of the total life cycle emissions (Ramesh et al., 2010) and the majority are associated with the operational emissions (Ibn-Mohammed et al. 2013). However as large reduction in operational emissions make embodied emissions much more significant, and with the introduction of clean energy to supply the operational demands, the embodied emissions become most of what is left. Designers are then left with exploring the use of other building materials and techniques to further reduce the emissions. One such technique keeping building height low enough to enable mass timber construction as opposed to concrete saves very large amounts of carbon emissions (Kremer and Symmons 2015) due to the high carbon intensity of cement production (Worrel et al. 2001).

There are examples of mothership like structures and developments that implement individual ideas or combinations of those mentioned above that have been built around the world such as Apple Park, Hammerby Sjöstadt (2019), Bahnstadt Heidelberg (2019), Maldives Airport Economic Zone Mixed-use Development (2018), and Dockside Green (2019).

A previous study conducted by Norman et al. is similar in in goal, but different in scope. They perform an economic life cycle assessment of the building materials of a low density and high-density building type. Additionally, they look at the energy use and emissions due to transportation and building operation. They find that low density uses more energy and emits more CO_2 per person than high rise buildings, and break down these values into their sources. However only two building types are considered, and the operational energy use is obtained through statistical data as opposed to computational building simulation of the buildings.

Another study by O'Brien et al. examines how net energy use changes with building density (low, medium and high density), specifically considering the effect of building density on solar energy gains and total energy use. They also consider transportation energy. They conclude that high density development has lower energy use even when considering the reduced solar gains, mainly due to significant reductions in transportation energy. Only when collector and transportation efficiencies are significantly increased does low density achieve lower net energy use. The study does not investigate the emissions associated with the energy use or embodied in the building materials.

This paper's framework examines the energy use and emissions associated with the building's operation, as well as embodied in the materials from which it is built. Additionally, the emissions from transportation is also considered. The results for the buildings are obtained through building simulation of individual models created for the building types, whereas the transportation analysis uses statistical data from local transportation surveys. Doing these types of analyses together holistically has not been conducted before.

Table 6 Table showing examples of mixed-use developments and their residential population

Apple Park	12,000 employees (workspace only)

Hammerby Sjöstadt	26,000
Bahnstadt Heidelberg	6,800
Dockside Green	2,500

5.4. Analysis framework

5.4.1. Overview

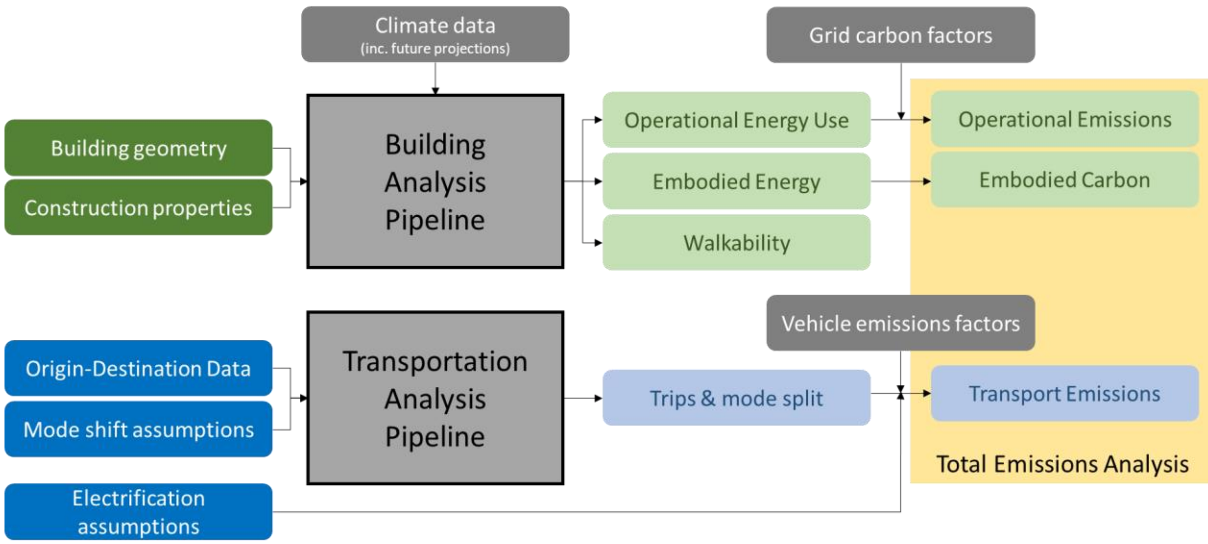

Figure 23: The proposed analysis framework that combined building operation, embodied and transport emissions.

The analysis framework developed in this paper is shown in Figure 23. It combines a building analysis pipeline with a transport analysis pipeline so that the impact of urban density and mixed-use development on total carbon emissions can be assessed. The building analysis pipeline involves simulating the operational energy use using a detailed building energy model and calculating the embodied energy in the construction materials. This is implemented using a toolchain in which it is possible to represent many small buildings or single very large buildings. The simulation results in terms of energy use are the translated into emissions using grid carbon intensity factors. In parallel, the transportation analysis pipeline assesses the impact of two factors: the elimination of a portion of daily vehicle trips due to the mixed-use nature of the mothership, and the effect of the mothership's transportation hub providing anchor load for a bus rapid transit (BRT) line. Predicted trip and mode data is then translated into transport emissions using vehicle emissions factors and assumptions about electric vehicle uptake. The final total carbon emissions arising from building operation, materials and transportation can then be compared between the base case (traditional archetypes) and the high-density mixed-use option (the mothership).

5.4.2. Building analysis pipeline

Figure 24: Workflow for the energy simulation process

The building analysis pipeline, shown in Figure 24, consists of creating the building geometry using the CAD environment Rhinoceros 5 (Rhino) (Rhino3d, 2019) utilizing the parametric design plugin Grasshopper (Grasshopper3d, 2019). Grasshopper allows input parameters to be controlled with sliders, which lets the geometry be varied in real time by manipulating the sliders. The building geometry was then used by another Rhino plugin, the Urban Modeling Interface (UMI) (Reinhart et al. 2013) developed at the Sustainable Design Lab at MIT. UMI uses the geometry, an .epw weather file and customizable building parameter profiles to the estimate operational energy use, the embodied energy and emissions associated with the building materials, as well as the daylighting potential and walkability of urban scale building models. The energy simulation is performed using EnergyPlus (Crawley et al. 2001) through UMI. UMI determines the solar gains for all exterior surfaces and clusters them into similar groups. For each of these groups it creates a thermal zone and performs a detailed energy simulation at hourly time intervals for a year with the given weather and building parameter files. The results for each zone are then scaled and extrapolated for the floor area that is represented by their cluster. The energy demands for the building are the sum of the demands for each cluster. Climate resilience analysis is also incorporated through the use of future projection weather files generated as described in Belcher et al. (2005). UMI determined the embodied energy and CO2 emissions of the building materials as described in the program documentation (MIT Sustainable Design Lab 2019) and in Davila and Reinhardt (2013).

5.4.3. Transportation analysis pipeline

The goal of the transportation analysis pipeline is to estimate the effects of the mothership concept on transportation emissions. These emissions reductions are gained through three main pathways:

1. Mixed-use developments help eliminate daily trips because instead of needing a vehicle to travel to a mall, residents can walk to nearby stores and offices. The same would be true for residents of surrounding areas who are within walking or cycling distance. By fulfilling these trips using non-vehicle modes, there is a significant reduction in emissions.
2. High-density developments form an anchor load for a public transit hub to provide a high capacity rapid transit for connection with other main destinations such as a nearby central business district. The analysis presented here uses a Bus Rapid Transit (BRT)

line with dedicated bus lanes and bus prioritization systems, but could be adapted to other transit solutions.

3. High-density developments make a car sharing program feasible to provide transportation for trips that are not easily met by active means or public transport, as the fleet will be located within walking distance for all residents.

These are in addition to the assumed gradual electrification of the private vehicle fleet, which is also considered for the base case. Transportation emissions reductions accounting for the above items can then be combined with estimated savings from other areas such as building form and density.

5.4.4. Baseline emissions

The baseline transportation emissions are estimated using origin - destination, purpose and mode split data together. First we calculate C_{gas} and C_{EV}, the carbon emissions per kilometer driven. For gas vehicles this is calculated as

$$C_{gas} = \eta * A * I_g$$

(Equation 1)

where η is the average fuel efficiency of gasoline vehicles, A is the energy density in kWh of gasoline and I_g is the carbon intensity of gasoline (Ecoscore, 2019). For EVs this is the energy use per km multiplied by I_e, the carbon intensity of the electricity grid. These factors are then applied depending on Φ, the proportion of personal vehicles that are battery electric.

Daily emissions E ($kgCO_2$) for each trip purpose i are estimated using **Error! Reference source not found.**.

$$E_i = (\phi C_{EV} + (1 - \phi)C_{EV}) * \sum_i N_i * \beta_i * D_i$$

(Equation 2)

Where N is the number of daily trips for that purpose, β is the fraction of trips of that type made using personal vehicles, and D is the average length of the trip in kilometers.

5.4.5. Eliminated emissions

The reduction in emissions for factors discussed above are calculated in the following ways:

- The number of each journey type N_i is reduced by a factor R_i that correspond to the reduction in the need for that journey type due to the mixed-use nature of the development. These journeys are now performed on foot within the mothership, so have no emissions.
- The remaining number of commuting trips N_c is reduced by the mode switch factor M, indicating the percentage of trips that switch from personal vehicles to the bus rapid

transit. These journeys are now allocated to the BRT, and emissions are calculated for C_{BRT}, the emissions factor for the rapid transit system.

- A proportion of remaining journeys for all other types are shifted to EVs, to account for the provision of an electric vehicle car sharing fleet. This shifts them from C_{gas} to C_{EV}.

Additional emissions reductions due to the use of the EV car sharing fleet and the BRT by residents of surrounding areas are not accounted for in the analysis, to maintain comparability with the base case.

5.5. Case study

This section gives details of a case study in which the framework outlined above is applied to a hypothetical new suburb of the city of Victoria, British Columbia, Canada.

5.5.1. Buildings

Three urban development type are analysed for this case study: single detached (SD), low rise apartments (LRA) and the mothership (MS). These represent the low-density status quo for urban sprawl, a higher-density comparison case that still uses traditional forms, and the proposed high-density mixed-use case respectively. Figure 25 shows a visual comparison of the land area required to house 10,000 people using each development type. Each case was scaled to give the same provision of residential (400,000m^2 or 40m^2 per resident), office (50,000m^2) and retail space (50,000m^2). These are based on the space provisions found in typical buildings found in the Greater Victoria Area. For the SD and LRA cases the retail and office components were six storey buildings with square footprints with side lengths of 91m ; these were run as separate models and the results combined. The mothership design consists of a ring-shaped design, as shown in Figure 26. The dimensions and other massing parameters of each case are given in

Table 7. Many more variations were analysed in a previous paper, including duplexes, 5, 10 and 42 storey apartment buildings, retail and office buildings varying from expansive single-story warehouses to 20 storey towers, and nine different mothership designs. For results see (Bowley et al. 2019) [chapter 4 of this thesis].

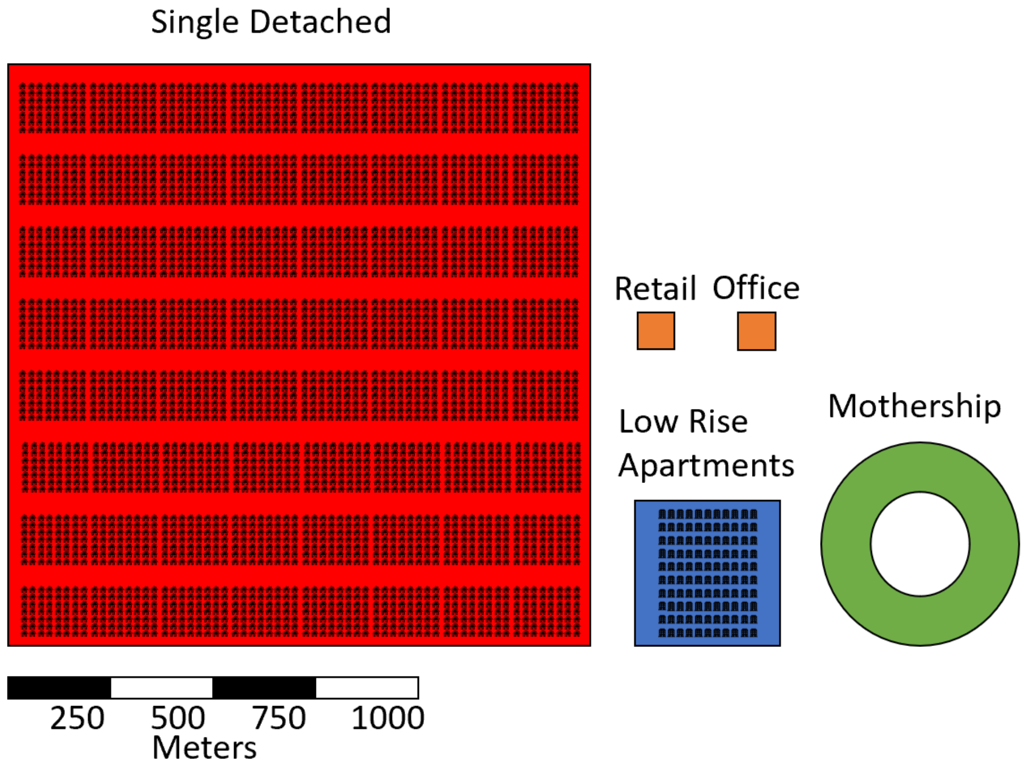

Figure 25: Comparison of the land area required by single detached homes, low-rise apartments and mothership to house 10,000 residents. The area of the land used by the single detached homes is about 1.5km^2 while the low-rise apartments and mothership use 0.13km^2 and 0.14km^2 respectively.

