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The relationship between net energy use and the urban density of solar buildings

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Abstract. There is a paradoxical relationship between the density of solar housing and net household energy use. The amount of solar energy available per person decreases as density increases. At the same time, transportation energy, and to some extent, household operating energy decreases. Thus, an interesting question is posed: how does net energy use vary with housing density? This study attempts to provide insight into this question by examining three housing forms: low-density detached homes, medium-density townhouses, and high-density high-rise apartments 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. Solar energy availability is determined on the basis of an effective annual collector efficiency. The results show that under the base case in which solar panels are applied to conventional homes, the high-density development uses one-third less energy than the low-density one. Improving the efficiency of the homes results in a similar trend. Only when the personal vehicle fleet or solar collectors are made to be extremely efficient does the trend reverse—the low-density development results in lower net energy.

1 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 current urban population is about 50% of the total world population, and is expected to reach 60% by 2030, absorbing all new population growth (Cohen, 2004). With this flux comes an opportunity to rethink the way cities are expanded. Among the common development styles are densification of previously developed areas, brownfield development (ie development of previously developed but abandoned land), and greenfield development (ie development of farmland or virgin land).

Typical suburban, single detached houses are associated with the so-called 'American dream' with a large yard, multicar garage, relatively cheap 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 for compact forms (Downs, 1999). Suburban developments are associated with health problems because of 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 (IBI Group, 2000). Another consideration is that many new subdivisions are built on farmland, thus reducing local agricultural production and quite possibly driving it to less productive land (Hasse and Lathrop, 2003). 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. This solar energy can contribute to household operating energy, personal transportation energy, and home-scale food production (Pogharian et al, 2008).

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). They may also provide less green space. 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. Denser building forms also translate to a greater volume to exterior area ratio, leading to theoretically lower space-conditioning loads. They also enable more efficient use of district heating, which relies on relatively dense building spacing to minimize thermal losses from distribution networks. 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 potential for solar energy collection. 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.

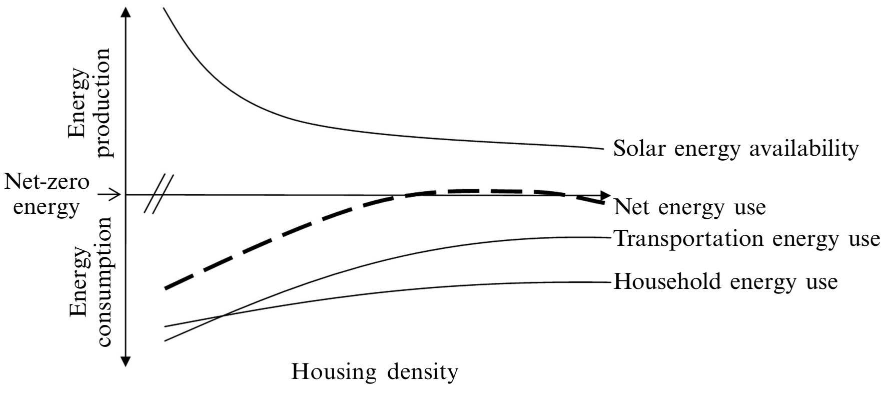

Figure 1. Trends in energy use (or solar availability) versus housing density.

A number of studies have quantified the relationship between urban density and transportation energy. One of the most recognized, by Newman and Kenworthy (1989) plotted the two metrics for a large number of North American, Asian, and European cities and found that the average population density of a city has a tremendous influence on personal transportation energy. However, their findings are based on aggregate quantities of the entire cities. The Transportation Tomorrow Survey (University of Toronto, 2003) collected detailed information from Toronto residents about their transportation habits. The IBI Group (2000) performed a multivariate regression analysis (MRA) on the basis of this data. They 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) dominated the total emissions of suburbanites in Toronto. Their data confirm that overall emissions generally increase with distance to downtown.

The benefit of building compactness to reduce the surface area to volume ratio is beneficial to some extent but it also reduces access to solar energy, daylight, and fresh air. Batty (2008) looked at the form of buildings and compared them with organisms, stating that as they become larger in volume, the area must attempt to grow proportionally to gain exposure to air and solar energy. Similarly, Steemers (2003, page 13) suggested that there is a balance that must be achieved: "the energy implications of compact densification are balanced between the benefits from reduced heat losses and the nonbenefits of reduced solar and daylight availability." As housing design begins to incorporate higher levels of opaque envelope insulation, such as in the EcoTerra demonstration solar house in Canada (http://www.canmetenergy-canmetenergie.nrcan-rncan-cg.ca/), it is the direct gain fenestration and ventilation air heating that become the key factors for heating loads (Athienitis 2008). Athienitis also pointed out that two-storey homes are preferred over single-storey homes in terms of energy performance and land use.

