THE RELATIONSHIP BETWEEN PERSONAL NET ENERGY USE AND THE URBAN DENSITY OF SOLAR BUILDINGS

William O'Brien[3], Christopher Kennedy[1], Andreas Athienitis[3] and Ted Kesik[2]
[1]Deparment of Civil Engineering, University of Toronto
[2]Faculty of Architecture, Landscape, and Design, University of Toronto
[3]Department of Building, Civil, and Environmental Engineering, Concordia University
1455 de Maisonneuve Blvd. West, Montréal, Québec, Canada, H3G 1M8
Phone: 514-848-2424 ext. 7080
Email: w_obrie@encs.concordia.ca

ABSTRACT

There is a dichotomous relationship between the density of solar housing and household energy use. The amount of solar energy available per person decreases approximately linearly as density increases. At the same time, transportation energy, and to some extent, housing energy decreases. Thus, an interesting question is posed: how does net energy use vary with housing density? This paper attempts to provide insight into this question by examining three housing forms: low-density detached homes, medium-density townhouses, and high-density high-rises in Toronto. The three major quantities of energy that are summed for each are building operational energy use, solar energy availability, and personal transportation energy use. The results show that only when all systems are made to be extremely efficient does the low-density development result in lower net energy use. Thus, this study underpins the necessity of considering new housing developments in the context of their surroundings.

INTRODUCTION

It is necessary to plan urban areas to minimize energy use and the associated greenhouse gas (GHG) emissions, in order to approach sustainability. The fact that there is a worldwide trend towards urbanization, in addition to overall population growth, provides an opportunity for a more sustainable form of development (Satterthwaite, 2005).

Typical suburban, single detached houses are associated with the so-called "American Dream" with large yards, multi-car driveways, relatively inexpensive land, and supposedly safe, quiet neighbourhoods. However, they are also associated with monotony, car-dependency, big box stores, urban sprawl, and huge infrastructure investments (Hasse and Lathrop, 2003). The infrastructure cost to support sprawling neighbourhoods has been estimated to be 20% higher than compact forms (Downs, 1999). Moreover, a relationship has been found between suburban developments and health problems due to the car-dependent lifestyle (Ewing et al., 2003; Lopez, 2004). They also tend to depart from grid-like street patterns to irregular and curvilinear forms. This increases the distance between source and destination, as well as encouraging energy-intensive transportation modes. However, sparsely populated urban forms are well suited for solar energy collection because of the large amount of land area (and consequently, solar energy) available per capita.

Denser housing forms, such as townhouses and high-rise buildings were traditionally considered undesirable because of inner cities' association with crime and pollution (Nechyba and Walsh, 2004). However, from an energy standpoint, compact buildings reduce heat loss and promote walking, bicycling, and cost-effective mass transportation. Additionally, amenities such as commercial districts, places of employment, and educational facilities tend to be closer. Thus, both the transportation distance and mode lead to lower transportation energy use and emissions per person. However, dense housing forms have less available solar energy per capita both because there is less land per capita and because tall buildings complicate the shading patterns on buildings.

A clear trade-off emerges: low-density housing is energy intensive but has the potential to capture substantial amounts of solar energy, while high-density housing is less energy-intensive but has less solar energy potential. Three major quantities of energy are considered in this study: building operational energy, personal transportation energy, and solar energy availability. Their trends with population density are illustrated in Figure 1. It shows the general trends as well as the sum of the three energy quantities – the theme of this research.