Table 7: Dimensions, number and total area of buildings for each base case.

	X Dimension [m]	Y Dimension [m]	Height [m]	Inner Radius [m]	Outer Radius [m]	Number of Residential	Number of Retail Floors	Number of Office Floors	Number of Buildings	Total Building Area [m2]	Residential Extension [m]
Single Detached (SD)	10	10	6	n/a	n/a	2	0	0	4160	832,000	n/a
Low Rise (LR)	26	26	15	n/a	n/a	5	0	0	125	422,500	n/a
Retail & Office	91	91	18	n/a	n/a	0	6	6	1	50,000	n/a
Mothership, Wood (MS-W)	n/a	n/a	18	137	187	4	1	1	1	506,940	27
Mothership, Concrete (MS-C)	n/a	n/a	30	137	187	8	1	1	1	500,000	n/a

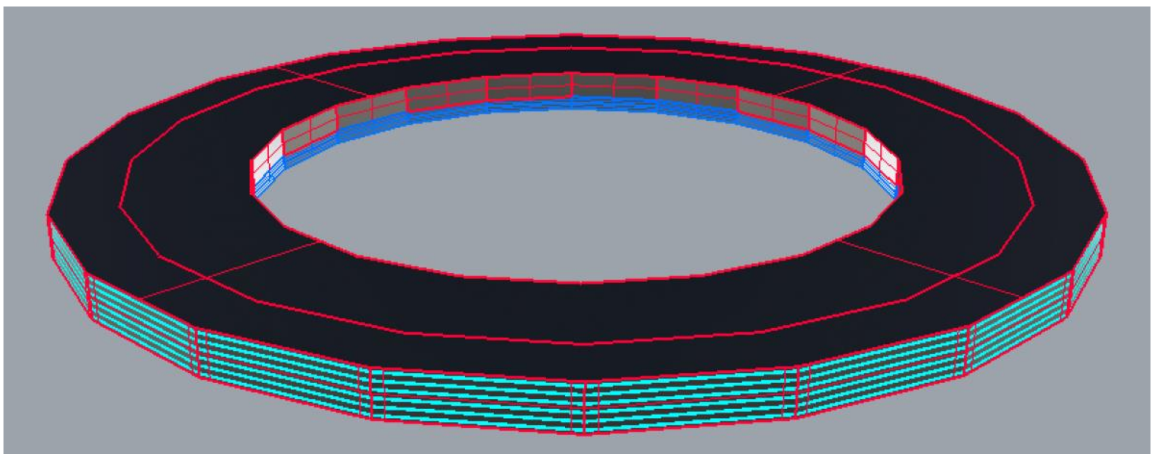

Figure 26: Three-dimensional model showing the geometry of the mothership. Most of the building is residential space, with dark blue outlines indicate retail and office space.

For the detached and apartment cases two levels of insulation were examined (the higher level or passive house design denoted 'PH'), to investigate whether highly-insulated building envelopes make these urban forms more practical. In both cases construction is assumed to be timber, as this is the predominant material for these building forms in North America. The mothership design used high insulation levels only, but the difference between wooden and concrete construction are examined, with the wooden design (MS-W) being 6 storeys[1] and the concrete design (MS-C) 10 storeys. The building parameters are shown in Table 8. The building energy simulations used weather files for Victoria and all made use of natural ventilation. All PH buildings used a heat recovery ventilator at 90% efficiency since they are nearly always implemented in passive houses. Future climate projections were also applied for 30-year periods (referred to by their median decade) for 2020, 2050 and 2080.

[1] Mass timber construction is limited to 6 storeys in the British Columbia Building Code (British Columbia Ministry of Municipal Affairs and Housing, 2009).

Table 8: Important modelling parameters used for the BC Building Code and Passive House (PH) cases

Parameter	BC Building Code	Passive House (PH)
Wall Insulation U-Value, W/m^2K	0.05	0.022
Roof Insulation U-Value, W/m^2K	0.066	0.022
Floor Insulation U-Value, W/m^2K	0.08	0.17
Window U-Value, W/m^2K	0.5	0.22
Infiltration Rate, AC/h	0.35	0.35
Ventilation Rate, AC/h	0.6	0.6
Heating Set Point, °C	20	20
Cooling Set Point, °C	24	24
Heating System CoP	1	1
Cooling System CoP	1	1
Heat recovery Ventilator Efficiency	N/A	90%

5.5.2. Transport

The transportation analysis pipeline is applied to the scenario of a mothership located adjacent to the commuter suburbs of Victoria, where there is much new development. The analysis uses data from the 2017 Capital Regional District Origin Destination Household Travel Study (Malatest, 2018). The total daily commuting car trips were 5,899[2]. The average fuel efficiency of gasoline vehicles in Canada $\eta = 8.8l/100km$ is obtained from (IEA, 2017). The BRT is assumed to use $\eta = 20l/100km$. EVs are assumed to use 20 kWh/100km.

The journey type-specific numbers, distances and reduction assumption values used in the analysis are summarized in Table 9.

[2] This value and those in Table 4 are scaled to reflect the mothership population of 10,000 people.

Table 9: Input values for transportation emissions calculations

Trip Destination	*% Daily Trips*	*Trip Length D_i, km*	*% Trips Using Car*	*% Trips Eliminated by Mixed Use R_i*
Work	*16*	*6.7*	*67*	*50*
Post Secondary	*2*	*6*	*30*	*95*
K-12 School	*3*	*2.7*	*50*	*95*
Personal Business	*6*	*5.3*	*77*	*0*
Recreation/ Social	*11*	*7*	*85*	*50*
Dining/Restaurant	*4*	*3.3*	*70*	*15*
Shopping	*11*	*3.7*	*77*	*50*
Pick-up/ Drop-Off	*8*	*4.8*	*92*	*0*
Return Home	*38*	*5.2*	*70*	*50*
Other	*1*	*79.3*	*56*	*0*

The following assumptions were made in the emissions reductions section of the transportation analysis pipeline:

- Personal vehicles in this analysis are all assumed to be gasoline powered or battery electric. For the base case, battery electric vehicles satisfy 10% of personal vehicle trips.
- The BRT takes 23% of remaining commuter journeys. This high ridership assumption is consistent with the use of dedicated bus lanes as well as transit prioritization at traffic lights so that buses are not delayed by rush hour traffic. This closely matches the measures implemented in a BRT line in Metro Vancouver (Hartmann et al. 2006).
- It is assumed that 50% of remaining personal vehicle journeys use the EV car share fleet, i.e. the new Φ value is 50%.
- The origin destination study data is only for weekday trips; it is assumed that longer trips and weekend journey are not affected, and these emissions are not accounted for in this study
- For the reduction in work trips, the estimated number of jobs provided by the mothership (3,300) was determined by combining the floor areas for each use type (office, retail, restaurants, recreation, schools, and medical facilities) with employment intensity data (Home & Communities Agency, 2015).

5.6. Results and discussion

5.6.1. Building energy use and emissions

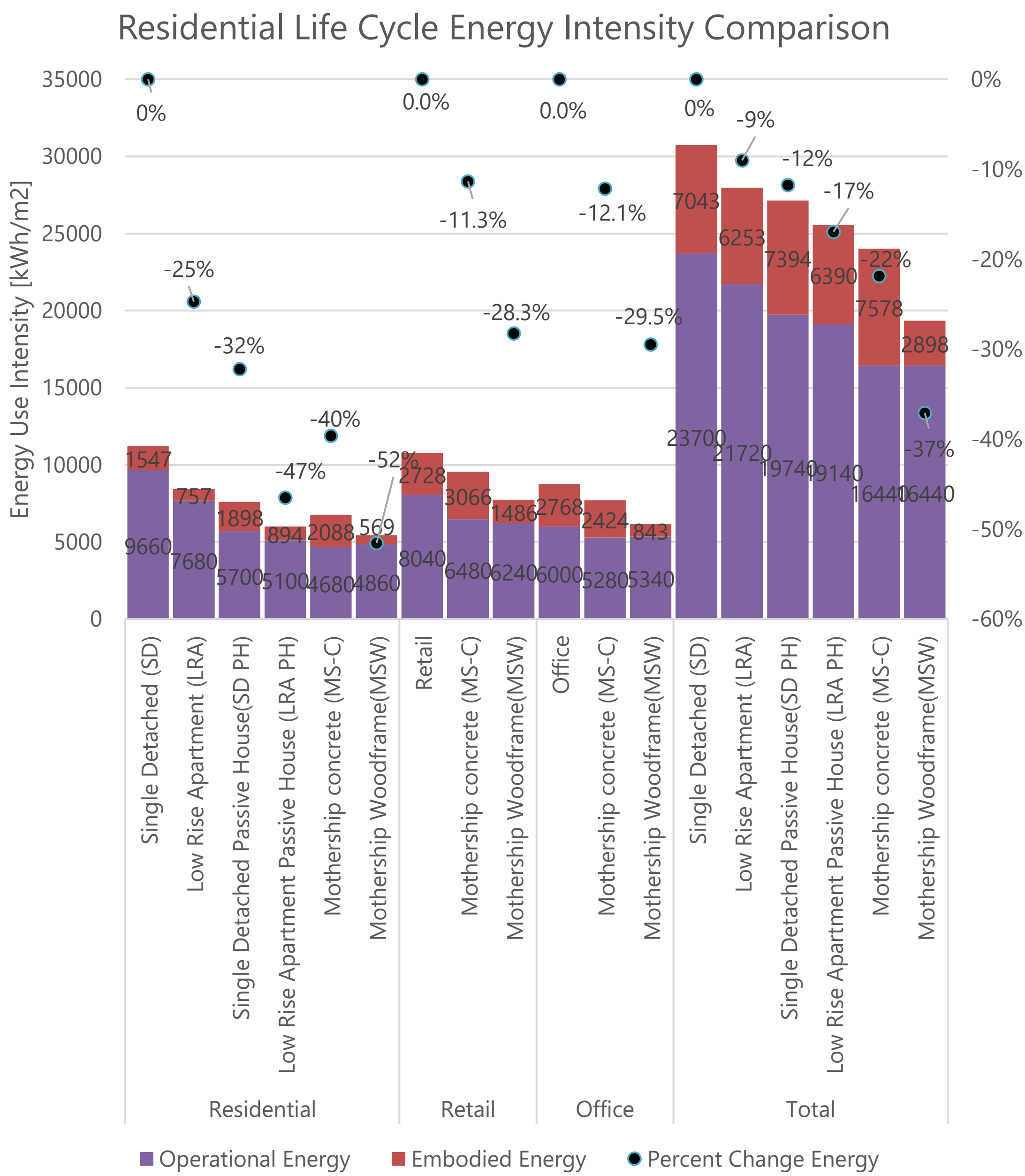

Figure 27: Operational and embodied energy per square meter over the 60-year lifetime for each case. The percentage change is given relative to the base case for each category (the left-hand column in each category). Values are given for the space types individually, then for the combined mixed-use development.

Figure 27 shows the energy intensity for all building space types and for the total combined multi-use developments over a 60-year lifetime. As expected, the operational energy use decreases with increasing density, as well as with increasing insulation levels. The embodied energy also decreases, unless concrete is required due to the building height. The operational energy use does change significantly between the two material choices for the mothership. The operational energy use is very similar between the three retail and office building forms, as these are dominated by internal loads that are less affected by massing, and the base cases have relatively compact building forms. The wood framed mothership reduced operation and embodied energy use by 37% over the base case of single detached homes for the combined mixed-use development. It is important to note the significance of material choices, as the concrete mothership only reduces energy use by 22%, even though the operational energy use is the same as the wood framed variety. This is solely due to the high embodied energy use in concrete. The operational energy use of the highly insulated versions of single detached and apartment buildings performed poorer than expected given the typical energy reductions building to this standard achieves.

Figure 28 shows the life cycle operational and embodied emissions. It is important to note that the operational energy demands are met with heat pumps and low carbon electricity, which is why the operational emissions is so low compared to the embodied emissions. The concrete office, retail and mothership designs perform very poorly, with more than double and in some cases triple the emissions of the timber framed motherships. The concrete mothership had an increase of 7% over the single detached base case in total emissions, despite having a lower operational energy use and emissions. The embodied emissions of the highly insulated versions of the single detached and apartment building use types is slightly higher due to higher levels of insulation and typically higher quality building materials. This is usually overshadowed by the reduction in operational emissions in areas where the grid carbon factor is higher or when natural gas heating systems are used. However, in this case, the nearly carbon free electricity has so few emissions that the change is almost unnoticeable. This illustrates the importance of material choice in buildings when low-carbon electricity is available.