Norman et al (2006) compared a typical suburban house with a multiunit high-density residential building. They considered the GHG emissions and energy associated with infrastructure, building operations, and transportation. They concluded that the low-density house is 2.0 – 2.5 times more energy and GHG-emission intensive than the high-density home per capita. However, if the functional unit is changed to per unit area of living space, that number drops to 1.0 – 1.5. Thus, the functional unit that is reported is particularly critical to results. This conclusion is equally relevant to this study.

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

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 known as net-zero energy buildings. Recently, the Canada Mortgage and Housing Corporation challenged Canadian builders to design and construct net-zero-energy detached houses (CMHC, 2008). This program yielded fifteen net-zero energy (or near net-zero energy) houses. However, most of the focus is on buildings of relatively low density.

On an annual basis, Toronto receives about 4.7 GJ/m^2 of solar radiation on the ground, while the average residential building stock consumes about 1 GJ/m^2 (NRCan, 2008b). This means that a retrofitted single-storey building with roof-integrated solar collectors must convert about 21% of solar energy to useful energy to achieve net-zero energy. Naturally, the challenge is increased for multistorey buildings. Torcellini and Crawley (2006) examined the potential for converting commercial buildings in the US to net-zero energy. They considered the percentage of buildings that could achieve net-zero energy and concluded that nearly 100% of one-storey buildings would succeed while the percentage drops to 50% and 10% for two-storey and three-storey buildings, respectively. 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 (page 13) 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 study uses three types of development, based on Toronto data, to establish the trends in energy use as a function of housing density. It is a multidisciplinary 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.

2 Methodology

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 figure 2, energy sinks are denoted by the arrows leaving the centre, while energy sources are denoted by the arrow leading towards the centre. The resulting net energy use (the sum of sources and sinks) of three typical neighbourhood types is compared.

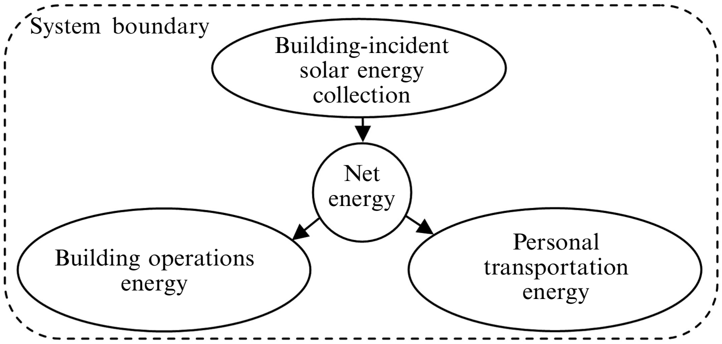

Figure 2. Scope of the study.

This methodology is applied to the following four scenarios:

1 *Base case* (Base): Average new-home performance, average vehicle fleet, nominal solar collector efficiency.

2 *Efficient home*s (EHs): Energy-efficiency measures and ground-source heat pumps (GSHPs) are added to the base case.

3 *Efficient vehicles* (EVs): EHs plus personal automobiles are upgraded to plug-in hybrid automobiles.

4 *Efficient solar collectors* (ECs): EVs plus collector efficiency is improved while the economical threshold is lowered.

2.1 Case studies: development types

The development of three different types of neighbourhoods is examined. The buildings in each neighbourhood type are assumed to be 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. While it is possible, in practice and theory, to have a housing density that does not correspond to the distance to the CBD (eg high-rise buildings in the outer suburbs), urban land-rent theory suggests that this is not optimal (Ball, 1985). It suggests that land at the center of the CBD is the most valuable and thus only the densest of developments are justified there. Likewise, land only becomes sufficiently inexpensive to justify low-density development in the outskirts of a city. The discussions section of this paper qualitatively examines these situations. Each neighbourhood is summarized in table 1.

The shape of the buildings (shown in figure 3) 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. An aspect ratio of about 1.3 is reported by Athienitis and Santamouris (2002) to be optimal for passive solar performance. All buildings are oriented with the cardinal directions, with the intention of maximizing south-facing-facade solar exposure.

Table 1. Summary of neighbourhood characteristics.