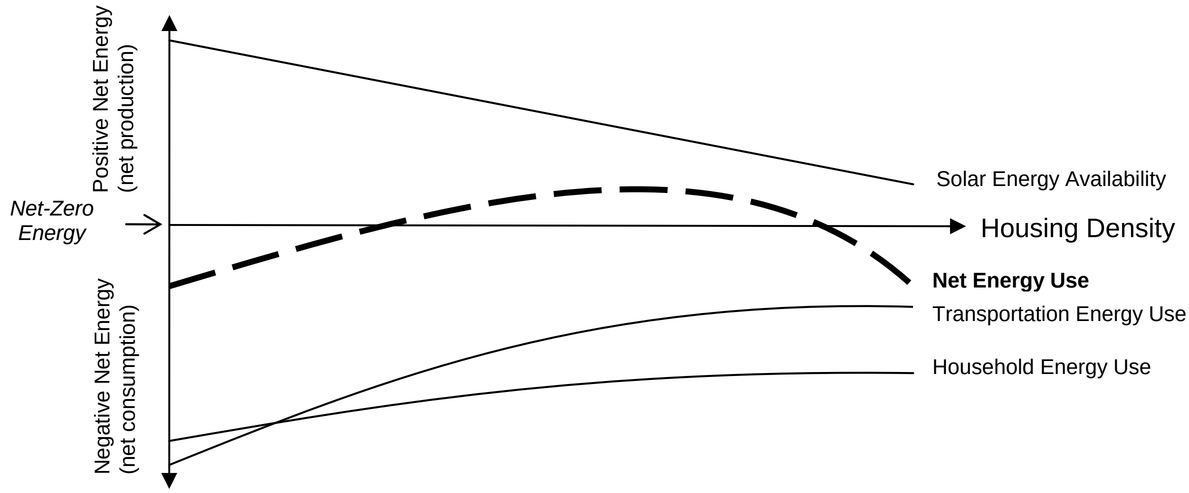


Figure 1. Trends in energy use (or solar availability) versus housing density

The Transportation Tomorrow Survey collected detailed information from Toronto residents about their transportation habits (University of Toronto, 2003). The IBI Group (2000), who performed a multivariate regression analysis (MRA) based on this data, found that transportation energy is most sensitive to the number of vehicles per household, distance to the central business district (CBD), number of jobs within a 5-km radius, and household income. Interestingly, local density itself has little impact on transportation energy. However, one should recognize that it is high-density development that enables shorter distances to the CBD, amenities, and economical public transportation services. Thus, density positively impacts all geographical variables that were explored. VandeWeghe and Kennedy (2007) found that transportation-related GHG emissions (which are connected to energy use) from transportation dominated the total emissions of suburbanites in Toronto. Their data confirm that overall emissions generally increase with distance to downtown.

Several studies have been conducted on solar energy availability on the urban scale (Compagnon, 2004; Gadsden et al., 2003; Kristl and Krainer, 2001; Tombazis and Preuss, 2001). Compagnon proposes a methodology for estimating the amount of solar energy available to existing neighbourhoods. He established generalized standards for determining the economic and practical threshold level of annual solar energy on a surface for conversion into useful energy. This is the scheme used for this paper.

Buildings that supplement some or all of their operating energy with solar energy that is collected on-site are emerging as a new trend. Buildings that produce as much energy as they consume on an annual basis are classified as net-zero energy. Recently, the Canada Mortgage and Housing Corporation (CMHC) challenged Canadian builders to design and construct net-zero energy detached houses (CMHC, 2008). This program yielded 15 net-zero energy (or near net-zero energy) houses. However, most of the focus is on buildings of relatively low density. This favourable perspective on low-density development is incompatible with the objective of densification to reduce transportation energy. An extensive literature review yielded little recognition of these conflicting priorities. Several works have acknowledged the inclusion of solar energy potential in whole-city energy analyses including: Cobodan and Kennedy (2008); Naess (1995), and Steemers (2003). Steemers looked at the influence of housing density on each quantity of energy separately and stated: "…there is a need for an analytical approach to provide information on which the decisions will be based. The potential role for research is evident."

This paper uses three types of development, based on Toronto data, to establish the trends of energy use as a function of housing density. It is a multi-disciplinary study that proves the importance of collaboration between building designers and urban planners. The objective of this study is to quantify the importance of balancing transportation energy and solar energy availability for buildings, in the context of net energy use. The results suggest that urban form should not be driven by solar energy availability alone, but rather the consideration of all major energy sources and sinks.

<u>METHODOLOGY</u>

The scope of this study is to examine the following aspects of a household’s energy use: building operations, personal transportation, and solar energy availability (Figure 2). In this figure, energy sinks are denoted by arrows leaving the centre, while energy sources are denoted with arrows leading towards the centre. The resulting net energy use (the sum of sources and sinks) of three typical neighbourhood types is compared.