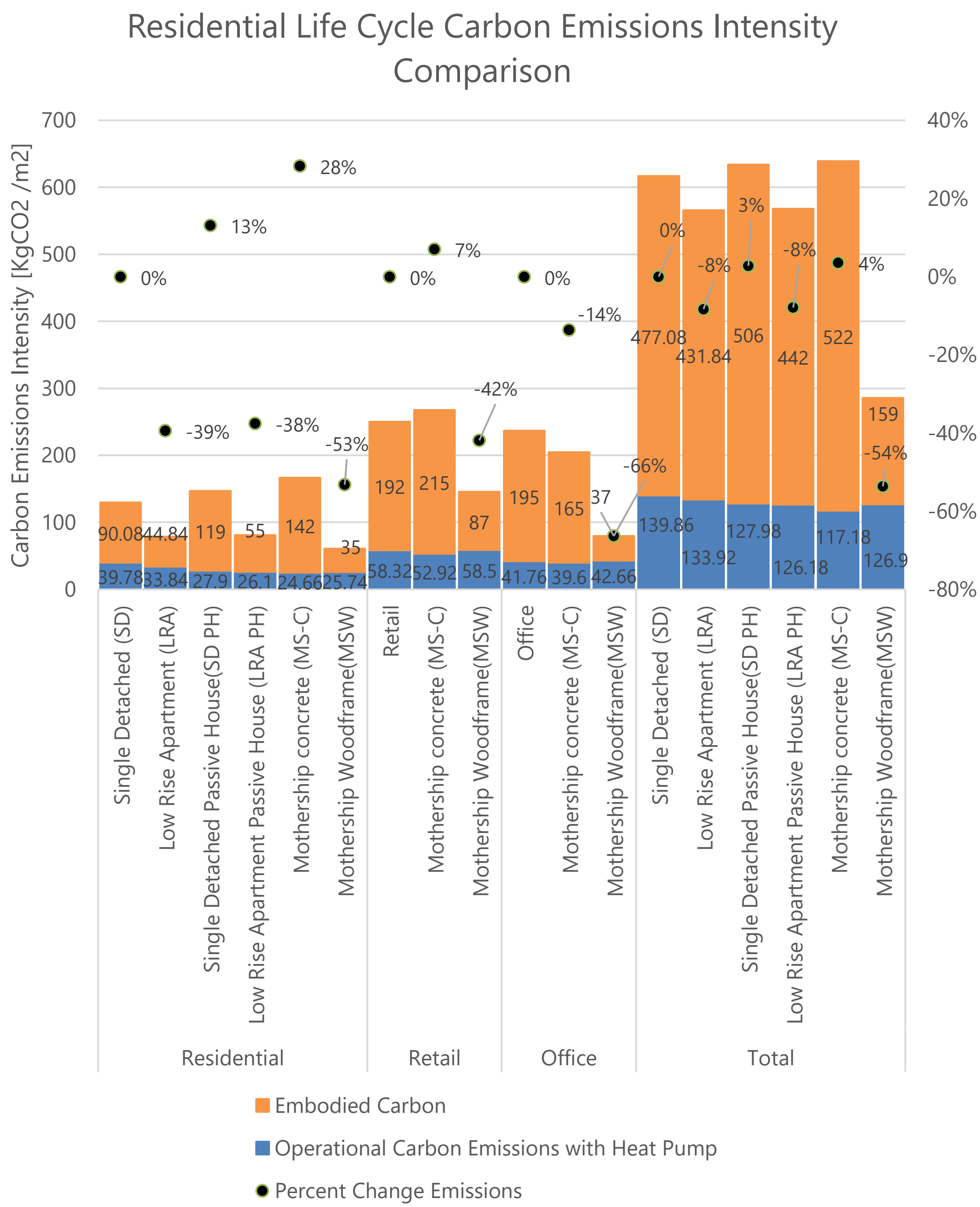

Figure 28: Operational and embodied carbon emissions per square meter over the 60-year lifetime for each case. The percentage change is given relative to the base case for each category (the left-hand column in each category). Values are given for the space types individually, then for the combined mixed-use development. Operational energy use is assumed to be met with heat pumps using low-carbon electricity, so the operational emissions are relatively low.

5.6.2. Climate resilience

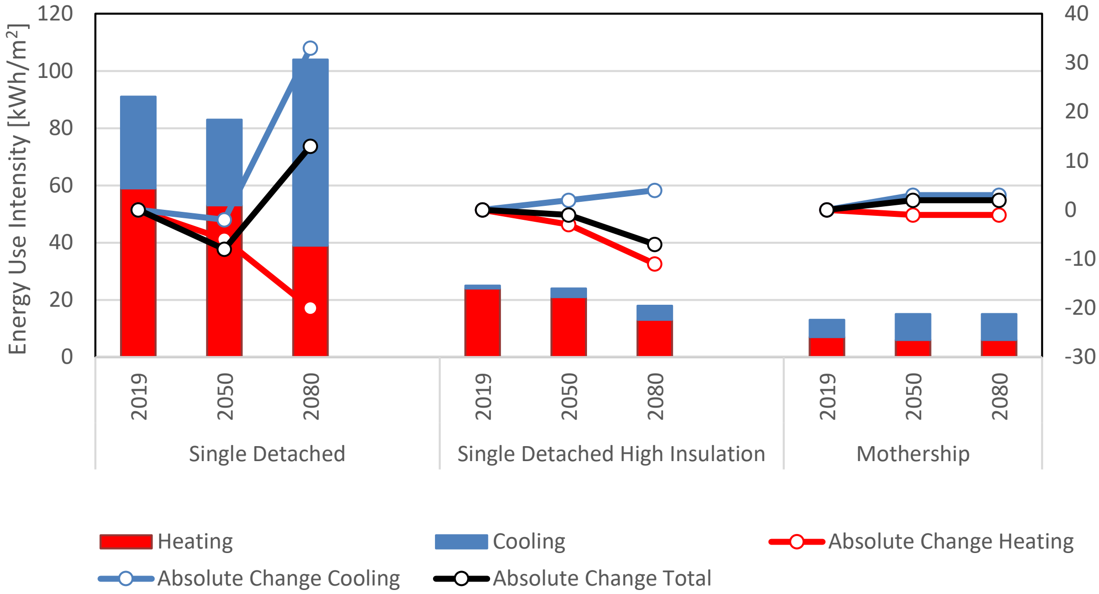

Figure 29: Residential heating and cooling energy intensity for current and future climate scenarios. The percentage change is calculated relative to 2019.

Figure 29 shows how the heating and cooling loads change over time for residential buildings. The absolute changes are calculated relative to 2019. The cooling load increases due to the warming climate, however the heating load decreases. For single detached homes, energy use intensity decreases for 2050, but then increases significantly by 2080 as the decrease in heating load is made up for by increased cooling load. Interestingly the energy use intensity for the highly insulated single detached homes decreases for 2050 and 2080, although the cooling load increases. The energy use intensity of the mothership increases very slightly but remain mostly constant over time.

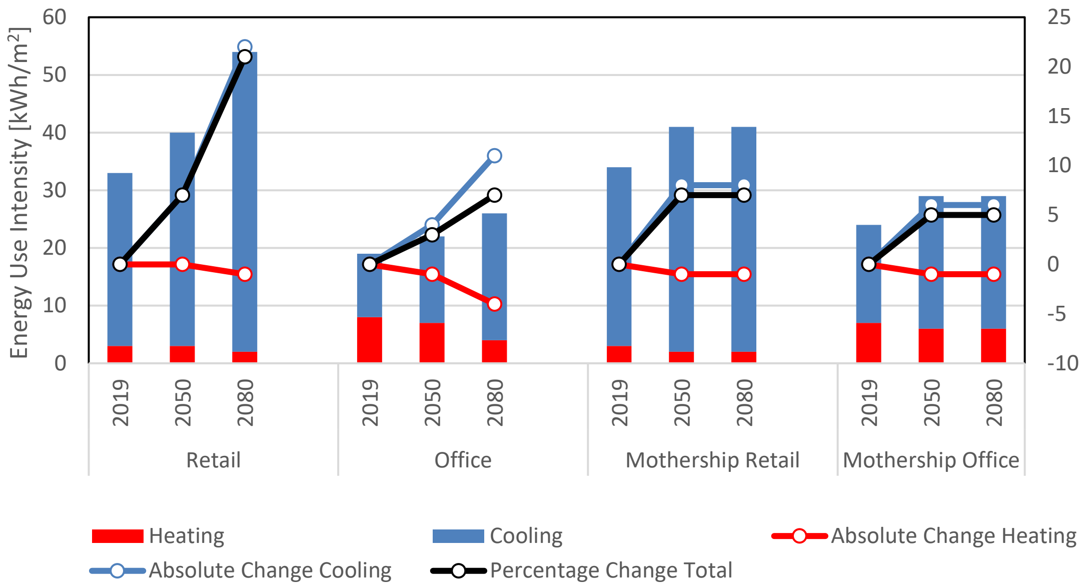

Figure 30: Retail and office heating and cooling energy intensity for current and future climate scenarios. The percentage change is calculated relative to 2019.

Figure 30 shows the heating and cooling load changes over time for retail and office buildings, which are cooling dominated, with little heating needed. The mothership spaces have similar heating loads which don't change much over time, whereas the base cases decrease with as climate warms. Base case cooling load increases with time, whereas mothership cooling load increases for 2050 but remains almost constant for 2080. Mothership office spaces has higher total EUI than the base case, with mothership retail being similar to base case retail, except for 2080 where the base case increases significantly.

Overall, the climate sensitivity analysis results indicate that the mothership is affected by the changing climate, although to a lesser extent than the base cases, especially for the residential spaces.

5.7. Transportation emissions

Table 10:Baseline transportation emissions calculations.

Trip Destination	Trips/Day	km/day	Gas km/day	EV km/day	Gas Emissions [kg CO2/day]	Electricity Emissions BC [kg CO2/day]	Electricity Emissions CA [kg CO2/day]	Total Emissions BC [kg CO2/day]	Total Emissions CA [kg CO2/day]
Work	4,803	21,690	19,521	2,169	4,322	4	61	4,326	4,383
Post Secondary	600	1,092	982	109	218	0	3	218	221
K-12 School	901	1,204	1,083	120	240	0	3	240	243
Personal Business	1,801	7,360	6,624	736	1,467	1	21	1,468	1,487
Recreation/Social	3,302	19,740	17,766	1,974	3,934	4	55	3,937	3,989
Dining/Restaurant	1,201	2,778	2,500	278	554	0	8	554	561
Shopping	3,302	9,383	8,445	938	1,870	2	26	1,871	1,896
Pick-up/Drop-Off	2,402	10,571	9,514	1,057	2,106	2	30	2,108	2,136
Return Home	11,407	41,582	37,424	4,158	8,286	7	116	8,293	8,402
Other	300	13,379	12,041	1,338	2,666	2	37	2,668	2,703
TOTAL	30,020	128,779	115,901	12,878	25,661	23	361	25,685	26,022

Table 10 shows the baseline emissions calculations. The baseline emissions for the base case are estimated to be 25,685kgCO_2/day, or 0.67 tons CO_2/year[3] per resident. This value is for a BC electricity grid, however this only rises to 26,022kgCO_2/day if the Canada-wide grid factor is used, even though we assume 10% EV use in the base case. This is because gas vehicles emit 0.22kgCO_2/km, while EVs emit 0.0018 kgCO_2/km in BC and 0.028 kgCO_2/km using the Canada average, an order of magnitude higher but still an order of magnitude below gas vehicles. Excluding return trips (which account slightly under 50% due to multi-purpose trips), work trips account for 25% of the emissions, with recreation/social at 23%.

Table 11 gives the mixed-use emissions reduction calculations and Table 12 gives the EV car share and BRT emissions reductions calculations. Mixed use reduces 9,860

[3] Note that this only includes weekday travel emissions, as weekend emissions are excluded from this analysis due to lack of input data.

$kgCO_2$/day (38% of emissions) using BC grid factors, with reductions using Canadian grid factor giving similar results (37%). Accounting for further reductions due to EVs and BRT, the resulting emissions for the BC grid factor are 9,903 kgCO2/day, and 10,918 kgCO2/day for the Canadian grid factor, representing overall reductions of 61% and 58% for BC and CA grid factors respectively. It is interesting to note that mixed use reduction has a nearly equal effect at reducing emissions than implementing EVs and BRT. This is important because the buildings are going to be built because of growth, regardless of the design. So, it is logical to design and build them in such a way so that they provide the functions that they were meant to, but also have numerous indirect benefits, such as emissions reduction shown here, but there are others such as reduced congestion and health benefits that were discussed previously. Additionally, these benefits come at the cost of locating multiple use types together, compared with the cost of developing new vehicle technology and installing the required infrastructure. The most emissions efficient car trip is the one that doesn't have to made.

Table 11: Mixed-use transportation emissions reductions calculations.

Trip Destination	Mixed use reduction, %	Emissions Reduction CA [kg CO2/day]	Emissions Reduction BC [kg CO2/day]	New km/day
Work	0.5	2,163	2,191	10845
Post Secondary	0.95	207	210	55
K-12 School	0.95	228	231	60
Personal Business	0	-	-	7360
Recreation/Social	0.5	1,969	1,994	9870
Dining/Restaurant	0.15	83	84	2361
Shopping	0.5	936	948	4692
Pick-up/Drop-Off	0	-	-	10571
Return Home	0.5	4,147	4,201	20791
Other	0	-	-	13379
TOTAL		9,732	9,860	79,983

Table 12: Car share and BRT transportation emissions reductions calculations.