Characteristic	Neighbourhood type		
	low-density outer suburbs	medium-density inner suburbs	high-density inner city
Primary building type	detached houses	townhouses	high-rise multiunit residential buildings
Distance to central business district (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.

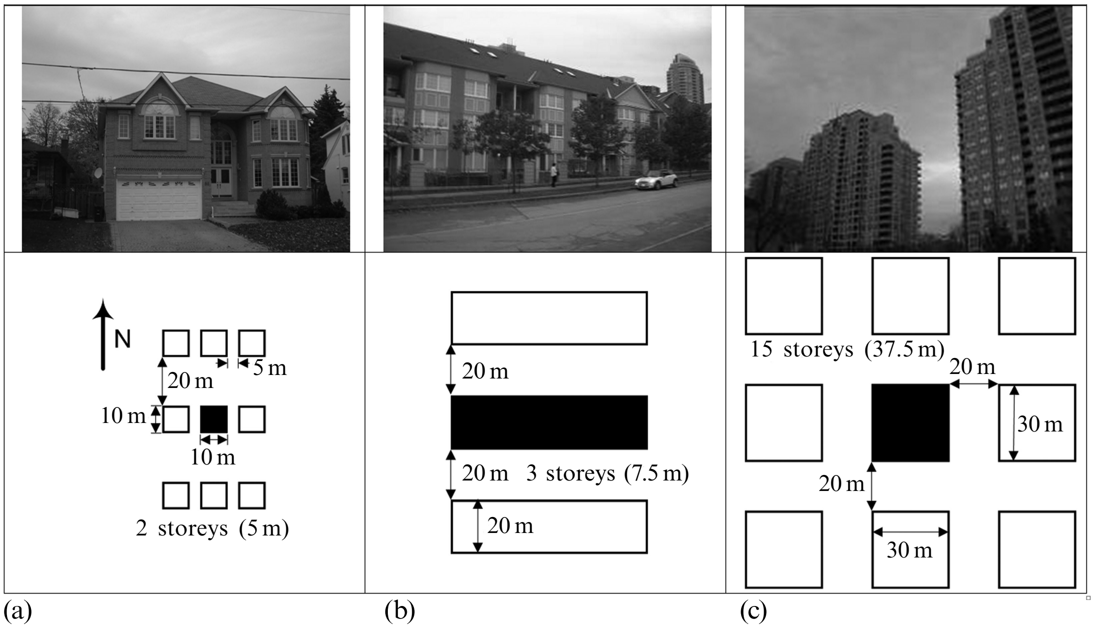

Figure 3. Building layout and representative photographs for each housing type: (a) detached house, low density; (b) townhouses, medium density; (c) high-rise accommodation, high density.

The curvilinear road layouts often seen in new subdivisions would possibly lead to inferior solar exposure, and thus, a rectilinear pattern was modeled.

2.2 Functional units

As concluded by Norman et al (2006), the functional unit is critical to reporting such comparisons. Per capita is useful for assessing the energy needs of populations. However, because dwelling floor areas vary with population density, detached homes face a penalty because of their large floor space per person. Reporting on a per square meter basis alleviates this problem, but is less suitable for determining the energy use for a population. This paper reports in both functional units. All building types are assumed to be fully 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.

3 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 base case and the relevant improved scenario.

3.1 Household energy use

Household energy was obtained from NRCan (2006; 2008b), which have comprehensive data for detached and attached homes and apartments. These sources provide data for each Canadian province. Thus, building energy in Toronto is assumed to be equivalent to that for Ontario. 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, 2006a). The data are for existing homes, but the primary intention of this study is to provide advice for 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 that of 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 (2008b). From table 2, it can be seen that more compact forms show considerably less energy intensity. However, the effect is diminished by the fixed energy consumption of most households from common appliances and domestic hot water use, which tend to be independent of the floor space of a home. These fixed demands account for about 40% of the total (NRCan, 2008b).

Table 2. Annual building operating energy (base case).

