Determinants of Urban Energy Use: Density and Urban Form

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ABSTRACT: With a particular focus on urban energy use, this study investigates the implications of mixed-use high-density development in a small urban community to curb sprawl in terms of the relationship of urban form and urban density. Every building as a part of the urban core not only affects the urban form but also modifies density, microclimate, and energy use. These relationships are location specific. The interconnected nature of these physical, spatial and environmental characteristics is untangled by investigating individual building form and functions as well as their relationship with other buildings as a function of urban spatiality and density. The first part of this paper explores the potential for increased urban density employing Ralph Knowles' seminal Solar Envelope Concept. The second part investigates the relationship between development density and urban energy use intensity. The microclimatic modifications of increased density development are then compared with the existing urban form and their impacts on energy use are studied employing a simulation approach. In conclusion, the suitability of energy implications of a mixed-use development as a part of urban form and density are suggested. The outcome of this investigation provides insights on building and urban form, achievable density and urban energy needs. This research is relevant to the community and local government that will decide on a new development paradigm. This study also provides a platform for future integration of the socio-economic aspects of introducing high-rise, high-density developments.

KEYWORDS: Urban Energy Use, Urban Form, Urban Density, Mixed-use Development, Microclimate

INTRODUCTION

The population of Bozeman, MT is growing at the rate of 3% to 4% per year and is expected to double in next 20 years from 40,000 to 80,000 (US Census Bureau, 2010). This increase in population and the towns currently adopted low-rise development guidelines may potentially lead to urban sprawl in an ecologically sensitive area. The negative impact of sprawl threatens to replace fertile land with impervious surface areas and will expose the community to increased vehicular traffic, environmental pollution, social segregation, and increased infrastructural cost. However, using smart growth principles (CNU, 2010), the mixed-use high-rise density development will not only help accommodate the growing population but also provide an opportunity to live and work in close proximity. Further, the population can be within walkable distance from the amenities they need and enjoy like retail, co-operatives, banks, schools, museums, libraries, theatres, parks, trails, outdoor activities and more. This will be crucial as 70% of the future population is expected to be retirees, students and professionals and, nuclear families who will seek an urban experience per the Bozeman Community Plan (2009).

The major drawback of dense downtown areas is that they consume a significant amount of urban energy within a small area (Steemers, 2003). Also, tall buildings may potentially prevent solar access in habitable spaces. Further, the downtown area is warmer than surrounding areas due to trapped urban heat and as a result modifies microclimates (Oke, 1988; Mills, 2006) as well as urban climates (Cleugh and Grimmond, 2012). It particularly affects urban air temperature which increases space cooling energy needs (Bhiwapurkar and Moschandreas, 2010). However, a cold and dry climate can benefit from reduced heating energy needs. In order to explore the suitability of mixed-use high-rise developments, this paper seeks answers to the following questions;

- What is the relationship between urban form and density?
- What is the relationship between urban density and energy use intensity?
- How does urban form influence microclimate?
- How does microclimate modify building energy use?

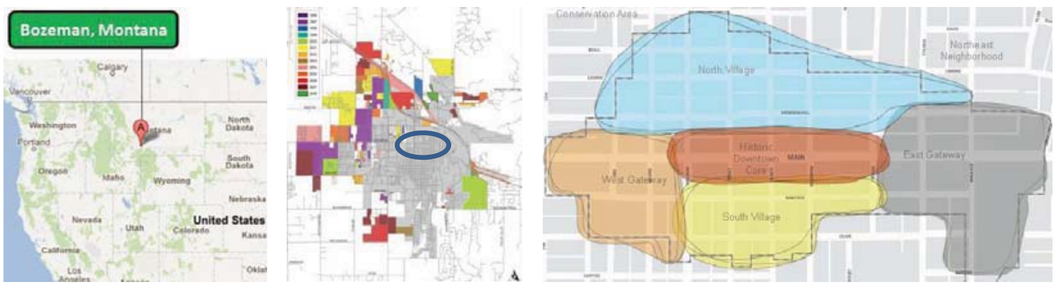
in the context of Bozeman, MT as a case study.