Trip Destination	Gas km/day	EV km/day	Gas Emissions [kg CO2/day]	Electricity Emissions BC [kg CO2/day]	Electricity Emissions CA [kg CO2/day]	Total Emissions BC [kg CO2/day]	Total Emissions CA [kg CO2/day]
Work	4175	4175	2,180	8	117	2,187	2,297
Post Secondary	27	27	6	0	1	6	7
K-12 School	30	30	7	0	1	7	8

Personal Business	3680	3680	815	7	103	821	918
Recreation/Social	4935	4935	1,093	9	138	1,102	1,231
Dining/Restaurant	1181	1181	261	2	33	264	294
Shopping	2346	2346	519	4	66	524	585
Pick-up/Drop-Off	5285	5285	1,170	10	148	1,180	1,318
Return Home	10396	10396	2,302	19	291	2,320	2,593
Other	6689	6689	1,481	12	187	1,493	1,668
TOTAL	38,745	38,745	9,834	70	1,085	9,903	10,918

5.8. Total emissions

To compare the effect that of electricity grid carbon intensity on overall emissions, results are shown for both the British Columbia grid (0.009 $kgCO_2/kWh$) and the Canadian average (0.14 $kgCO_2/kWh$). The emissions reduction for building form is typically tied to the operational energy use, and its heating and cooling system (space and hot water) and whether it emits carbon during operation. The results show that this is not the only significant mode of emissions. In this case there are two scenarios that were studied, both cases use electric heat pumps, but one uses the BC grid factor, and the other uses the Canadian average, which is much higher, but it itself is relatively low. Figure 31 and Figure 32 show the breakdown of lifecycle emissions by source (operational, embodied and transportation emissions and reductions compared to base cases) using the BC and Canadian average electricity grid carbon intensities respectively.

The cases estimate the emissions reductions provided by the increased density of the mothership compared to normally insulated single detached homes, both utilizing electric heat pumps. Both cases have the same lighting and plug loads. Embodied emissions are those associated with the material choices in the building. Transportation emissions are those associated with personal vehicle trips. Mixed use transport reductions are those associated with estimated reductions in personal vehicle trips that the mixed-use nature of the mothership provides versus the typical suburb where there would be some sort of mall or main street that would be driven to. The public transportation emissions are those associated with the saved emissions by having a bus rapid transit line from the mothership (located in Langford for this analysis) into the main job center (downtown Victoria) using dedicated bus lanes and/or other transit prioritization measures. Also included in the transportation emissions section is the effects of implementing an electric vehicle car sharing fleet. The reductions category is the sum of the reductions for each of the categories.

Embodied emissions are relatively insignificant when transportation emissions are considered, only making up 17% of the emissions for single detached homes, and 9% for the mothership in the BC case (8% and 4% respectively for the Canadian case). As density increases and the emissions associated with the building decrease along with energy use, transportation makes up a greater proportion of the remaining emissions. The resulting urban area emissions issue quickly goes from a buildings problem to a transportation problem if clean electricity is available. This illustrates the importance of implementing holistic urban plans where transportation and reducing personal vehicle use is the key issue. Another important point to note is that even if all single detached homes were highly insulated and heating and transport electrically powered with everyone using electric vehicles, it still does not address congestion or health issues that mixed-use developments can.

Figure 31: Emissions breakdowns by source for each urban form and reductions between forms, using the BC carbon factor. The cases are: Single Detached (SD), SD Passive House (SD PH), Low-Rise Apartments (LRA), LRA-PH, Mothership (MS).

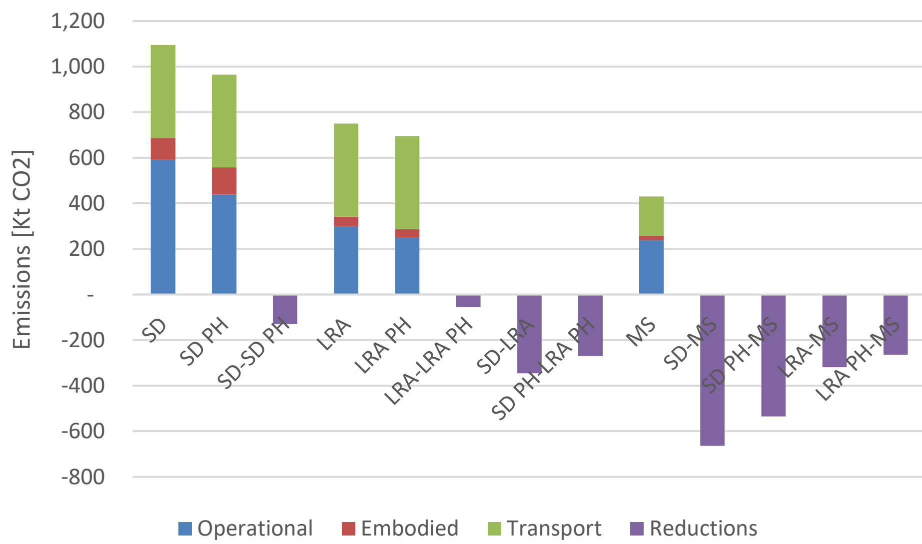

Figure 32: Emissions breakdowns by source for each urban form and reductions between forms, using the Canadian average carbon factor. The cases are: Single Detached (SD), SD Passive House (SD PH), Low-Rise Apartments (LRA), LRA-PH, Mothership (MS).

This results section spends a lot of time discussing emissions, as opposed to energy use. The reason for this is that in a climate change context, the problem stems from carbon emissions, not energy use. Where carbon emissions are directly tied to energy use, then it is logical to prioritize them more equally. However, in locations where grid electricity is low-carbon, then it is much more important to focus on emissions.

It can also be noted that there is a lack of tall building forms. This is because it was found that the higher building densities such as medium and high-rise apartments at 10 and 42 storeys respectively, did not perform better in terms of energy use or carbon than lower forms such as low-rise apartments at five storeys, or the timber framed motherships at 6 storeys. Medium rise apartments had equivalent if not slightly better residential energy use intensity than motherships, however their greater height necessitates concrete for the main building material which drastically increases the embodied energy and carbon. High rise apartment showed significantly higher energy use intensities than motherships or low-rise apartments, despite having a higher residential density (Bowley et al. 2019) [chapter 4 of this thesis]. This suggests that there may exist an optimum floor height that minimizes energy intensity while keeping embodied emissions and energy in check. Alternatively changes in building codes to allow higher mass timber structures.

5.9. Conclusions

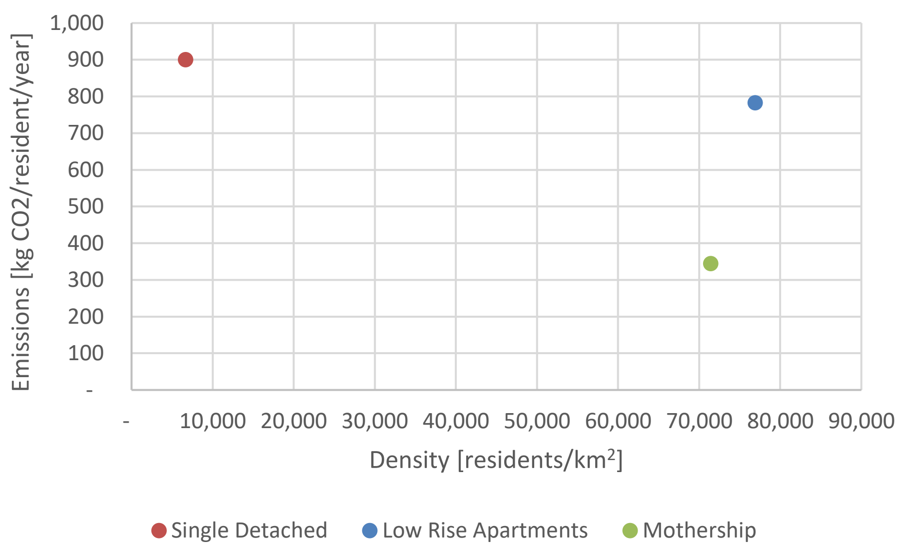

Figure 33: Comparison of the total emissions per resident per year as a function of density (for BC grid emissions intensity).

The analysis presented in this paper looked at a high-density mixed-use development called a Mothership as a potential holistic solution to urban sprawl. Numerous mothership designs were modeled and compared to traditional residential, retail and office use types and building forms. Additionally, a transportation analysis was performed to estimate potential emissions reductions of the mothership based on eliminated vehicle trips resulting from co-locating amenities with residential units and creating a walkable community. Further transportation emissions reductions were estimated based on the implementation of an electric car sharing fleet, and bus rapid transit line being implemented between the mothership and the central business district in downtown Victoria. Building energy reductions of the mothership compared to single detached home base cases of 69% were estimated. The operational and embodied carbon emissions reductions of the mothership compared to single detached homes with electric heat pumps for space conditioning was estimated at 73%. The transportation emissions reductions were estimated at 58%. This gives a total emissions reduction of 61%.

There is much potential for future work in this study. One area would be to explore the relationship between building height, shape and materials to find an optimum combination that minimizes building energy and emissions. There is great potential for future work in looking at the mothership's energy system, and its potential for being a test platform for different energy systems and technologies such as renewable generation, negative emissions generating technology, and electrical and thermal energy storage. Further, there is potential to exploit the complimentary load profiles of the different building use types to make use of excess energy such as heat extracted from server banks in office spaces, to heat water for use in residential units. There is even potential to utilize a battery electric car share fleet as battery storage. To do this, the 'Energy Hub' model formulation will be used (Evins et al. 2014).

The transportation analysis pipeline should also be refined to include weekend and longer journey data, if suitable inputs are available.

One of the main conclusions of this paper is that the relationship between urban form and transportation should be examined alongside the relationship with building energy use. As the electricity grid gets cleaner with the addition of more renewables, the carbon emissions associated with operational energy become a smaller portion of the overall life cycle emissions of the building. As building emissions decrease, transportation emissions increase in significance. Therefore, it is critical that new development be as holistic as possible and attempt to reduce transportation emissions as well as those associated with the built environment. It has been shown that simply locating amenities within walking distance of residences, or in this case co-locating them in a mixed-use development, can have very significant reductions in transportation emissions.

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6. Energy System Optimization of a High-Density Mixed-Use Development

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Wesley Bowley[1], Ralph Evins[1]
[1]University of Victoria

6.1. Abstract

This paper applies the 'energy hub' model to the complex energy system of a high-density mixed-use development, termed a 'mothership', under numerous scenarios. Results are compared to base cases representing standard development approaches. The scenarios explore how the energy system changes in response to a series of design questions, including a carbon tax, net metering, net-zero emissions limits, and negative emissions targets; these are applied in the context of two different electricity grid carbon intensities. Negative carbon options are included by assessing the optimality of bio-char based technologies by extending the energy hub model to include material streams alongside energy streams. Another modelling novelty is the definition of a Storage Utilization Factor, which allows the benefit of each energy storage technology to be quantified.

The base cases show that the annualized cost and total emissions of the standard mothership with a simple energy system are 4 and 8.7 times lower respectively than single detached houses because of the increased efficiency and smaller load of the mothership building type. Of the mothership cases examined, the lowest annualized cost ($2.98M) was achieved with a net zero carbon emissions restriction. Many of the cases had negative operating costs due to the sale of renewable energy or carbon credits. This illustrates that the integration of renewable energy technologies is not only beneficial for reducing emissions but can also act as an income pathway for energy systems. These results give hope that developments may be able to implement low cost solutions that have zero-net emissions.

6.2. Introduction

Urban populations around the world are growing, so cities must expand or densify [United Nations, 2018]. In North America, much of this growth is in the form of urban sprawl. Urban sprawl is characterized by single use type developments, typically single detached homes, where transportation is dominated by personal vehicle use (White et al. 1974). Single detached homes are less energy efficient than other denser forms of housing, due to higher surface area to volume ratio, meaning more area for heat transfer, as well as the greater overall floor area, number of appliances etc. Single dwellings also use more resources to build than higher density residential buildings to house the same number of residents.

In Bowley et al. (2019) [chapter 4 of this thesis] we propose a potential solution: a high-density mixed-use building that we term a Mothership, designed to contain all amenities of a typical suburb for 10,000 residents in one large building. Advantages of this style of building includes reduced surface area for heat transfer, more practical use of high-performance building envelope. There are also many advantages in terms of reduced emissions from transportation: co-location of amenities eliminates many trips, and a public transportation hub and an electric vehicle car share fleet reduce the use of personal vehicles.

The emissions sources of an urban area are largely from building operation, the emissions embodied in the materials of the buildings, and transportation emissions (O'Brien et al. 2010). There are numerous ways to reduce the emissions from thesis sources. High performance building envelopes can reduce heating and cooling loads, which could then be met with renewable energy and heat pumps. The embodied emissions in buildings can be reduced through minimizing the use of cement, either through reducing concrete use, or using supplementary cementitious materials such as fly-ash instead of cement. Transportation emissions could be lowered through numerous ways including public transportation measures, eliminating vehicle trips by creating walkable neighbourhoods, or using electric vehicles powered with clean energy. It is rare however, to reduce these energy demands to zero. Therefore, it is important that these remaining minimized loads be satisfied in the most efficient, cleanest, and cost-effective manner.