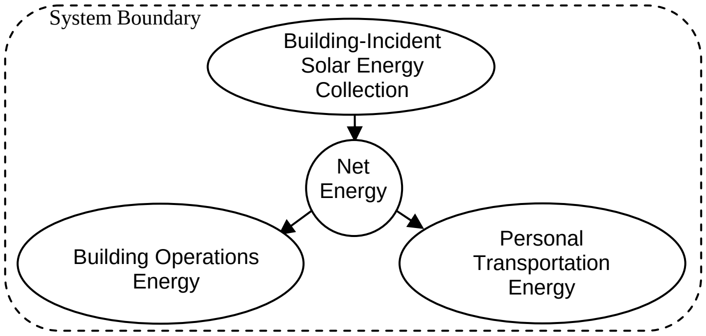


Figure 2. Scope of the study

This methodology is applied to two scenarios:

1. Base Case: Average new home performance, average vehicle fleet, and nominal solar collector efficiency.
2. Efficient Case: Energy efficiency measures and ground source heat pumps (GSHP) are added to the homes. The vehicle fleet is upgraded to plug-in hybrids and the solar collector efficiency is doubled.

Case Studies: Development Types

The development of three different types of neighbourhoods is examined. The buildings in each neighbourhood type are assumed to be the identical and appropriate for the location in the city. Buildings of identical geometry are assumed to extend sufficiently far in each direction for the purpose of shading calculations. Urban land rent theory suggests that land at the center of the CBD is the most valuable and thus only the densest of developments are justified in that location (Ball, 1985). Likewise, land only becomes sufficiently inexpensive to justify low-density development in the outskirts of a city. Each neighbourhood follows this trend and is summarized Table 1.

Table 1. Summary of neighbourhood characteristics

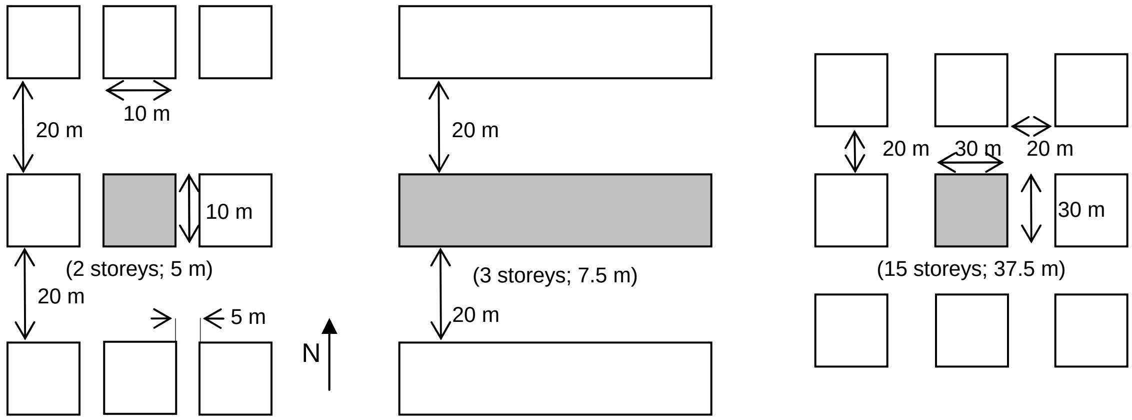
Neighbourhood Type	**Low-density, outer suburbs**	**Medium-density, inner suburbs**	**High-density, inner city**
Primary Building Type	Detached houses	Townhouses	High-rise MURBs (multi-unit residential buildings)
Distance to CBD (km)	30	10	5
Housing density[a] (units/ha)	21	115	540

[a] Determined by the inverse of the land area (including share of road and lot) per unit

The shape of the buildings is shown in Table 2. Building layout and representative photographs of each housing type was aimed to balance practicality with solar availability. For, instance, an elongated, south-facing house has greater solar energy availability but requires a wider lot, requiring longer roads and other infrastructure. All buildings are oriented with the cardinal directions, with the intention of maximizing south-facing solar exposure.