1.0 METHODS

In order to investigate the relationship of urban form, urban density, urban energy and microclimate, this study was divided into four parts. The first part of this paper employs Ralph Knowles' (1985) seminal Solar Envelope Concept to explore the potential for increased urban density. The second part investigates the less explored energy potential of the solar envelope (Knowles, 2005) towards urban densification. The third part focuses on the investigation and comparison of the energy implications of increased density for single use development and mixed-use development within the existing downtown core. This part constitutes a major component of this paper. The fourth part explores the microclimatic modification of increased density development. The microclimatic conditions of an existing urban form is compared with proposed new urban form and its urban energy modifying characteristics are analyzed. In the conclusion, energy implications and warming trends of a mixed-use development are suggested to inform evolving urban form and urban densification. Adopting a simulation approach for microclimatic investigations as well as whole building energy studies, this paper focuses on the eight blocks of the historic downtown core of Bozeman, MT.

1.1 Urban form

The Bozeman Community Plan covers the City as well as nearly two-mile area around the city. The city is approximately 50.50 km² (12,477 acres) and the planning area is 171.71 km² (42,463 acres) including the City (Figure 1). Over the past decade, a significant amount of land has been annexed because of population growth and hence urban sprawl is inevitable. At the core of the city, is the historic downtown spread over 3.92 hectares (9.7 acres) of land, which consists of 8-urban blocks along the East-West axis formed by the Main Street. This area has been studied for potential increase in development density as the majority of urban commercial activities are located here. Each block is approximately 43 meters (140 feet) long and 24 meters (80 feet) wide, although most of them vary marginally in sizes. Particularly, the Eastern blocks (Figure 2) are wide and are averaged as 168 meters (550 feet) and 24meters (80 feet) deep.



(a) (b) (c)

Figure 1: (a) Location map (source: Google maps) (b) Development map (c) Downtown Bozeman, MT consists of five distinct zones; Historic Downtown Core, East Gateway, West Gateway, North Village and South Village (Source: Downtown Bozeman Improvement Plan, 2009)

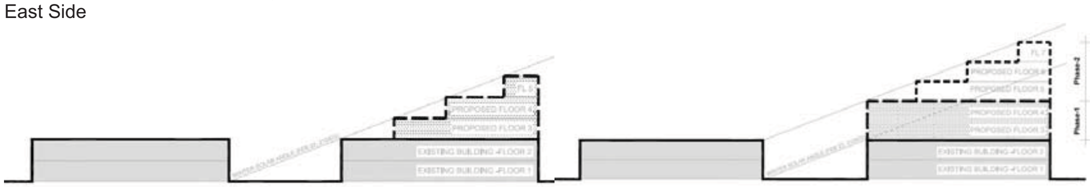
Buildings in the downtown core are 2-story high and the Main street façade is characterized by a combination of brick walls and storefronts. A majority of the buildings are late 19th century buildings with wood frame construction, which host a variety of functions including offices, retail shops, restaurants, local services as well as convenience stores with a few apartments. There is a mix of building uses in each urban block, most of which are locally owned, which makes it very special for the community. These blocks are symmetrically organized along 24 meter (80 feet) wide E-W oriented Main Street. 4-blocks along the Main Street are separated by N-S oriented arterial roads of 18 meters (60 feet) wide (Figure 2). The street width includes sidewalks

1.2 Density

The density of the downtown core is estimated by calculating total land area divided by the actual built area. As most of the development is commercial, its density is represented by square meters/hectare (m²/ha) and dwelling units/hectare (du/ha) represents density of residential units. The historic downtown core covers 3.92 ha (9.7 acres) of land area and there is 59,030.60 m² (635,400 sf) of built area, which gives a density of 15,058.82 m²/ha (65,505 ft²/acre). The few residential units that exist in the core are not accounted for this study. In order to accommodate the growing population, the city is considering increasing the density of the downtown core, an opportunity explored in this paper. As local climatic conditions are primarily cold and dry, solar access to each urban unit is very important. Therefore exploration of the Solar Envelope Concept (Knowles, 1985) is considered useful for this study, keeping in mind the streetscape and construction feasibility of a proposed new development.

(a) (b)

Figure 2: (a) Block view of the study area (b) Historic Downtown Core consists of eight urban blocks and are equally divided by the Main Street along East-West axis and are bounded by Grand Street on West side and Rouse Street on East Side



Option-1 Option-2

Figure 3: Increased development density using the solar envelope concept. Option-1 provides year round solar access to existing commercial units on north side of the street. Option-2, explores the possibility of further densification on south side of the street considering that north side commercial development are internal load dominated building that mostly depend upon artificial lighting. As a result, the solar cutoff angle begins at/is the roof level of north block. Two alternatives are considered under this option. Phase-1 proposes two additional floors of exactly same size on existing building. Phase-2 includes addition of three more floors within solar envelope.