	Housing type			Source
	low density	medium density	high density	
Energy per household (kWh)	49 200	30 800	18 400	NRCan (2006; 2008b)
Floor area/unit (m^2)	200	130 [a]	100 [a]	estimated
Energy intensity (kWh/m^2)	246	237	184	
People per household	3.3	2.8	2.1	Statistics Canada (2006b)
Energy per person (kWh)	14 900	11 000	8 800	

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

For the EH scenario 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 (eg, heating, cooling, appliances, and lighting). A further improvement is implemented using a GSHP with an average coefficient of performance (COP) of 3. Thus heating and cooling energy is reduced by two thirds. Most closed-loop GSHPs have COPs of 2.5 – 4 (NRCan, 2008c). The building operating energy for the EH scenario is summarized in table 3. These improvements slightly favour noncompact housing forms because heating and cooling represent a greater portion of their energy use. Athienitis (2008) reports that the energy consumption in a passive solar house built in 2006 with a GSHP and a 1.9 kW BIPV/T (building-integrated photovoltaic/thermal) system is about 50 kWh/m^2 (with approximately R2000 levels of insulation and heat recovery ventilation); this is without triple glazing and without the high levels of insulation required to achieve net-zero energy consumption. Thus, the numbers shown in table 3 are expected to drop significantly in the next five to ten years.

Table 3. Annual building operating energy (efficient home scenario).

	Housing type		
	low density	medium density	high density
Energy intensity (kWh/m^2)	112	114	98
Energy per household (kWh)	22 480	14 823	9 787
Energy per person (kWh)	6 812	5 294	4 661

The urban heat island effect is the phenomenon in which cities tend to be several degrees warmer than their surroundings because of a high albedo and a high concentration of waste heat as a byproduct of human activities (Taha, 1997). This effect is not explicitly included in this study because housing-energy data are aggregate, meaning that high-rise energy use is based on buildings in the core and suburbs, alike. The importance of explicitly including this would be greater for warmer climates.

3.2 Transportation energy

Transportation energy is difficult to model because it is based on a family's socioeconomic 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 factors that they found to be significant. 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) from a variety of household and geographical inputs. The VKT data account for the fact that some automobile trips include one or more passengers. Table 4 and 5 summarize the distances traveled and energy use for each mode of transportation, respectively. Table 6 shows the resulting energy use. Since the data from the Transportation Tomorrow Survey were collected for a single weekday, VKT is slightly under reported while PKT is slightly over reported. Factors of 390 and 300, respectively, were used to annualize the daily data (IBI Group 2000). The former value indicates that, on average, people travel slightly further at weekends than on weekdays.

For the EV scenario, 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). Midsized 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

Table 4. Daily distance traveled for each neighbourhood type (base case). Percentages are shown in parentheses.

	Distance (km)		
	low-density neighbourhood	medium-density neighbourhood	high-density neighbourhood
VKT[a]/household	97.7	54.1	15.8
PKT[b]/household	19.5	15.1	10.2
subway	8.9 (45.4)	8.5 (56.0)	6.2 (60.6)
commuter train	2.7 (13.8)	0.1 (0.6)	0.0 (0)
bus	8.0 (40.9)	6.6 (43.4)	4.0 (39.4)

[a] VKT = personal vehicle km traveled.

[b] PKT = passenger km traveled.

Table 5. Energy use for transportation (base case).

Mode	Energy	Source
Automobile	1.01 kWh/VKT[a]	Norman et al (2006)
Subway	0.12 kWh/PKT[b]	Kennedy (2002)
Commuter train	0.10 kWh/PKT[b]	Kennedy (2002)
Bus	0.46 kWh/PKT[b]	Kennedy (2002)

[a] VKT = personal vehicle km traveled.

[b] PKT = passenger km traveled.

Table 6. Total transportation energy use (base case)

	Low-density neighbourhood	Medium-density neighbourhood	High-density neighbourhood
VKT[a]/household	26 048	12 618	4 838
PKT[b]/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

[a] VKT = personal vehicle km traveled.

[b] PKT = passenger km traveled.

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 7 summarizes these data. Assuming that the average distance traveled per vehicle represents the actual daily distance traveled for everyone, 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 holds for thirteen out of fourteen days, while the excess distance is traveled on the fourteenth day.

Table 7. Household vehicle ownership and daily range and revised daily energy use (EV scenario).

	Low-density neighbourhood	Medium-density neighbourhood	High-density neighbourhood
Vehicle/household	1.9	1.38	0.79
Average daily VKT[a]	97.7	54.1	15.8
Average daily VKT[a]/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

[a] VKT = personal vehicle km traveled.

This long trip is quantified in table 7. 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).

3.3 Solar energy availability

Building-integrated solar energy collection is accomplished by integrating solar energy collectors into building facades 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 facade. The optimal equator-facing window area is about 30% of the facade area for detached houses (Athienitis, 2008). PV panels tend to be among the most expensive means for collecting 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 GSHPs, which usually have a COP 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 day lighting. 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). The secondary benefit of this combination is that the PV modules are cooled, allowing them to perform more efficiently.