Table 2. Building layout and representative photographs of each housing type

Low-density	Medium-density	High-density
		



Note: Drawings not to scale.

Functional Units

As concluded by Norman et al (2006), the functional unit is critical for this type of study. This paper reports in both energy per unit area of living space and energy per capita. All building types are assumed to be 100% occupied. All values are on an annual basis. This is important for both building operating energy and solar availability because a year represents an entire cycle in climate patterns.

DATA

An effort was made to use reliable, publicly available data for this study. The following three sections outline the data sources and assumptions. Each section explains both data for the two cases.

Household Energy Use

House energy was obtained from NRCan (2006) and NRCan (2008b), which have comprehensive data for detached and attached homes and apartments. These sources provide data for each province. Thus building energy in Ontario is assumed to be equivalent to Toronto. This is justified by the fact that two-thirds of Ontario's population is concentrated in Southern Ontario where the climate is similar or the same as Toronto's (Statistics Canada, 2006). The data are for existing homes, but the primary objective of this study is to provide guidance on the establishment of new neighbourhoods and their buildings. In Ontario, on average, new homes are 17% less energy intensive than the average building stock. This was assumed to apply to all building types being considered. The average size of new homes is greater than the average building stock. Thus, the floor area of new housing units was estimated from Toronto real estate listings in 2008. The low-, medium-, and high-density housing energy data are based on detached houses, attached houses, and apartments, respectively, according to NRCan (2008).

Table 3. Annual household energy use (Base Case)

	Low-density	**Medium-density**	**High-density**	**Source**
Floor area per unit (m^2)	200	130[a]	100[a]	estimated
People per unit	3.3	2.8	2.1	(NRCan, 2008b)
Energy Intensity (kWh/m^2)	246	237	184	(NRCan, 2006), (NRCan, 2008b)
Energy per household (kWh)	49,200	30,800	18,400	
Energy per person (kWh)	14,900	11,000	8,800	

[a] Includes common areas (hallways, foyers, stairs, etc.)

For the Efficient Case, a 30% reduction in energy use is achieved by implementing energy efficiency measures, as seen with the R-2000 program (NRCan, 2008a). This improvement is assumed to be distributed among all energy end-uses (e.g., heating, cooling, appliances, and lighting). A further improvement is implemented using a ground source heat pump (GSHP) with an average coefficient of performance of 3. Thus heating and cooling energy is reduced by two-thirds. Most closed-loop GSHPs have coefficients of performance (COP) of 2.5 to 4 (NRCan, 2008c). The building operating energy for the EH scenario is summarized in Table 4. Athienitis (2008) reports that the energy consumption in a passive solar house built in 2006 with a GSHP and a 1.9 kW building integrated photovoltaic (BIPV/T) system is about 50 kWh/m^2. Thus, the numbers shown in Table 4 are expected to drop significantly in the next 5 to10 years.

Table 4. Building operating energy (Efficient Case)

	Low-density	Medium-density	High-density
Energy/household (kWh)	22,480	14,823	9,787
Energy/Person (kWh)	6,812	5,294	4,661
Energy/m^2 (kWh)	112	114	98

Transportation Energy

Transportation energy is difficult to model because it is based on a family's socio-economic situation as much as its geographical characteristics. Fortunately, the MRA performed by the IBI Group (2000) established extensive relationships for transportation mode and distance depending on all significant factors. The product of this work is a spreadsheet-based model that can be used to predict household automobile VKT (personal vehicle km traveled) and transit PKT (passenger km traveled) based on a variety of household and geographical inputs. The VKT data accounts for the fact that some automobile trips taken include one or more passengers. Table 5 and Table 6 summarize the distances traveled and energy use for each mode of transportation, respectively. Table 7 shows the results the resulting energy use.