1.3 Energy Use Intensity

The energy use intensity (kWh/m² per annum) is estimated by dividing total annual energy use by all buildings types of the eight blocks divided by the total built area. The energy use intensity of the existing urban block provides a "Baseline" for comparative analysis of proposed new urban form. Amongst above densification alternatives, Phase-2 of Option-2 is considered most relevant for such comparison in this study which is expected to provide insights on densification. For the purpose of evaluating energy performance, this option is further developed as a single-use (Baseline+1) and a mixed-use development (Baseline+2) to explore applications of the solar envelope concept beyond recent studies of Niemasz et al. (2011) for a cold climate. The single-use development, by addition of two floors on existing two story buildings, would result in a total build up area of 118,061.18 m² (1,270,800ft²). The mixed-use development considered residential development for an additional two floors, which would result in total commercial, build up area of 59,030.59 m² (635,000 ft²) and total residential build up area of 59,030.59 m² (635,000 ft²). This comparative urban energy use analysis of urban form focuses on total energy use as a result of a combination of uses and densification and the other building parameters are kept constant during the course of the study.

On-site building surveys are conducted to identify building use, construction type, surface thermal properties/R-values, and occupancy schedule in order to identify and establish representative/prototypical buildings used in energy simulations (Table 1), similar to some previously completed studies (Bhiwapurkar and DeBaillie, 2007). The identified building types are office, retail-bar and lounge, retail-local stores, and restaurants with complete menu as well as fast food services. The utility data would have helped in order to make the energy model of existing urban blocks more realistic and the author wishes to incorporate it in future works. This simulation model acts as a test run for further developments, and provides strong foundations for seeking answers to the research questions posed in this paper as demonstrated in some previous works of Bhiwapurkar et al. (2007).

Table 1 provides accumulated values of various individual units of each building type, which are conditioned by a packaged single zone DX system with furnace. The efficiency of packaged units is averaged to EER of 8.5 and furnace efficiency average of 80% is most appropriate considering the age of these installed units and partially available nameplate data. Also, the natural gas non-residential domestic hot water system is modeled at 80% efficiency. The set points – 24.4ºC (76ºF) for cooling and 21.11ºC (70ºF) for heating are kept constant through the study. A whole energy simulation program, eQUEST 3.64 (DOE, 2009) has been previously validated for its algorithm and published elsewhere, and is considered suitable for this study (Bhiwapurkar and Moschandreas, 2010).

Table 1: Building prototypes and characteristics.

	Building Type/Function	Total Area (m²)	R-Values		Roof Albedo	Glass Properties		Lighting Power Density [W/m²] (W/ft²)
			Roof	Wall		SHGC	U-Value(W/m²K)	
A	Office	16,648	R-21	R-6	0.5	0.63	0.48	16.14 (1.50)
B	Restaurant-Bar/Lounge	16,648	R-14	R-6	0.5	0.8	1.04	16.14 (1.85)
C	Retail-Departmental Store	8,324	R-21	R-12	0.5	0.8	1.04	25.61 (2.38)
D	Retail-Service Station and Convenience Store	17,410	R-21	R-12	0.5	0.8	1.04	25.61 (2.38)
E	Residential (proposed)	59,030	R-38	R-20	0.5	0.35	0.48	5.38 (0.50)

1.4 Microclimate

In order to perform microclimatic simulations, urban texture (Figure 4) is analyzed based on the information gathered from Google images and compared with GIS shape files provided by the city of Bozeman. This information on urban texture includes parcel size, building footprint, roof surfaces, parking lots, street and pavement surfaces, and vegetation as shown in Figure 4. The Majority of the urban surfaces are hard pavements (around 90%); mostly asphalted roof surfaces, some of which are painted white although they are in a deteriorated condition. The asphalt surface area also includes roads and parking lots. Most sidewalks are made of paved concrete (2%) along the street. Vegetation in this study area is less than 5% although parks, creeks, farmlands, and mountains surround the downtown core. Vertical building surfaces are two stories high with mostly red brick surfaces and storefronts, which are more prominent at street level. The average roof and wall albedo values for this study is considered as 0.4 and 0.3 respectively based on the existing surface types and their condition that are visually inspected and compared with thermal properties of the material mentioned in the literature (ASHRAE Handbook, 33.3, Table 3: Properties of Solids). The prevailing wind direction of N-NW as a starting condition, urban roughness of 0.1 and total simulation time of 18 hours which provided the required starting conditions starting at 3:00 am is considered for this study. The urban climate simulation program, ENVI-met 3.1 Beta 4, used for this study has been previously validated (Bruse, 1999) and is commonly used for similar studies.