There are many potential technologies to choose from, each with advantages and disadvantages, from simple gas boilers and heat pumps to more complex combined heat and power systems. There is potential to implement promising emerging technologies, and even negative emissions technologies that sequester more carbon than they emit. One such technology is char-optimized pyrolysis, which can be used for boilers or combined heat and power plants. Biomass feedstock is heated up in the absence of oxygen, which thermally decomposes the volatile organic compounds, leaving behind the structure of almost pure carbon or char. Depending on the conditions of the pyrolysis, about 50% of the carbon of the feedstock is converted to char (Daugaard and Brown, 2003), which can be use in agriculture (Lehmann et al. 2006, Kuppusamy et al. 2016), water filtration, and other uses. The carbon in this form is recalcitrant, meaning it is stable and will stay in that form for potentially hundreds to thousands of years depending on conditions (Schmidt et al. 2018). As a result, biochar (so called when char applied to soils) producing systems is considered a negative emissions technology by the IPCC if the carbon is sequestered and not subsequently burnt (de Coninck et al. 2018, Werner et al. 2018). The other 50% of the carbon is released as pyrolysis oils and gases that can be combusted for energy and to provide the process heat to perpetuate the pyrolysis.

There is also the potential to integrate renewable energy generation technologies and storage systems in the building. There is a significant roof area for solar collectors, either solar photovoltaic or solar thermal collectors. Different storage technologies such as hot water thermal energy storage, traditional lead acid and lithium ion batteries, compressed air, and hydrogen. Some technologies like hydrogen, do have a higher cost, but have the additional advantage that you can also sell the hydrogen as well as store it, providing an additional income stream.

In this paper, we explore the benefits of high-density mixed-use development related to the energy systems that provide power and heat, with the mothership serving as an example of any form of high-density mixed-use development. The size of the loads and the range of different demand profiles present can enable district-scale energy systems that aid renewable energy integration, without the expense and complexity of traditional district heating networks. Because one energy system can serve the development, combinations of multiple technologies can be used, whereas for single buildings this would be impractical.

However, this makes it more challenging to find the correct combination and sizes of technologies that provide a balance between the most cost-effective option and the option with the lowest carbon emissions. This cannot be determined in advance without examining the hour-by-hour requirements and availability of many different energy streams. The ‘energy hub’ model formulation (Evins et al. 2014) is used to achieve this, by optimizing a proposed energy system for the predicted loads of the mothership. This is conducted as a multi-objective optimisation that can explore the balance between the lowest overall cost and low carbon emissions for a variety of options.

In addition to finding the optimal energy system design for a general case, additional scenarios are explored to see how this optimum changes in response to these additional constraints. These scenarios will be constructed to answer the following questions:

- What is the most cost-effective energy system to meet the required loads?
- What is the optimal capacity of solar PV or solar thermal? Is the rooftop area sufficient or would more space be desirable?
- Does seasonal storage at this scale make sense? Would the storage size be too large to be practical?
- What is the impact of hydrogen production and storage? Is it used for storage or for export?
- Do biochar technologies get used? What is the impact of carbon negative power and heat production?
- What is the impact of a strict carbon budget, such as being net-zero carbon? What if a negative carbon budget was enforced, meaning that carbon is sequestered each year?
- What is the effect of carbon credits and carbon taxes? What is the threshold for fossil fuels to be avoided?

This paper presents a comprehensive analysis of the energy systems options available for a large high-density mixed-use development, and propose new developments to the energy hub model formulation to facilitate this. The new developments are the formulation of a storage utilization factor, to describe how much a storage technology is used in the system, and the use of materials streams alongside energy streams, to capture the benefit of carbon-positive technologies. These are detailed in the methodology section. Next, we first establish a reference case based on a standard expansive single-dwelling development, then compare this to various high-density cases using the mothership concept as an example. We examine the impact of many different exogenous factors such as carbon taxes and technology availability that affect the optimal system configuration, assessing the differences in cost and emissions. Finally, conclusions are drawn regarding the performance of different energy systems options for a high-density mixed-use development.

6.3. Literature review

Multi-objective optimization applied to energy-related aspects of building design is becoming more common as a process to lower costs, energy use and emissions (Evins, 2013). This can be used to vary many properties of the buildings themselves, for example envelope properties, massing and glazing areas. However, often such decisions are taken for aesthetic or practical reasons, which are hard to incorporate into a computational analysis.

Complex buildings with a mix of uses, complex energy systems or finite renewable sources of energy require an optimization process that can balance demands and supplies of energy at each moment. One method for doing this is the 'energy hub' model originally proposed by (Geidl and Andersen, 2007). This uses mixed integer linear programming (MILP) to find combinations of technologies (renewable generation, storage, energy converters, etc.) that best meet a specified design goal defined by the objective function. More recent work (Evins et al. 2014) has extended the model formulation.

Energy hubs and similar models have been used many times before. Krause et al (2011) discuss how energy hubs can be used to optimize energy systems in a variety of scenarios with multiple energy carriers. They also discuss some of the benefits of using this model framework. Brahman et al (2015) apply an energy hub to a residential building, integrated electric vehicle charging and other types of demands. Best et al (2015) models and optimizes the energy systems for an urban area using a similar model to the energy hub. Orehounig et al (2015) use the energy hub model to decentralized energy system at neighbourhood scale. These works use the same or similar energy hub models to similar situations (large residential buildings, district energy network with multiple energy types) however, they are not at a smaller scale than the work in this paper.

There are other methods that can be used to model district energy systems other than energy hub, as reviewed in Allegrini et al, (2015). Mathematical programming tools can be used such as mixed integer linear programs (MILP) as in Weber and Shah (2011). Mixed integer non linear programming can also be used to model non linear systems in the same way, as demonstrated in Pruitt et al, (2013).

Another popular tool that has been around for decades is 'TRNSYS' which is used to simulate the behavior of transient systems. It was designed for modeling solar thermal systems but has expanded to thermal and electrical systems in general and has many packages that specialize in modeling different system types. It is not designed to model energy flows at a district or urban scale however. Torío and Schmidt (2010) use exergy analysis in TRNSYS to improve the efficiency of a district heating network.

Modelica is a relatively newer tool which uses a system of equations modeling approach to solve complex problems that can different time scales. Schweiger at al. (2017) introduce a Modelica framework for simulating 4th generation district heating systems and show how it is well suited for large scale systems.

One of the more novel aspects of this work is that a material flow is integrated into the energy hub model for biochar, the solid product of slow pyrolysis of biomass. Biochar combined heat and power plant is included in the model in order to produce biochar can be sold for financial gain and sequester carbon, Biochar production systems have been modeled before, for example, Ubando. at al. (2014) used fuzzy mixed integer linear programming to optimize a multi-functional bioenergy system with biochar for carbon sequestration. The integration of biochar as a material flow into energy hub has not been done before.

This work focuses on applying an energy hub model to a large mixed-use building which combines load patterns from residential, retail, and office spaces together. It also introduces a material flow, rather than only energy flows, to the model, and defines a storage utilization factor to track the benefit of storages in the system.

6.4. Methods

This analysis uses an energy hub model to explore the design goals of low costs but also low carbon emissions. The analysis process is outlined in Figure 36. First, heating, cooling, appliance, lighting, and hot water loads for proposed designs are obtained using the Urban Modeling Interface (UMI) (Reinhart et al. 2013), using geometries defined in Grasshopper (Grasshopper3d, 2019), a parametric extension of the Rhinoceros 5 (Rhino3d, 2019) CAD software. These hourly-resolution annual time series (summarized in Table 15) are then used as loads that need to be satisfied in energy hub models. The full time series for the combined loads of single detached, retail and office spaces, and the mothership are show in Figure 34 and Figure 35 respectively. Table 13 lists the dimensions of the building designs used in the analysis. Table 14 lists the important building parameters used in the applied templates. Single detached, retail and office spaces use the values in the "BC Building Code" template, and the mothership uses the values in the "Passive House" template. The general shape of the single detached, retail and office buildings are rectangular, and each use type are separate buildings. The mothership is in the shape of a ring with the majority of the first floor being retail, the majority of the second floor being office space, and floors 3 through 6 being residential.

Table 13 The important dimensions of the buildings and how many of each there are.

	X Dimension [m]	Y Dimension [m]	Height [m]	Inner Radius [m]	Outer Radius [m]	Number of Residential	Number of Retail Floors	Number of Office Floors	Number of Buildings	Total Building Area [m2]
Single Detached (SD)	10	10	6	n/a	n/a	2	0	0	4160	832,000
Retail	91	91	18	n/a	n/a	0	6	6	1	50,000
Office	91	91	18	n/a	n/a	0	6	6	1	50,000
Mothership	n/a	n/a	18	137	214	4	1	1	1	506,940

Table 14 Shows the important parameters used in the building templates. Single detached, retail and office buildings use the "BC Building Code" template, and the mothership uses the "Passive House" template.

Parameter	BC Building Code	Passive House (PH)
Wall Insulation U-Value, W/m²K	0.05	0.022
Roof Insulation U-Value, W/m²K	0.066	0.022
Floor Insulation U-Value, W/m²K	0.08	0.17
Window U-Value, W/m²K	0.5	0.22
Infiltration Rate, AC/h	0.35	0.35
Ventilation Rate, AC/h	0.6	0.6
Heating Set Point, °C	20	20
Cooling Set Point, °C	24	24

Heating System CoP	1	1
Cooling System CoP	1	1
Heat recovery Ventilator Efficiency	N/A	90%

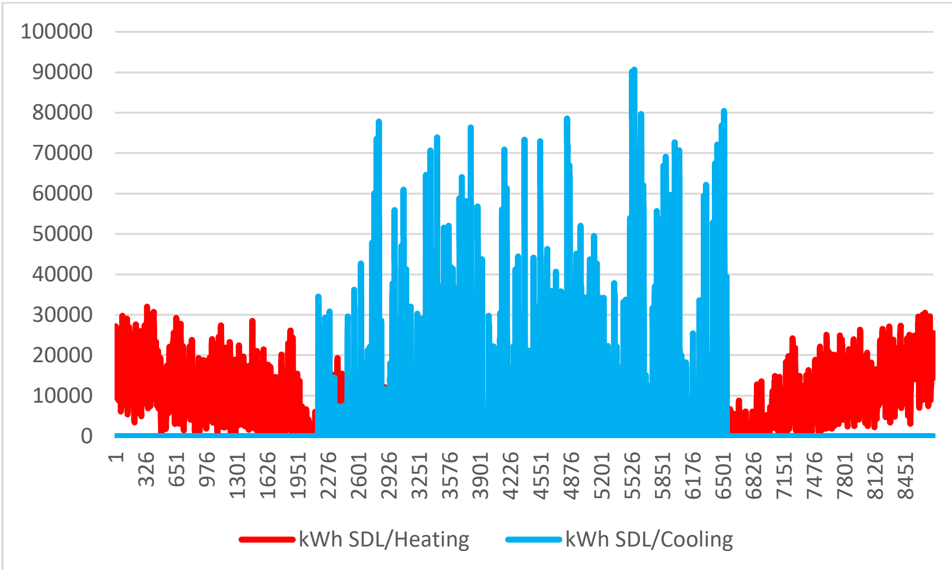

Figure 34 Annual heating and cooling demand for the combined single detached homes and retail and office buildings.

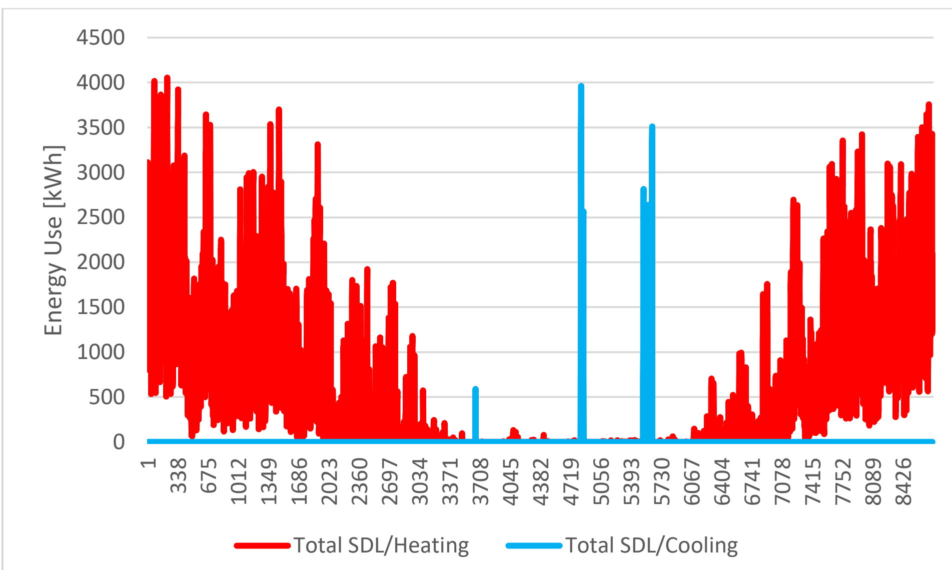

Figure 35 Annual heating and cooling demand for the mothership building.

Table 15: The annual sum and peak loads for the different load types for the base case buildings and the mothership.