Table 5. Daily distance traveled for each neighbourhood type (Base Case)

	Low-density	Medium-density	High-density
VKT/household	97.7	54.1	15.8
PKT/household	19.5	15.1	10.2
Subway km, (%)	8.9, (45.4%)	8.5, (56.0%)	6.2, (60.6%)
Commuter Train km, (%)	2.7, (13.8%)	0.1, (0.6%)	0.0, (0%)
Bus km, (%)	8.0, (40.9%)	6.6, (43.4%)	4.0, (39.4%)

Table 6. Energy use for transportation (Base Case)

Mode	Energy	Source
Automobile	1.01 kWh/VKT	(Norman et al., 2006)
Subway	0.12 kWh/PKT	(Kennedy, 2002)
Commuter Train	0.10 kWh/PKT	(Kennedy, 2002)
Bus	0.46 kWh/PKT	(Kennedy, 2002)

Table 7. Total transportation energy use (Base Case)

	Low-density	Medium-density	High-density
VKT/household	26,048	12,618	4,838
PKT/household	1,547	1,360	970
Subway	1,221	1,166	853
Commuter Train	94	3	-
Bus	232	191	117
Total/household (kWh)	28,059	14,387	6,099
Total/person (kWh)	8,503	5,138	2,904
Total/m^2 (kWh)	140	111	61

For the Efficient Case, the public transportation fleet is assumed to remain the same, while the private vehicle fleet is assumed to be upgraded to plug-in hybrid electric vehicles (PHEV). Mid-sized PHEVs use about 0.19 kWh of electricity per km driven (Kintner-Meyer et al., 2007). Such vehicles use stored electrical energy in a battery until that energy is consumed, but can recharge the battery using gasoline. Ideally, the battery is charged using electricity from the grid or locally produced electricity. Kintner-Meyer et al suggest an electric-only range of 33 miles (53 km) on a single charge. Daily travel distance of personal vehicles, thus, becomes important. The transportation model used predicts vehicle ownership per household. Thus, average distance traveled per car per day can be determined. Table 8 summarizes this data. Assuming that the average distance traveled per vehicle represents the actual daily distance, all households can rely on electricity – barely – to fuel their vehicles. However, this is a very optimistic assumption. The transportation model suggests that the average daily VKT is 7% (390/365) greater than the average weekday VKT. To be more conservative, it was assumed that the average daily VKT for 13 out of 14 days holds, while the excess distance is traveled on the 14th day. This assumption leads to a 5.5% increase in energy use over the optimum for the low-density case. Once the battery becomes discharged, gasoline is consumed at a city-highway rate of about 56 mpg (0.41 kWh/km) or about double that of the consumption for electricity (Kintner-Meyer et al., 2007).

Table 8. Household vehicle ownership and daily range and revised daily energy use (EV scenario)

	Low-density	Medium-density	High-density
Vehicles/household	1.9	1.38	0.79
Average daily VKT	97.7	54.1	15.8
Average daily VKT/Vehicle	51.4	39.2	20.0
Long trip distance (km)	106.4	81.1	41.4
Electricity share (%)	50	65	100
Gasoline share (%)	50	35	0%
Annual automobile energy/household (kWh)	7,618	4,327	1,306
Annual transit energy/household (kWh)	1,547	1,360	970
Annual transportation energy/person (kWh)	2,777	2,031	813
Annual transportation energy/m^2 (kWh)	46	44	23

Solar Energy Availability

Building-integrated solar energy collection is accomplished by integrating solar energy collectors into building façades or roofs. Aside from displacing purchased energy, solar collectors can replace traditional building materials, such as cladding. There are four major categories of building-integrated solar energy collection: passive solar heating, photovoltaic (PV) panels, solar thermal collectors, and daylight. Passive solar heating is often considered to be the most economical and has the byproduct of daylighting, but the energy collected is typically passively stored in the building materials and is thus under practical and thermal comfort constraints (Hastings, 1995). Also, its usefulness is limited to the heating season, making it most suitable for the near equator-facing façade. PV panels tend to be among the most expensive means to collect solar energy but the electricity produced is more valuable and flexible than thermal energy. Electrical energy does not need be stored on-site (for grid-tied systems) and can be used to power ground-source heat pumps, which usually have a coefficients of performance of about 3 (NRCan, 2008c). This means that three units of heat energy can be produced for every one unit of electrical energy. Solar thermal collectors are efficient, but their performance is dependent on demand (Duffie and Beckman, 2006). With typical storage tanks, heat can be stored for several days. However, excess heat production cannot easily be used; leading to diminishing returns with increased collector area. Daylight has limited value for reducing energy use in the residential sector. It only consumes about 5% of household energy use (NRCan, 2008b). Also, it is available only during the day, when homes tend to be unoccupied.