Figure 4: Surface texture maps of historic downtown core distinguish paved surfaces; streets, sidewalks, parking lots and vegetated surfaces.

2.0 RESULTS AND ANALYSIS

2.1 Urban form and urban density

The application of the solar envelope concept to increase density of the buildup area in the downtown core is demonstrated in Figure 3 along with possible new urban forms. This paper looks into two densification scenarios. The Option-1 considers increase in built area by addition of three floors on the existing building in order to allow year round solar access to commercial buildings on north side of the street. Option-2, especially Phase-1, is developed to benefit from thermal behavior of commercial buildings and these internal heat-load-dominated buildings would be shaded during day time to minimize solar heat gain. Both these options propose new developments over existing buildings and retain open spaces for future use, although most it is currently used as parking lots.

Using Option-1, the built-up area can be increased to 95,787 m² (1,031,040 ft²) which is an increase of 36,756 m² (395,640 ft²) add percentage over an existing urban core as shown in Table 2. This percentage increase in built-up area increases existing development density from 71,748,544 m²/ha (65,464 ft²/acre) to 116,376,568 m²/ha (106,183 ft²/acre), made possible by the addition of three new floors to the existing building that follows winter solar angles and are recessed from the street side. Adopting Option-2 increases existing built-up area by 83,917 m² (903,280 ft²) as a result existing density increases to 173,675,448 m²/ha (158,463 ft²/acre). This option can be implemented in two phases. Phase-1 adds two floors on existing buildings that increase existing built-up area by 59,031 m² (635,400 sf) and existing density increases to 173,675,448 m²/ha (158,463 ft²/acre). The additions of three more floors in Phase-2 increases existing built-up area by 83,917 m² (903,280 ft²) and raise existing density to 173,675,448 m²/ha (158,463 ft²/acre). Option-2 provides few development scenarios that include targeting specific blocks to be developed over others. Both these options provide maximum densification with controlled solar access to the neighboring buildings with a possible addition of floors over existing buildings.

Table 2: Densification of downtown core using solar envelope approach.

	Land Area (hectares)	Built-up Area (m²)	Increase in Built-up Area (m²)	Density (m²/ha)
Downtown Core	3.92	59,031	-	71,748,544
Option-1	3.92	95,787	36,756	116,376,568
Option-A (Phase-1)	3.92	118,061	59,031	143,586,960
Option-B (Phase-2)	3.92	142,948	83,917	173,675,448

The current densification proposal per the Bozeman Improvement Plan includes 20 du/acres in the downtown area with residential unit sizes ranging from 93 m² -139 m² (1000 ft²-1500 ft²). Adopting Phase-1 of Option-2 would add two floors per block and comfortably meet suggested density which needs 194 dwelling units in the downtown area by considering maximum unit size of 139 m² (1500 ft²). That provides extra built-up area of 56,883 m² (612,280 ft²) for other urban functions like community places, retail shops and other community needs including parking structures. Thus, the solar envelope provides enough flexibility not only to build residential units of various sizes and parking structures but also accommodate other community needs and provides solar access to urban buildings.