		Heating	Cooling	Hot Water	Lighting	Equipmen t
Individual Single Detached	Sum [kWh]	13,609	8,186	8,099	2,708	3,278

	Peak [kW]	8	37	4	1	1
Retail	Sum [kWh]	249,245	1,412,942	287,988	3,442,240	1,290,840
	Peak [kW]	975	1,767	82	800	300
Office	Sum [kWh]	1,290,247	8,817	762,187	1,945,200	1,348,800
	Peak [kW]	923	786	285	600	400
All Single detached with Retail and Office	Sum [kWh]	58,154,750	35,476,825	34,741,709	16,651,056	16,277,784
	Peak [kW]	34,804	153,616	18,678	5,319	3,628
Mothership	Sum [kWh]	4,315,693	1,295,663	17,493,837	10,943,972	9,321,953
	Peak [kW]	4,161	5,201	9,223	2,940	1,927

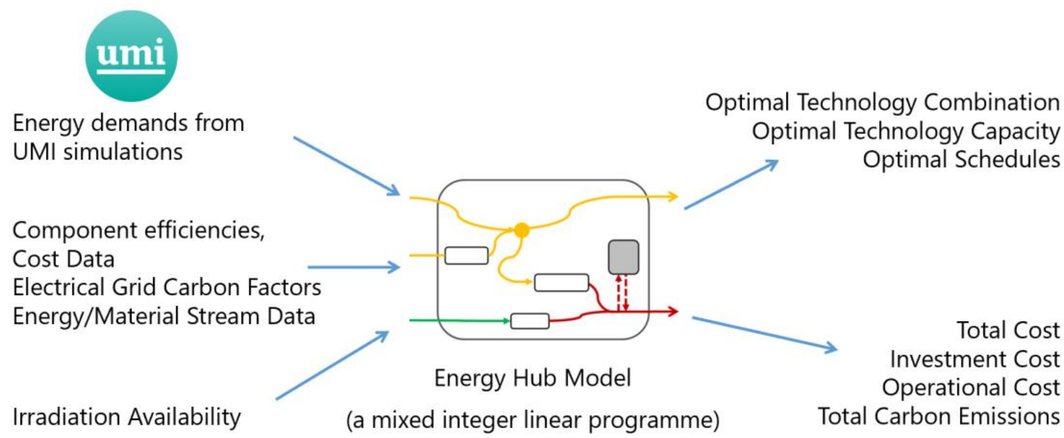

Figure 36: Analysis flow chart, showing inputs on the right and outputs on the left.

6.4.1. Energy hub models

This paper uses the general energy hub model formulation of (Evins et al 2014), which is outlined in the equations below. Additions to the model for this paper are covered in subsequent sections. Overall the model balances energy demands that need to be met at each time step using energy sources such as grid electricity, natural gas, solar radiation, etc. In between there are technologies which convert one energy stream into one or more other streams. There are also storage technologies which can store a specific energy streams for later use. The model formulates these balances as a system of linear constraints to an optimization problem, in this case to minimize cost or carbon emissions. This problem is then solved using Mixed-Integer Linear Programming (MILP) as explained in the implementation details below.

The key equations and constraints are outlined below (with slightly updated nomenclature from Evins et al 2014).

$$\text{Cost} = \sum_{t,j} p_j P_j(t) + AEC\left(\sum_j C_j P_j^{capacity} + \sum_k C_k E_k^{capacity}\right) \quad (1a)$$
$$\text{Emissions} = \sum_{t,j} F_j P_j(t) \quad (1b)$$

Equations 1a and 1b define the two possible objective functions of the optimization problem, to minimize costs and carbon emissions respectively. In 1a the operating cost is the energy input *P* times price *p*, summed over all converters *j* in the system and all time steps *t*, plus annual equivalent cost (AEC) of the capital costs, which multiply capacities by costs *C* for all converters *j* and storages *k*. In 1b the total carbon emissions are calculated from the energy inputs and the emissions factor *F* associated with that energy stream.

$$L_i(t) = \theta_{i,j} P_j(t) + \epsilon_k^- Q_k^-(t) - \varepsilon_k^+ Q_k^+(t) \quad (2)$$

Equation 2 is the core energy balance, stating that the load L to be met must equal the output from each converter (input energy *P* times the efficiency θ), energy from storage (discharge Q^- times discharge efficiency ε^-) minus the energy used to charge the storage (charge Q^+ times charging efficiency ε^+).

$$\frac{P_j(t)}{P_j^{capacity}} \leq I_j^{max}(t) \quad (3)$$

The availability of energy is sometimes limited, for example irradiation to PV panels, which is defined as a time series *I* in equation 3.

$$E_k(t+1) = (1-\eta_k)E_k(t) + Q_k^+(t) - Q_k^-(t) \quad (4)$$

Equation 4 enforces the storage continuity: the state of the storage *E* is equal to the state at the last time step (minus the decay loss η) plus any charge minus any discharge.

$$0 \leq P_j(t) \leq P_j^{capacity} \quad (5)$$
$$0 \leq E_k(t) \leq E_k^{capacity} \quad (6)$$
$$0 \leq Q_k^-(t) \leq Q_k^{-max} \quad (7)$$
$$0 \leq Q_k^+(t) \leq Q_k^{+max} \quad (8)$$

Equations 5 and 6 ensure that converters and storages operate below their capacities, and Equations 7 and 8 do the same for storage charging and discharging rates.

$$0 \leq P_j^{capacity} \leq P_j^{capacity\ limit} \quad (9)$$

Finally, Equation 9 turns the capacities of converters into optimization variables themselves, which can be varied up to a fixed capacity limit.

Minimum loads were not included, as the model formulation required for this increases the model runtime dramatically (see [Evins et al 2014]). Fixed capital costs and maintenance costs were also not included, though could be easily incorporated in Equation 1a. Storage capacities are fixed rather than optimized. Ideally, the capacity of the storage technologies would be optimized along with the converter capacities. However, the computational time of the model goes up dramatically with the addition of more storage technologies. This is because the storage equations mean that the energy flows at each time step are dependent on storage state at the previous and next steps, so the model takes a very long time assessing whether it is better to store the energy for later use or not. Giving wide capacity ranges for multiple storages with different efficiencies and costs makes this problem much more convoluted. The run time for the hard-coded storage capacity models are many orders of magnitude shorter. The cost of the unused portion of each storage technology is subtracted from the total cost after the optimization is completed. This is not a true replacement for an optimization in which the storage capacity is a variable to be optimized, but it is a reasonable approximation that retains a reasonable run time.

The energy hub models in this paper are implemented in PyEHub[4]. PyEHub is an energy hub modelling library written in Python that forms part of the Building Energy Simulation, and Optimization and Surrogate (BESOS) modeling platform[5]. PyEHub performs MILP optimization using IBM CPlex via intermediate python libraries (PyLP and PULP).

6.4.2. Storage utilization factor

In order to evaluate the utility of storage technologies in the energy system, including how much they were used, we define a 'storage utilization factor' (SUF) as the sum of the discharge from the storage (kWh) for each hour of the year, divided by the capacity of the storage technology (kWh).

$$SUF_i = \frac{\sum_t Q_-^i}{E_{max}^i} \tag{11}$$

This factor, which is analogous to the capacity factor used for renewable generation technologies, gives an indication of how much the storage is used. For example, SUF=100 means that overall the storage discharges fully 100 times per year, or cycles from full to 50% and back 200 times per year. Larger values indicate that the storage is being utilized more, however it does not indicate the manner in which it is used (lots of short charging and discharging cycles, or fewer larger ones), nor the effectiveness of this utilization at reducing costs.

6.4.3. Materials streams

This paper extends the energy balancing and conversion performed in the energy hub model to include a material stream for a carbon-negative material called *char*. Carbonization uses the same underlying pyrolysis process as gasification, but is optimized for different purposes, with gasification producing mostly gas and carbonization producing a charcoal-like product called char. The advantage of gasification is that nearly all the biomass is consumed in the process and converted to energy, meaning solid waste is low

[4] See https://gitlab.com/energyincities/python-ehub/.

[5] See https://besos.uvic.ca.

and energy per unit feedstock is relatively high. However, there are still carbon emissions associated with this process, even though many would consider it carbon neutral. Carbonization, depending on the feedstock and the process parameters, converts about 50% of the carbon from the biomass into the char; the other half is eventually converted into carbon. As a result, the energy produced per unit of feedstock is lower, but the carbon in the char is recalcitrant, meaning it is stable and won't be released into the atmosphere over time. This provides interesting opportunities to get carbon credits as part of the revenue stream as well as selling the char itself. Carbonization does have the downside that it requires more feedstock than gasification, because it doesn't utilize it entirely for energy. Both gasification and carbonization systems are included as the potential technologies. Char can be sold as an export for financial and carbon credit in the model.

6.5. Analysis cases

In this paper, we compare a standard low-rise expansive development without advanced energy systems with the energy systems options available for a high-density mixed-use case, using the mothership as an example of the latter. Both cases consist of residential space for 10,000 people, plus 50,000m^2 each of retail and office space.

Each of these building types will have individual energy hub models, and in the single detached case, the results will be scaled based on the number of homes that are required. For the mothership case, there will be one model for the combined residential, retail and office spaces, since they are all in the same building. The retail and office floor area in the base case and the mothership are the same. The residential floor area is not, because the floor area per resident ratio for single detached homes is much higher than that for apartment style residential spaces.

The configuration of the energy system to be optimized for the mothership is shown in Figure 37, giving all possible converters (orange) and storage technologies (green) along with the energy and material streams that connect them. This configuration is defined by the inputs to the energy hub model that govern the input and output streams of each converter and storage, which are discussed in more detail in the following sections.

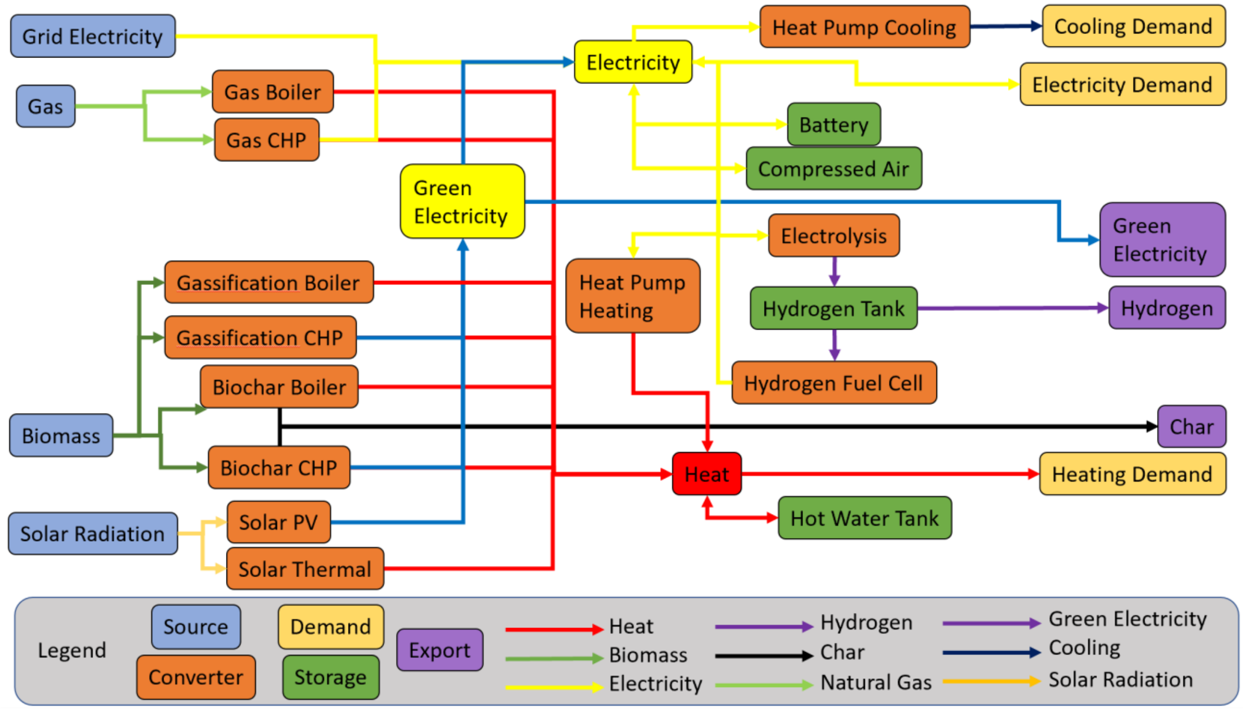

Figure 37: The configuration of the overall system to be optimized using the energy hub model, showing all possible storage and conversion technologies, as well as the different energy and material streams and how they are connected. Blue boxes on the left indicate input energy streams that are converted (orange boxes) and stored (green boxes), eventually to supply the demands in the tan coloured boxes on the right. The purple boxes indicate exports that can be sold to provide income and carbon credits. The lines indicate energy or material flows. The technologies shown are all those available for the model – not all are used in the optimal solutions.

6.5.1. Converters

Converters are technologies that change energy (or in this case also materials) from one form to another. Table 16 gives the properties of the converters included in the model. Many typical technologies are provided, including heat pumps, gas boilers, gas-powered combined heat and power (CHP) systems, photovoltaic (PV) panels and solar thermal collectors. These are relatively common and mature technologies. Other technologies that are less mature include biomass gasification (for a boiler or CHP) and hydrogen electrolyzer and fuel cell components. Finally, the highly novel carbonization technologies are included to generate heat for a boiler or CHP system as well as making carbon-negative char as an output.

Table 16 shows the capital cost per kW capacity of each technology (*C* in Equation 1a), the efficiency (θ in Equation 2), the lifetime used to calculate the Annual Equivalent Cost, the input energy stream, the output energy stream(s), and the maximum capacity ($P^{capacity\text{-}limit}$ in Equation 9). If more than one output stream is produced by the converter, the ratio is given in brackets, for example the CHP produces 1.73 units of heat for every unit of electricity. There is no maximum capacity for technologies[6], except for PV and solar thermal capacity which is limited by roof area depending the scenario.