It should be noted that there is potential to pair forms of solar energy collection including: PV and thermal, PV and daylighting, and passive solar heating and daylighting. For instance, BIPV/T collectors pass a fluid (such as air) behind PV modules. Waste heat from the PV modules, which is transferred to the fluid, can be used for a number of applications such as space heating or domestic hot water heating (Athienitis, 2008; Charron and Athienitis, 2006).

Since housing energy data is based on existing homes with a certain fraction of their envelope made up of windows, walls cannot be completely covered by solar collectors. Thus, windows were estimated to take up 15% of detached house walls and 25% of townhouse and high-rise exterior walls. Windows are assumed to be distributed equally on all walls. Passive solar gains from these windows are implicitly included in the building operating energy data. Roofs are assumed to be void of fenestration.

Further constraints to solar collector area are caused by economics. All walls of a building receive some solar radiation throughout the year, although it may only be diffuse or reflected. However, since solar collectors can be expensive, there is a threshold below which, installing collectors becomes uneconomical. Compagnon's (2004) recommended thresholds are summarized in Table 9.

Table 9. Economical Thresholds for solar energy systems (adapted from Compagnon (2004))

Solar Energy Use	Façade-Mounted	Roof-mounted
Passive Solar Heating[a]	356 $kWhm^{-2}a^{-1}$ (during heating season)	356 $kWhm^{-2}a^{-1}$ (during heating season)
Photovoltaic Systems	800 $kWhm^{-2}a^{-1}$	1000 $kWhm^{-2}a^{-1}$
Solar Thermal Collectors	400 $kWhm^{-2}a^{-1}$	600 $kWhm^{-2}a^{-1}$

[a] Adapted to the Toronto climate

For the current analysis, it is not the collector efficiency that matters, but rather the effective annual system efficiency, which is defined as:

$$\eta_{eff} = \frac{\text{Reduction in annual household energy use}}{\text{Annual incident solar energy}}$$

Because it would be impractical to attempt to model the tens of possible solar energy system configurations, a representative solar collector is modeled. This fictional solar collector is assumed to have a 10% efficiency and 700 kWh/m^2/year economical threshold. That is, only surfaces receiving more than this threshold have solar collectors mounted to them. To put these values in context, Table 9 and Table 10 provide some values for common solar collector technologies. The exact threshold is dependent on local current and forecasted economic conditions as well as equipment costs. However, the methodology remains valid.

Table 10. Solar collector and system efficiencies

Solar Energy Use	Collector Efficiency (%)	Annual Effective Efficiency (%)	Source
Passive Solar Heating	49[a]	9[b]	calculated
Photovoltaic Systems	5 to 20	4.75 to 18[c]	(GSES, 2004)
Solar Thermal Collectors	up to 70	up to 35[d]	(GSES, 2005)

[a] Based on winter conditions: 1000W/m^2 on facade , a temperature difference of 30°C outside, SHGC=0.75; window U-value=1.3 W/m^2K; utilization factor of 0.7.
[b] Estimated as suggested by Compagnon (2004); Toronto has 4200 heating degree days; unwanted solar gains are assumed to be rejected.
[c] Based on inverter/uptake efficiency of 90%.
[d] Depends on what thermal energy is used for. For SDHW, it could be 35%. For heating with air based collectors, it could be much lower since demand is seasonal.

Large façades may experience substantially different levels of annual incident solar radiation because of shading. For the analysis, each wall is discretized by storey. Thus, based on the aforementioned threshold, a multi-storey building may have collectors mounted on only the top several floors and the roof. For this study, each suitable surface is assumed to have collectors covering its entire area. While there is opportunity to orient surfaces to exceed the annual solar radiation threshold, this is most appropriate for roofs only. However, horizontal surfaces already exceed the threshold. Thus, roofs were modeled as being flat and horizontal.