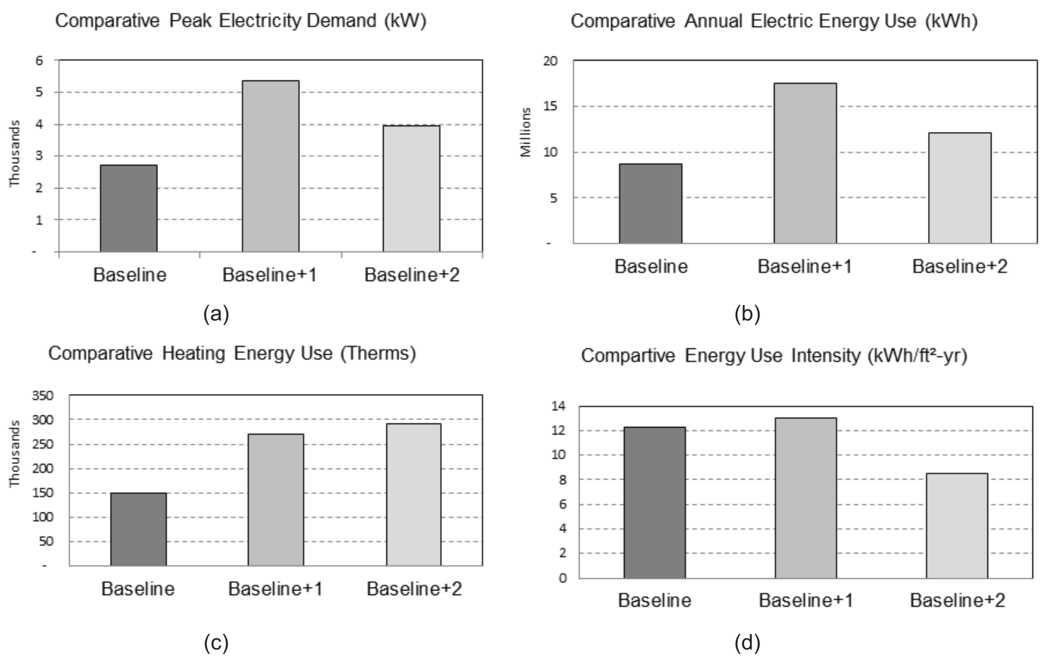
An increase in residential development would also complement new retail activities in the downtown core to meet growing urban demands. For example, a convenience store of 1858-2787 m² (20,000-30,000 ft²) and a neighborhood center of 5574.2-7432.24 m² (60,000-80,000 ft²) require a density of 600-800 du/ha (6-8 du/acres) in order to be financially feasible (Farr, 2007). This suggests possible additional retail development. In this manner, increased numbers and varying sizes of residential units for sale, rental and ownership in the downtown core will support retail investment and vice versa. Thus, encouraging financial investment in the downtown area will not only boost the local economy, as observed by the community in the past, but also help curb urban sprawl. Most importantly, the proposed residential units will have a close proximity to amenities like banks, grocery, schools, parks, post office and so on that are already a part of the downtown core and are commonly suggested for smart growth. In this way, urban densification would contribute towards completeness of the urban neighborhood by providing flexibility in urban building functions to meet changing needs of the community. In addition, downtown densification will help generate more tax revenues compared to the suburban development (About Town, 2012) and the city invests additional revenues earned beyond 1995 tax regulations in the development of the downtown core (City of Bozeman Economic Development Plan, 2009). Recently built public library, town hall, parking structure, and street furniture are examples of this scheme and the community benefits are evident. The following section looks into the implications of mixed-use development on urban energy usage intensity that is crucial for deciding the power infrastructure.

2.2 Urban density and urban energy use intensity

In order to understand the additional energy infrastructural needs of urban densification, this section compares the energy needs of the existing urban form with the proposed new urban form. This comparison is based on a peak electric demand as well as annual energy generation capacity of the power plant required to meet the urban energy needs.

Using simulation results, the Baseline (existing urban form) peak energy demand is 2700 kW that occurs at 3:00pm on August 2 and the annual energy need is 8.7million kWh (Figure 5). Using this data, the estimated energy use intensity of the existing downtown core is 131.52 kWh/m²-year (12.3 kWh/ft²-year). This energy usage is in the acceptable range when compared with the Commercial Building Energy Survey Consumption Survey data for Climate Zone-1 (EIA, 2013). The Baseline+1 represent a single use but doubled density of the downtown area per Phase-1 of Option-2. The simulation results shows that the peak electric demand of Baseline+1 is increased to 5,355kW and it is shifted to July, 12 at 3:00pm whereas annual energy need is raised to 17.5 million kWh. This is an increase of 98% and 100% in the peak energy demand and annual energy use respectively. Thus, doubled peak demand and annual energy trends are observed as a result of doubled density development.