[6] For technical reasons, a capacity constraint of 999,999,999 kW is used to avoid unbounded variables. This limit is never reached.

	Capital cost ($/kW)	Efficiency	Lifetime (years)	Input	Output(s) (output ratio in brackets)
Grid connection	0.1	1	1000	Grid purchase	Elec
Air-source Heat Pump	1400	3.2	20	Elec	Heat
Chiller	1500	3.2	20	Elec	Cooling
Gas Boiler	500	0.94	30	Gas	Heat
MicroCHP	3400	0.7	20	Gas	Heat (1), Elec (0.16)
PV panels	2000	1[7]	20	Irradiation	Green Elec
Solar thermal panels	2000	1.5	35	Irradiation	Heat
CHP	2275	0.3	20	Gas	Elec (1), Heat (1.73)
Ground-source Heat Pump	2777	6	50	Elec	Heat
Biomass CHP	6227	0.3	20	Biomass (Gasification)	Green Elec (1), Heat (1.2)
Biomass Boiler	4567	0.85	30	Biomass (Gasification)	Heat
Biochar Boiler	5023	0.75	30	Biomass (Pyrolysis)	Heat (1), Char (0.07)
Biochar CHP	6850	0.29	20	Biomass (Pyrolysis)	Green Elec (1), Heat (2.3), Char (0.2)
Electrolyser	5902	0.92	15	Elec	Hydrogen
Hydrogen Fuel Cell	4719	0.4	15	Hydrogen	Elec

Table 16: Converter technology properties. If more than one output stream is produced by the converter, the ratio is given in brackets, for example the CHP produces 1.73 units of heat for every unit of electricity.

6.5.2. Storage technologies

The storage technologies that could be used in the model are shown in Table 17. The five options used standard lead-acid and lithium-ion batteries, a hot water tank, and more novel options like compressed air storage and a hydrogen storage tank. The table gives the stream that the technology can store, capital cost per kWh capacity of each technology (*C* in Equation 1a), the lifetime used to calculate the Annual Equivalent Cost, the efficiencies (ε^+ ,ε^- and η in Equations 2 and 4), and the maximum charge and discharge rates ($Q^{-\,max}$ and $Q^{+\,max}$ in Equations 7 and 8). As discussed in the previous section, costs are updated after the optimization to remove the cost of any unused storage capacity.

	Lead-Acid battery	Li-Ion battery	Hot water	Compressed air	Hydrogen
Energy Stream	Elec	Elec	Heat	Elec	Hydrogen
Capacity (kWh)	10000	10000	26900000	10000	10000
Capital cost ($/kWh)	390	272	1.33	78	20
Lifetime (years)	20	10	20	30	20
Charging efficiency	0.99	0.8	0.99	0.8	0.75
Discharging efficiency	0.99	1	0.99	1	1

[7] = 1.038 kW_{peak}/m^2 * 20 panel efficiency*0.9 system efficiency*5.56 m^2/kwh installed capacity

Decay efficiency	0.001	0.001	0.001	0.001	0
Max charging rate	0.3	0.3	0.3	0.5	1
Max discharging rate	0.3	0.3	0.3	0.5	1

Table 17: Storage technology properties.

6.5.3. Streams

The streams that are used in this analysis are show in Table 18. Streams are flows of energy or materials that are converted or stored by one of the converters or storages respectively. They can also be imported or exported, as indicated by the presence of purchase price / carbon factor values and export price / carbon credit values respectively.

The grid carbon factor for the simulations was the Canadian average, which is still relatively low at 0.14 kg CO_2/kWh. Electricity produced by PV panels, biomass CHP or biochar CHP is denoted 'Green Elec', meaning that if it is exported it receives a carbon credit. Hydrogen can also be exported for hydrogen powered vehicles and receives a carbon credit equal to the carbon intensity of natural gas. Units are calculated in kWh, so all streams are assessed in terms of energy content rather than for example by weight.

Name	**Grid purchase**	**Gas**	**Green Elec**	**Biomass (Gasification)**	**Biomass (Pyrolysis)**	**Char**	**Hydrogen**
Purchase price ($/kWh)	0.14	0.038		0.04	0.04		
Export price ($/kWh)			0.14			1.266	0.469
Carbon factor (kg CO_2/kWh)	0.14	0.21		0	0		
Carbon credit (kg CO_2/kWh)			0.14			2.6	0.14

Table 18: Energy and material stream properties.

6.5.4. Scenarios

Base case

There are three different base cases to compare the mothership scenarios against:

A. This case takes scaled peak and total heat, electrical, and cooling loads for a single-family house and sizes a gas boiler, grid connection and electric chiller to those loads and calculates the associated costs and emissions. The loads for a single house are scaled by 4160 to represent the same number of occupants as the mothership, and this is added to the loads for retail and office base case buildings. There is no PV or storage installed, the Canadian grid factor is used, and there is no carbon tax or carbon credit. This case represents 'business as usual' for low-density development with basic energy systems and no optimization.
B. This case uses the same loads as Case A, but runs separate optimization models for a single detached, office and retail building. The results for an individual single

detached home are then scaled like Case A and added to the retail and office loads. Storages are installed (1000kWh for each building), and PV is also allowed.

C. This case uses the mothership loads, and satisfies them with the same basic energy systems as Case A (gas boilers, grid electricity and electric chiller, with no PV or storage installed). This case represents the mothership high-density mixed-use concept with a basic energy system, to determine the relative benefits of the development concept and the energy system optimization.

Mothership cases

Below are the main scenarios to be explored in addition to the base cases, to address the questions posed in the introduction:

1. **Small storages:** 1,000 kWh each; Roof area PV capacity of 16,000 kW[8].
2. **Big storages:** Same as Case 1, but with the storage capacities listed in Table 15.
3. **Net-zero**: Same as Case 2 with maximum emissions of 0 $kgCO_2/a$, i.e. net-zero operational emissions.
4. **Carbon negative:** Same as Case 2 with maximum emissions of -10,000,000 $kgCO_2/a$, i.e. sequestering or offsetting one ton of CO_2 per resident per year.
5. **Net-zero with net metering:** Same as Case 3, but with the constraint that yearly electricity exports must be equal to or less than grid imports.
6. **Carbon tax:** Same as Case 2 but with a carbon tax of \$200/t CO_2.
7. **BC grid factor:** Same as Case 2, with a grid carbon factor of 0.009 tCO_2/MWh.
8. **BC grid factor, carbon tax:** Same as Case 7 but with a \$200/t CO_2 carbon tax.
9. **BC grid factor, hydrogen export:** Same as Case 7, but with hydrogen exportable at \$0.2/kWh
10. **BC grid factor, net metering:** Same as Case 7, but with the constraint that exported electricity can't be higher than grid imports.
11. **BC grid factor, net-zero:** Same as Case 7, but with maximum emissions of 0 $kgCO_2/a$.

6.6. Results

Table 19*: Results of the energy system optimization giving the metrics of cost and emissions and the optimal converter capacities, as well as the important input parameters that change between each case. The Retail, Office and Single detached cases are the optimization results for individual building loads. Results are given for Base Cases A, B, and C and Scenarios 1 - 11.*

[8] 50,000 m^2 roof area, 1.6 m^2/panel, 300 W/panel.

	Total Cost, $M	Total Carbon Emissions, Mkg CO2	Operating Cost, $M/a	Investment Cost, $M	Lead-Acid SUF	Li-Ion SUF	Compressed air SUF	Hot water SUF	BioCharCHP Capacity, kW	Grid Capacity, kW	HP cooling Capacity, kW	GSHP Capacity, kW	MicroCHP Capacity, kW	Gas Boiler	PV Capacity, kW	GreenElec Carbon Credit, kgCO2/kWh	Hydrogen Carbon Credit, kgCO2/kWh	Gas Cost, $/kWh	Grid Cost, $/kWh	Hydrogen Export Price, $/kWh
Retail	0.75	0.71	0.18	0.61	334	10	21	1,203	-	1,127	332	192	350	-	1,500	0.14	0.14	0.04	0.14	-
Office	0.57	0.52	0.01	0.57	226	51	77	231	-	835	151	102	360	-	1,500	0.14	0.14	0.04	0.14	-
Single detached	0.00	- 0.00	- 0.00	0.09	2.6	-	-	5.4	-	3.2	6.8	0.8	1.8	-	74,880	0.14	0.14	0.04	0.14	-
Base Case A	19.78	26.92	9.92	9.86					-	580	48,005	-	-	56,896	77,880	0.14	0.14	0.04	0.14	-
Base Case B	21.37	- 0.96	- 13.54	34.91					-	15,269	28,757	3,418	8,220	-	######	0.14	0.14	0.04	0.14	-
Base Case C	4.66	7.77	3.78	0.88					-	6,492	1,625	-	-	14,238	-	0.14	0.14	0.04	0.14	-
1 Small storages	3.53	2.10	- 1.38	4.91	273	230	239	831	-	4,210	1,237	2,061	2,610	-	16,000	0.14	0.14	0.04	0.14	-
2 Big storage	3.45	3.59	- 2.18	9.42	362	17	21	0.47	-	2,783	1,237	552	3,765	-	16,000	0.14	0.14	0.04	0.14	-
3 Net zero	3.57	-	- 3.55	10.91	359	21	19	0.47	2,173	2,794	1,237	533	3,721	-	16,000	0.14	0.14	0.04	0.14	-
4 Carbon negative	3.96	- 10.00	- 7.40	15.12	352	25	24	0.47	-	2,791	1,237	478	3,648	-	16,000	0.14	0.14	0.04	0.14	-
5 Net zero, net metering	3.65	-	- 0.17	8.11	145	-	-	0.40	3,479	3,726	1,237	542	2,405	-	-	0.14	0.14	0.04	0.14	-
6 Carbon tax	4.22	- 0.04	0.20	8.13	285	-	-	0.42	-	5,496	1,237	629	-	-	-	0.14	0.14	0.08	0.17	-
7 BC grid factor	3.37	6.64	- 2.18	9.40	361	15	20	0.46	-	2,811	1,237	551	3,724	-	16,000	0.01	0.21	0.04	0.12	-
8 BC grid factor, carbon tax	3.46	- 3.21	- 0.16	8.13	-	-	-	0.40	-	5,490	1,237	623	-	-	16,000	0.01	0.21	0.08	0.14	-
9 BC grid factor, hydrogen export	3.36	6.64	- 2.18	9.40	362	15	19	0.46	-	2,811	1,237	551	3,724	-	16,000	0.01	0.21	0.04	0.12	0.20
10 BC grid factor, net metering	3.38	5.94	0.98	6.48	290	-	-	0.42	-	3,164	1,237	558	3,230	-	2,502	0.01	0.21	0.04	0.12	-
11 BC grid factor, net zero	2.98	-	- 2.70	10.18	-	-	-	0.40	2,176	4,330	1,237	570	1,582	-	16,000	0.01	0.21	0.04	0.12	-

Table 19 shows the results of the energy system optimization giving the metrics of cost and emissions and the optimal converter capacities, as well as the important input parameters that change between each case. The input parameters that remain static throughout are given in the analysis cases and scenario descriptions in the previous section. The total cost values account for the cost for unused storage capacity.

The base case of single detached homes and separate retail and office buildings are given individually and in combination to give a basis for comparison for the mothership scenarios. The combined loads of the base case buildings are much higher than the mothership: 13.4, 1.6, and 27 times higher for heating, electrical and cooling loads respectively. Therefore, the investment costs and the emissions are much higher.

For Base Case B, the one advantage that the base case has is the greater total roof surface area available, permitting a total solar PV capacity of 78,000 kW as opposed to 16,000 kW for the mothership, resulting in much more power sold to the grid and reduced operating costs. The total cost of the energy systems in single detached homes scaled to 10,000 residents (4,160 homes) is almost $21 million (of which almost $15.8 million is for PV), which is much higher than any of the mothership cases. However, it is negative in total carbon emissions, due to the large amount of green electricity from solar PV that it sells to the grid in proportion to its load and the associated carbon credits received. It should be noted that this would be impractical in British Columbia, where the utility restricts the export of solar electricity in order to maintain the integrity of the electricity grid. The retail and office base cases also made heavy use of solar PV, however they did not achieve negative emissions, due to their heavy use of natural gas. For the same reason, results are not presented for the mothership case in which the PV capacity was unlimited, as this model attempts to install an infinite capacity of PV to generate a profit. The impact of specific PV limits is investigated in the net-metering case (scenario 10).

In the simple cases of base case A and C, comparing the mothership to the single detached homes case, the mothership has much lower costs, simply due to the smaller magnitude of its energy demands. Case A costs over four times as much and emits 3.5 times as much carbon dioxide.

In the following sections we discuss the answers to the research questions posed in the introduction.

- What is the most cost-effective energy system to meet the required loads?

The most cost effective option is Case 11, which is a net zero carbon emissions case, with a total annual equivilent cost of just under $3 million. One reason for this is through the use of the biochar CHP and the sale of the char and PV electricity. The most expensive scenario is unsurprisingly the case with the high carbon tax at $4.2 million. It is interesting to note however, that the yearly operating cost is negative for most of the cases that do not restrict the selling of green electricity and char. So although the investment costs are high, the building can make a profit from the sale of energy and carbon sequestration. Case 10 with net metering has relatively low total costs, likely due to the limited allowable solar capacity implimented reducing capital costs, however it also doesn't benefit from the lase of the electricity and has positive operating costs.