Solar energy availability was determined from annual computer simulations using ESP-r based on the Toronto climate (ESRU, 2007). ESP-r allows both the subject building and the surrounding buildings to be modeled. It then produces information about the amount of incident solar radiation on each surface of the subject building. The homes were assumed to be shaded only by neighbouring buildings (i.e., strategic landscaping is assumed to prevent shading of solar collectors). Only building-integrated collectors were considered. Detailed intermediate results are shown for the high-rise building in Table 11, while final results for all three building types are shown in Table 12.

Table 11. Annual solar radiation (kWh/m^2). Walls that do not meet the threshold are indicated by shaded cells. The roof of this building (and the other types explored) uniformly receives 1311 kWh/m^2 per year.

	South	East	North	West
Top Floor	1,002	775	396	793
14th floor	954	724	360	728
13th floor	909	656	331	657
12th floor	830	582	304	609
11th floor	773	539	298	561
10th floor	690	489	263	509
1st – 9th floor	*(solar radiation is less than the threshold for all orientations)*			

Table 12. Total useful annual solar radiation received by each building type

	Low-density	Medium-density	High-density
Per household (kWh)	47,982	14,328	2,876
Per person (kWh)	14,540	5,120	1,370
Per m^2 (kWh)	240	110	29

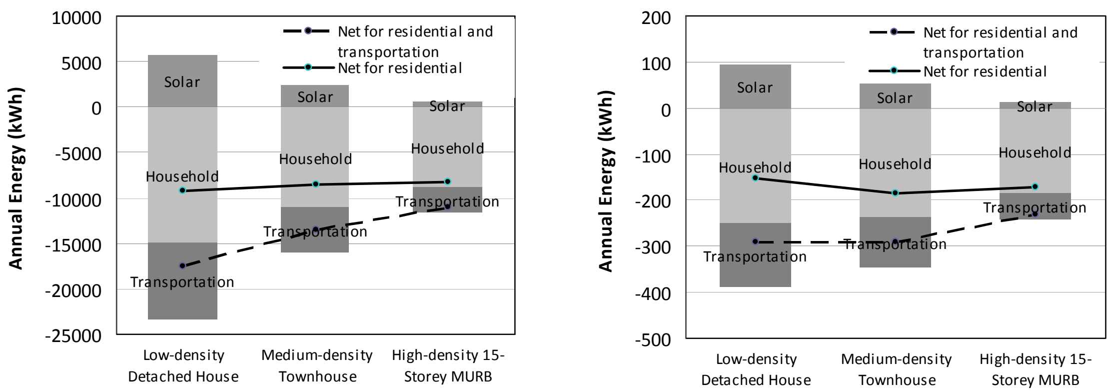
For the Efficient Case, collector efficiency is assumed to double to 20%. To maintain the same economic threshold in terms of absolute useful energy production, the threshold was halved to 350 kWh/m^2/year.

RESULTS

The results for the two cases are provided below.

Base Case

Figure 3 shows that the net residential energy (transportation energy excluded) is relatively insensitive to housing density. The advantage of compact housing is balanced with the lower solar energy availability. When transportation is included, the high-density neighbourhood is favoured for both functional units. However, the net energy is negative and high, suggesting that merely applying solar collectors to standard houses does not justify low-density housing.