The Baseline+2 shows a change from a single-use development to a mixed-use development in the existing urban downtown area per Phase-1 of Option-2. The peak electric demand, total energy use, and energy use intensity of the Baseline+2 is reduced by two thirds (67%), half (53%), and one third (37%) respectively, compared to the Baseline+1. The Baseline+2 electric demand peaks at 3,929 kW, consumes 12.13 million kWh annually and energy use intensity is 91.46 kWh/m²-yr (8.5kwh/sf-yr) as shown in Figure 5. Thus, a single-use densification proposal causes 98% increase in peak electric demand compared to a 45% increase by mixed-use densification in the existing urban area. It indicates that the electric demand for a single use development can support twice the size of mixed-use development. Similarly, the total electric energy use of Baseline+1, a single-use development, is increased in the order of 100% over the Baseline scenario. However, a mixed-use development suggested in the Baseline+2 can sustain within 39% increment over the Baseline. Importantly, urban energy use intensity of Baseline+2 is decreased by 31% due to mixed-use development over the Baseline.



where;

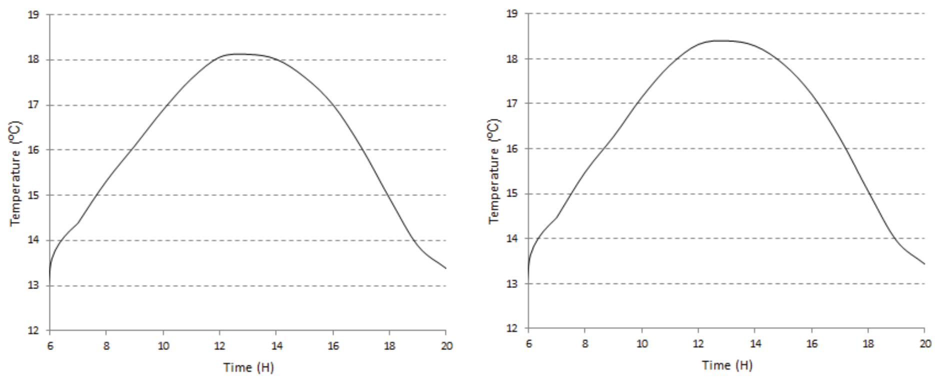
Baseline	Existing Downtown Core
Baseline+1	Option-2, Phase-1 (existing downtown Core + a single-use development)
Baseline+2	Option-2, Phase-1 (existing downtown Core + a mixed-use development)

Figure 5: Comparative energy performance of the existing urban form (Baseline) with a proposed single-use density development (Baseline+1) and a mixed-use density development (Baseline-2) (a) peak electric demand (b) annual electric energy need (c) annual heating energy (d) energy use intensity

It is also observed that the heating energy use is increased with the increase in the density of the downtown area. The Baseline+1 showed an increase in heating energy use by 82% over the Baseline scenario, which is proportional to the increase in the build-up area. The Baseline+2 heating energy use is increased by 97% over the Baseline. So, there is a difference of 15% in the annual heating energy needs of a single-use and a mixed-use development. This difference is a function of the increased internal volume and envelope surface area of residential units compared to commercial units, which increased heat losses to very low outdoor temperatures during winter months. Also, a change in time of use of residential and commercial buildings is considered as the main reason for this change in heating energy use. The peak energy use in residential buildings occurs in the morning as well as in the evening hours when outside temperature is either warming up or cooling down respectively, compared to the single use internally-dominated buildings that peaks around afternoon hours.

2.3 Urban form and microclimatic changes

The existing downtown core of eight blocks (Figure 4) separated by 24 meters (80 feet) wide E-W oriented Main Street and 18 meters (60 feet) wide N-S oriented streets are analyzed using urban microclimatic simulation program, ENVI-met 3.1 Beta 4, on July 12, 2012. The mean air temperature of an urban canopy, an imaginary urban void formed between two urban blocks on 24.38 meters (80 feet) wide street bounded by the ground plane and a roof height, is recorded at every 1.0 m from ground level to the top of the urban canopy at 10.0 m. This temperature data is then averaged to get temperature graphs presented in Figure 6. The Baseline (existing downtown) and the Baseline+2 (existing downtown + additional 2-stories) conditions are used for this analysis. The comparison between the existing and a proposed new urban form shows maximum change in the mean air temperature of 0.4 C during 1 pm as shown in Figure 6.



(a) (b)

Figure 6: (a) Temporal variation of mean canopy air temperature of the existing downtown core (Baseline) on 07/12/2012 (b) Temporal variation of mean canopy air temperature of the proposed densification of the downtown core (Baseline+2) on 07/12/2012.