Base case C, the simple mothership energy system that doesn't allow pv or storage, has a higher cost and higher emissions compared to the other mothrship cases. Additionally it has no form of income, so its operational costs are much higher. This illustrates that integrating renewable energy technologies is not only helpful for reducing emissions, but can have significant financial advantages.

- What is the optimal capacity of solar PV or solar thermal? Is the rooftop area sufficient or would more space be desirable?

The model never selects solar thermal in any of the runs. This is potentially due to solar PV being more versatile, in that the system can use the electricity to create heat or cooling through heat pumps, use it directly, or sell it and potentially earn export income and carbon credits.

The model uses the maximum PV capacity permitted in all simulations except for cases 10 and 5 due to net metering, and case 6 with the carbon tax. When size is limited to that of the mothership roof area, the maximum permitted capacity is installed. In Case 10 with net metering, the optimal PV capacity is found to be 2,582 kW, due to the restrictions on how much power can be sold to the grid. Interestingly the model decided to not install

PV in case 5 or 6, possibly due to the already high costs of the biochar tech needed for reducing emissions. As noted above, results are not shown for Case 12, where PV size was not limited, since this attempts to install an infinite capacity.

- Does seasonal storage at this scale make sense? Would the storage size be too large to be practical?

The models showed that certain types of storage are useful, namely the batteries and the hot water storage. Battery storage was typically used for short term storage to provide load shifting and peak shaving. Hot water was also used to store heat and has the potential to store large quantities for use during the winter, however the storage size needed is very large. The maximum permitted tank forms a disk with the diameter of the mothership (214m), and a height of three meters or one storey (3m) gives a potential storage of 26.9 million kWh, which is more than enough for the annual heating demand. The volume of the tank would be over one third of the building volume (due to the hollow ring shape of the building) and would cost an estimated $35M. The hot water SUF for this large storage was between 4 and 4.7, meaning in a year it fills and empties about half way, implying that a tank of approximately half this size would be optimal. It is notable that for a much smaller storage size of 1000kWh, the SUF is 865, meaning it fills and empties more than twice a day on average.

Compressed air is also used; however, this technology is only applicable at large scales which can only be implemented in certain areas. The model uses it minimally with a SUF of around 20 for the larger storage sizes, but quite a lot for the smaller storage size (SUF of 211). Hydrogen storage was also included as an option but is not used by the model.

- What is the impact of hydrogen production and storage? Is it used for storage or for export?

Hydrogen production and storage was included in the model so that it would be used as longer term/seasonal electricity storage, with the additional versatility of being sold to local consumers such as hydrogen fuel cell vehicles and public transit. The results show that when the sale of hydrogen is allowed, it isn’t used until a certain threshold in export price is reached, whereby the model maximizes production and uses all available energy (solar PV, biochar and gas CHP and grid) to produce and sell as much as possible. When the export price is lowered to $0.2 per kWh, the model does not make any hydrogen. While this shows that it could be cost effective to do so, it may not be practical or desirable to co-locate a hydrogen production facility with a residential development. An interesting question for future research is whether there is a viable local market for hydrogen in large volumes, which may be unlikely without a power to gas operation where the hydrogen is pumped into the natural gas grid.

- Do the biochar technologies get used? What is the impact of carbon negative power and heat production?

The usage of the biochar technologies was not as prevalent as expected. The model did not choose to build biochar boilers at all, and only built biochar CHP when there were carbon limits imposed on the model run in Cases 4, 5, and 7. In these cases, it was mainly used to offset the carbon released by the natural gas CHP or boiler that was also implemented.

Having both a natural gas and biochar CHP plant is impractical and complex, and likely would not happen if the building were built. The low cost of natural gas makes it difficult for other technologies to compete. Even when carbon credits are implemented, only case 6 where the tax is $200/ton does it stop using natural gas and chooses biochar CHP and heat pumps instead.

There is some promise with biochar systems in the sequestration aspect and receiving carbon credits for producing the char, as well as then having a marketable product that can then be sold or used on site for its numerous benefits to agriculture. Biochar and its benefits are not widely known, nor is there a widespread carbon marketplace where the carbon credits can be sold. Once these factors change in the future then the situation could change dramatically.

- What is the impact of a strict carbon budget, such as being net-zero carbon? What if a negative carbon budget was enforced, meaning that carbon is sequestered each year?

There are several effects that occur with the implementation of emissions restrictions. The main one is that biochar technology, typically the CHP plant type, is installed so that it's sequestration can counteract the emissions from using the grid, or natural gas.

Troublingly it seems that when the negative emissions requirement is implemented, instead of cutting sources of emissions, it builds more capacity of biochar CHP to produce more char to counter the emissions. Instead of cutting gas use, building heat pumps and biochar CHP along with maximum solar PV installed, it continues to use gas CHP in addition to the biochar. It is unlikely however that such a practice would occur in reality, as it is more likely that a larger system consisting of just one of the technologies would be built, to reduce complexity and redundancy. These constraints should be added to the model in future. The only case to eliminate natural gas use was Cases 6 and 8, both of which have carbon taxes. The sale of biochar does provide a good source of income for the building and could have numerous indirect benefits in the community depending on how the char gets used, as discussed in the material stream section above.

- What is the effect of carbon credits and carbon taxes? What is the threshold for fossil fuels to be avoided?

The implementation of a carbon tax had numerous effects. The total cost generally increased compared with similar cases without the tax. Emissions were also reduced for both cases. Interestingly, the utilization of storage was also reduced slightly. However, this could potentially be accounted for by the higher use of grid imports to power heat pumps, and therefore less need for storing intermittent renewable energy.

6.7. Conclusions

The analysis performed in this paper optimizes the energy system of a mixed-use high-density development under different scenarios and compares this to base cases consisting of single detached homes and office and retail buildings scaled to house the equivalent number of people. The different scenarios modeled are designed to explore the changes to the systems under different conditions such as more or less storage, a carbon tax of $200/t$CO_2$, a net metering scheme, and hydrogen export. Additionally, the effect of imposing a net-zero emissions constraint and negative (1-ton CO_2 per resident) emissions requirement was explored. When a carbon tax was implemented, less natural gas was used, instead using more grid power and heat pumps to meet the heating demand. Natural gas use was only eliminated when the carbon tax was implemented. Carbon sequestration was provided by a biochar producing combined heat and power plant which under the right conditions can produce carbon negative heat and power. The mothership cases consistently had better performance than the base cases in terms of total cost. Base case B had the advantage of much greater roof surface area, so energy produced was sold to the grid to offset costs. Base case A had much higher costs and emissions relative to the mothership under the same conditions due to the magnitude of its loads being 13.4 and 1.6 times higher for heating and electricity respectively. Base case C which used mothership loads but no renewable energy or storage technologies performed relatively poorly compared to the other mothership cases, with higher costs, more emissions, and no income (and higher operating costs) than most of the other mothership cases. This indicates that it is advantageous to implement renewable energy technologies not just because they reduce emissions, but because they offer significant financial rewards for doing so. The most cost-effective case in terms of total cost was a carbon neutral requirement. This shows that it may be possible to have a cost-effective energy system, while also achieving net zero emissions.

6.8. References

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7. Conclusions

7.1. Synthesis

The goal of this thesis is to use urban scale building simulation tools to assess a potential holistic solution to urban sprawl, and attempt to quantify some of the benefits of building in such a way. The operational and embodied emissions were estimated and compared to different base cases, but primarily single detached homes. The effect of the mothership's mixed-use features, electric car sharing program, and high capacity public transportation showed significant reductions in transportation emissions over the baseline dominated primarily by personal vehicles. Finally, energy system optimization for the mothership was also performed, likewise showing significant reductions in energy use and emissions.

The second chapter presents a building stock model for the city of Victoria, and the third chapter shows how a database of building retrofits and resulting energy use reductions was created for the City of Victoria. These highlight the importance of building properties such as use type, height, footprint area, and number of storeys in determining energy use. Armed with building stock models like this, municipalities can look to see where there are certain issues (energy inefficient building, aging buildings/infrastructure, for example) and can design policy that can be more targeted and hopefully more effective as a result. The specific results for the City of Victoria in chapter 3 form marginal abatement cost curves showing the most cost-effective retrofits (and hence the order in which to do them) to minimise greenhouse gas emissions from the residential buildings.

Beyond this examination of the different ways to improve the existing building stock, this thesis aims to provide a possible route for municipalities to plan future developments in a sustainable manner. The mothership concept and associated urban scale building simulation tools are introduced in chapter 4. 3D building models of the numerous mothership designs and traditional building archetypes were built and simulations performed. Mothership design parameters were explored, including shape, height, and main building material. The operational and embodied emissions for the base cases and mothership were then compared. Overall the timber framed mothership showed 71%, 73%, and 74% reductions in operational energy, embodied energy, and embodied carbon respectively over the base case of single detached homes. Highly insulated low rise apartments showed similar reductions over the baseline, however they do not provide the mixed use benefits that the mothership does, as well as the effects on transportation emissions.

The fifth chapter combines the building energy analysis of chapter 4 with an investigation into the impact of density on emissions from transportation. A transportation analysis was performed in order to quantify the transportation emissions reductions resulting from the mothership's mixed-use nature, allowing trips to be made through active means such as walking or cycling instead of driving. Further, the trips that are left over are reduced by two additional measures, the implementation of a bus rapid transit line between the mothership and the central business district, and an electric vehicle car share program for mothership residents. Through these methods, it was estimated that transportation emissions could be reduced by 58%. This, combined with the operational and embodied emissions reductions of 72%, amounts to a total reduction of 61%. This illustrates that there are great emissions reductions to be had by considering an urban area but not just its buildings, but also how they affect the transportation system, and designing with that in mind.

The sixth chapter brings this to the next level: energy systems design and renewable energy provision. The design of a building can have a very large impact on its energy demands, which can be minimized through concepts that are discussed in chapters 4 and 5. However, the building still needs to have its demands met, and doing so at a scale such as the mothership, with so many different technologies, and combinations to choose from and size, and doing so in a cost effective manner that also minimizes greenhouse gas emissions, is daunting. To face this, an energy system optimization analysis was performed for the mothership and base cases. Nine different mothership cases were run exploring scenarios with and without carbon taxes, different storage sizes, net metering, and net-zero and negative emissions limits. The mothership performed more cost effectively than the base cases, with the most cost-effective case being one with a net zero carbon emissions limit, which is not intuitive. This was made possible by using a negative emissions pyrolysis combined heat and power plant which produces a char that when used correctly (not combusted) can sequester up to 50% of the carbon in the feedstock.

This thesis combines many different aspects of urban design and engineering together with the goal of quantifying the different energy and emissions reductions that are achievable through different aspects of the built environment. It examines how building shape, height and materials and density affect operational and embodied energy use. It looks at the impact on transportation that a large high-density mixed-use building makes reducing the overall number of trips that use personal vehicles, and different benefits that a high-density node make when implementing public transportation and electric car share fleets. Finally, it incorporates the optimization and analysis of an efficient and cost-effective building energy system.

7.2. Lessons learnt

The choice of UMI was for its ability to quickly simulate building energy use for large buildings or many smaller buildings, in addition to estimating the embodied energy and carbon of the building materials. It is also able to perform daylight analysis and walkability. One of the big advantages that UMI has is that Grasshopper can create the geometry using parametric model definitions, allowing quick changes to the dimensions and properties of the buildings using sliders and other inputs. Grasshopper also has plug ins that allow for optimization and surrogate models to be created, so one could create a basic definition of a building's geometry defined with parameters controlled by sliders. One can then connect a genetic algorithm to the sliders, and the resulting energy simulations results into the objective function of the genetic algorithm. In this way the building form could be optimized to minimize energy. This was the goal of using UMI, so that it's operational energy, embodied energy, and embodied emissions results could be fed as input for an optimizer. It turns out that this is not possible (at least with the version of UMI available at the time). This is due to UMI being a Rhino plug-in, and so the simulations take place in this environment, and it cannot be easily accessed or controlled from the grasshopper environment. There are other building simulation tools such as Ladybug and Honeybee, and ArchSim that run exclusively in grasshopper, making it easy to apply optimization components to it, and in retrospect it could have been better to use one of these tools instead.

7.3. Future work

There is significant potential for future work with this project. As mentioned in the previous section, using a different simulation tool that is entirely in Grasshopper, thus enabling the application of optimization components would be very interesting. Perhaps the newer versions of UMI are able to operate in this way, which would be ideal.

It would also be beneficial to obtain and include transportation data for weekend trips instead of just those for the weekdays.

There are also many interesting directions for research when land use is also considered in addition to just the building-related aspects. If a new development was to be built, andinstead of building single detached homes a mothership was constructed instead, there would be a significant land saving of around 90%. This "freed up" land could be used for urban agriculture or food forests, recreation and park space, solar panel installation, growing woody biomass for biochar production, or other uses. It would be interesting to quantify the emissions and energy savings that these activities could provide.

It would also be interesting to include waste management onsite, both solid wastes ("regular" garbage, recyclables, compostable, etc.) and waste water treatment. Some streams could be used to produce energy, or compost or be sent to other facilities to be recycled further. Now that it is possible to implement material streams into energy hub, it could be added to a future version of the model. Refinements could also be made to the energy hub model such as getting better data on technologies and adding additional ones.

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