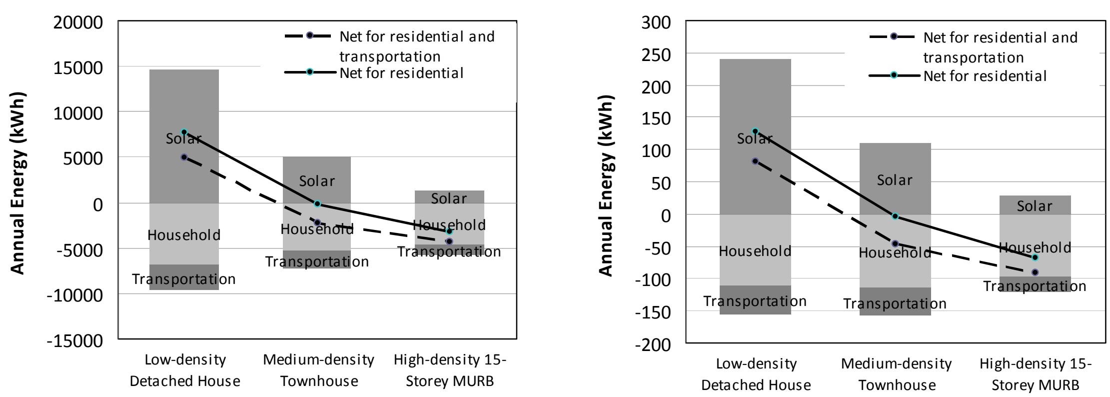


(a) Energy per person (b) Energy per m^2

Figure 3. Net energy for base case

Efficient Case

Figure 4 shows that when the efficiency of all systems considered is substantially increased significantly, the trend is revered. The results suggest that a housing form with a density that is slightly less than the medium-density case can achieve net-zero energy under these conditions.



(a) Energy per person (b) Energy per m^2

Figure 4. Net energy for efficient case

DISCUSSION AND CONCLUSIONS

This paper looked at housing energy, building-integrated solar energy collection, and personal transportation energy, in an attempt to quantitatively compare different housing forms and densities. The boundary of energy flows was drawn at the household level. The results demonstrate that generally, under current conditions, high-density development is superior with regards to net energy, regardless of the solar energy collection potential. The extra solar energy availability associated with low-density development is not justified by the greater transportation energy. Only once the all major energy consumers are upgraded does the trend reverse – the low-density development has a lower net energy than the medium- and high-density developments. However, this requires that the entire vehicle fleet be converted. Otherwise, encouraging low-density development pushes a city outwards and increases average transportation energy for all (whether or not they own PHEVs or equivalently efficient personal vehicles. It was found that when only two of the three upgrades (including house energy efficiency, solar collector efficiency, and vehicle fleet efficiency) are applied (not shown), low-density housing, at best, matches the net energy use of high-density housing.

This study focused on the energy balance at the residential level, and concluded that designing homes such that they can collect as much energy on-site as they consume may not be optimal because of the implications for transportation energy. However, that should not be extended to conclude that solar energy (or other forms of renewable energy) should not be collected elsewhere to achieve net-zero energy on the urban scale. For instance existing buildings with large roofs and relatively low energy consumption, such as big box retail stores and warehouses, have the potential to supply excess energy to other buildings.

This study was based on typical neighbourhoods in Toronto with current layouts of residential, commercial, and industrial zones. Ultimately, there is potential to reduce transportation energy by using good planning. Thus, this suggests that the traditional boundary (at the household level) for energy studies should be challenged. Instead, the boundary should be extended to the community or municipal level. Otherwise, the implications of transportation energy are overlooked.

While this study focused on energy, it should be repeated for GHGs and economics. Many other interesting aspects could be explored, including wind energy and urban agriculture as a form of solar energy collection. Also, the trend towards telecommuting should be considered, since it can reduce the correlation between transportation energy and housing density. For instance, Koenig et al (1996) found that individuals reduced their daily personal vehicle kilometers traveled by an average of 77% after beginning to telecommute.

This study assumed that all solar energy collected is useful and that excess electricity can be sold to the grid. This assumption is reasonable for relatively low levels of market saturation, but there is a point where instantaneous regional solar energy collection could exceed demand. At that point, energy storage would be required. Thus, future research is needed to consider peak production and loads of electrical grids that are highly saturated with solar energy collectors.

This study concludes that only if both building-integrated solar collectors and strict energy efficiency measures, (including upgrading to PHEVs), are applied on a city-wide basis, does low-density housing begin to prevail. New urban developments should not only contain low-energy buildings, but should also be situated in medium to high-density neighbourhoods with good access to public transportation. Buildings that obtain some or all of their energy from solar energy in an attempt to reduce energy use must not be assessed as an isolated system, but rather as an integrated part of the surroundings.

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