The changes in the mean air temperature shown in Figure 6 is much lower than expected, however while analyzing microclimatic changes, it is important to note that the only change in the baseline and the proposed model is of increased wall surfaces with fixed a albedo value of 0.3. So, the observed changes in microclimatic conditions are due to increased vertical wall surfaces, which are exposed to solar angles of 60º at noon and 40º at 9:00 am and 3:00 pm. Also, only the South facing urban canyon surface is exposed to the sun while street surface is shaded by low solar angles. Further, high Sky View Factor (Oke,1988) of low rise structures provides higher exposure to sky that helps in radiative cooling of a heated surface after the sunset, however if the ambient air temperature is lower than the wall surface then it helps constantly release heat to the outside environment which may affect canyon air temperature. This phenomenon, daytime temperature differences among various built environment, as a function of street geometry could be significant by creation of urban heat island or cool islands (Svenson and Eliassson, 2002), is considered as one of the reasons for low temperature differences observed in this study (Golany, 1996).

2.4 Microclimatic changes and urban energy use intensity

The modified air temperature changes due to increased surface areas of the Baseline+2 are incorporated in the weather file used for energy simulations. No significant change is observed in the energy use of the Baseline+2 conditions. The internal heat load dominated buildings and a low occupancy of residential units during daytime are considered as major reasons for this. The microclimatic changes during winter days is not modeled due to current limitations of the ENVI-met program to incorporate snow surfaces, typical of winter condition in the study area. So, energy changes during winter conditions are not estimated. However, it is expected that the compact urban development with high-density development would help retain urban heat and thus, this warming effect may benefit cold climates as observed in the studies conducted in Switzerland, for example (Frank, 2005).

Based on the work completed so far, it is evident that this work would benefit from the field measurements in order to validate urban climate simulation models as well as be able to test winter benefits of compact development. Also, field measurements would help account for the anthropogenic heat sources like the heat released by building forms and automobiles that could not be included in the microclimatic simulations. Further, establishing a rural climatic condition to explore microclimatic effects of the urban form in a small community would be helpful. Nonetheless, this study provides direction for future works.

CONCLUSION

By exploring urban form, urban density, urban energy use intensity and microclimatic conditions, this paper provides new insights on urban development process for small communities. Employing Knowles' seminal Solar Envelope approach, the first part of this paper performs solar analysis of existing urban form to increase the urban density and current development density of 71,748,544 m²/ha (65,464 ft²/acre), which can be increased to 140,877,452 m²/ha (130,927 ft²/acre). The second part of this paper investigates changes in the urban energy use intensity due to increased development density. Doubling the build-up area with a single-use development doubles the simulated urban energy use intensity of the downtown core. However, mixed-use development significantly reduces energy needs of increased density development in the third part of the investigation. The peak electric demand, total energy use, and energy use intensity can be reduced by approximately two thirds (67%), half (53%), and one third (37%) respectively indicating that the electric demand for a single use development can support twice the size of mixed-use development. Importantly, urban form with mixed-use development decreases urban energy use intensity by 31%, from 131.52 kWh/m²-year to 91.46 kWh/m²-year. The fourth part of the investigation focuses on microclimatic modification of increased density and compares it with the existing urban form. The average dry bulb temperature of the downtown core canopy is reduced by 0.4ºC on a summer day and a very marginal change in the urban energy use is observed at this time.

The significant outcome of this study is that there are urban energy implications and microclimatic effects of the solar envelope approach. Combining both these interconnected effects, it is critically important that the mere addition of new urban surfaces potentially modifies microclimatic conditions and this influences energy and environmental needs of the community. Further, this investigation indicates that small communities can benefit from microclimatic conditions it generates, especially in cold climates. Thus, by increasing development density in a compact manner can help balance urban growth and minimize negative energy and environmental impacts. Most importantly, the adopted approach in this paper is relevant to the community and local government that will decide on a new future development paradigm.

FUTURE DIRECTION

A current limitation of urban climate simulation model to simulate snowy conditions limits the heating energy investigation. The microclimatic conditions presented in this paper can further deteriorate by anthropogenic heat sources like heat released by the built environment and related vehicular traffic, which can be accounted by exploring the density and transportation relationship in future works.

ACKNOWLEDGEMENT

The author wishes to acknowledge a CA Block Grant provided by the Montana State University-Bozeman for this ongoing study. I wish to sincerely thank Prof. Ralph Johnson for encouraging me to initiate this project. The valuable feedback and support of Prof. Fatih Rifki and Prof. Tom Woods in the development of this paper is much appreciated.

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