Since housing energy data are 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 are 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. 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 8. These limits will decrease with time as collector costs decrease and efficiencies increase.

Table 8. Economical thresholds for solar-energy systems (kWh/m^2/annum). [Adapted from Compagnon (2004).]

Solar energy system	Facade mounted	Roof mounted
Passive solar heating[a]	356 (during heating season)	356 (during heating season)
Photovoltaic systems	800	1000
Solar thermal collectors	400	600

[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:

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

There are four main reasons why this value is necessarily lower than the collector efficiency:

1 *Collector losses*. The nominal values that are often stated for solar collectors are under favourable conditions: low collector temperatures and high solar radiation. However, in reality, collector temperatures tend to be high under high levels of solar radiation, leading to poorer performance.

2 *System losses*. Storage tanks and pipes lose some of the collected energy to the environment. For PV collectors, transmission losses and inverter losses occur.

3 *Seasonal usefulness*. Glazing oriented to capture solar energy in the winter only contributes to the useful energy during this time. Furthermore, undesired solar gains and heat losses resulting from poor thermal resistance of glazing must be subtracted from the useful gains. For some types of solar thermal collectors (eg open-loop, air-based collectors) it may be so cold outside that even with substantial solar radiation the output temperature of the fluid is insufficient to be useful.

4 *Excess production*. When daily demand for heat exceeds production, solar energy utilization is high. However, when the opposite is true and thermal storage is at capacity, the excess energy is not useful and does not contribute to reducing demand. For instance, if collectors are sized to meet domestic hot water demand in the winter, they would typically be grossly oversized for the summer, when daily solar radiation is much higher.

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 8 and table 9 provide some values for common solar collector technologies.

Table 9. Solar collector and system efficiencies.

Solar energy system	Collector efficiency (%)	Annual effective system efficiency (%)	Source
Passive solar heating	49 [a]	16 [b]	calculated
Photovoltaic systems	5–20	4.75–18 [c]	GSES (2004)
Solar thermal collectors	up to 70	up to 35 [d]	GSES (2005)

[a] Based on winter conditions: 1000 W/m^2 on facade, a temperature difference of 30 °C, solar heat gain coefficient = 0.75; window U-value = 1.3 W/m^2 K; utilization factor of 0.7.

[b] Estimated as suggested by Compagnon (2004); Toronto has about 4200 heating degree days and about 550 kWh/m^2 of south-facing facade during the heating season; 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 solar domestic hot water, it could be 35%. For heating with air-based collectors, it could be much lower since demand is seasonal.

Large facades may experience substantially different levels of annual incident solar radiation because of shading. For the analysis, each wall is discretized by storey. Thus, on the basis of the aforementioned threshold, a multistorey 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 (http://www.esra.strath.ac.uk/programs/ESP-r.htm) 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 (ie strategic landscaping is assumed to prevent shading of solar collectors). Only building-integrated collectors were considered. Detailed intermediate results for the high-rise building are shown in table 10, while final results for all three building types are shown in table 11.

In the EC scenario, 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. As shown in table 10, this causes more of the building surfaces to exceed the threshold.

Table 10. 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.

Floor	Orientation			
	south	east	north	west
Top	1002	775	▨ 396	793
14th	954	724	▨ 360	728
13th	909	▨ 656	▨ 331	▨ 657
12th	830	▨ 582	▨ 304	▨ 609
11th	773	▨ 539	▨ 298	▨ 561
10th	▨ 690	▨ 489	▨ 263	▨ 509
1st–9th	(solar radiation is less than the threshold for all orientations)			

Table 11. Total useful annual solar radiation received by each building type.

Annual solar radiation	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

4 Results and discussion

4.1 Scenario: base case

Figure 4 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.

4.2 Scenario: above plus EHs

Figure 5 shows that the near net-zero can be achieved for the total residential energy of detached homes, but the net energy increases with density. That is, the benefit of having greater solar energy potential outweighs compact building forms. However, once transportation energy is included, the high-density neighbourhood is favoured for both functional units. Interestingly, on a per square meter basis, the medium-density neighbourhood is shown to be slightly worse than both of the other types. This is merely a combination of the poorer solar availability not being offset by substantially better household or transportation energy. In fact, the household energy for the townhouse is slightly worse than for the detached house because there is less opportunity to reduce heating and cooling energy. This is because this space-conditioning energy for the townhouse represents 59% of the total compared with 66% for the detached house. For this scenario transportation energy becomes a dominant component of the net energy; thus leading to the next scenario, in which the vehicle fleet efficiency is improved.

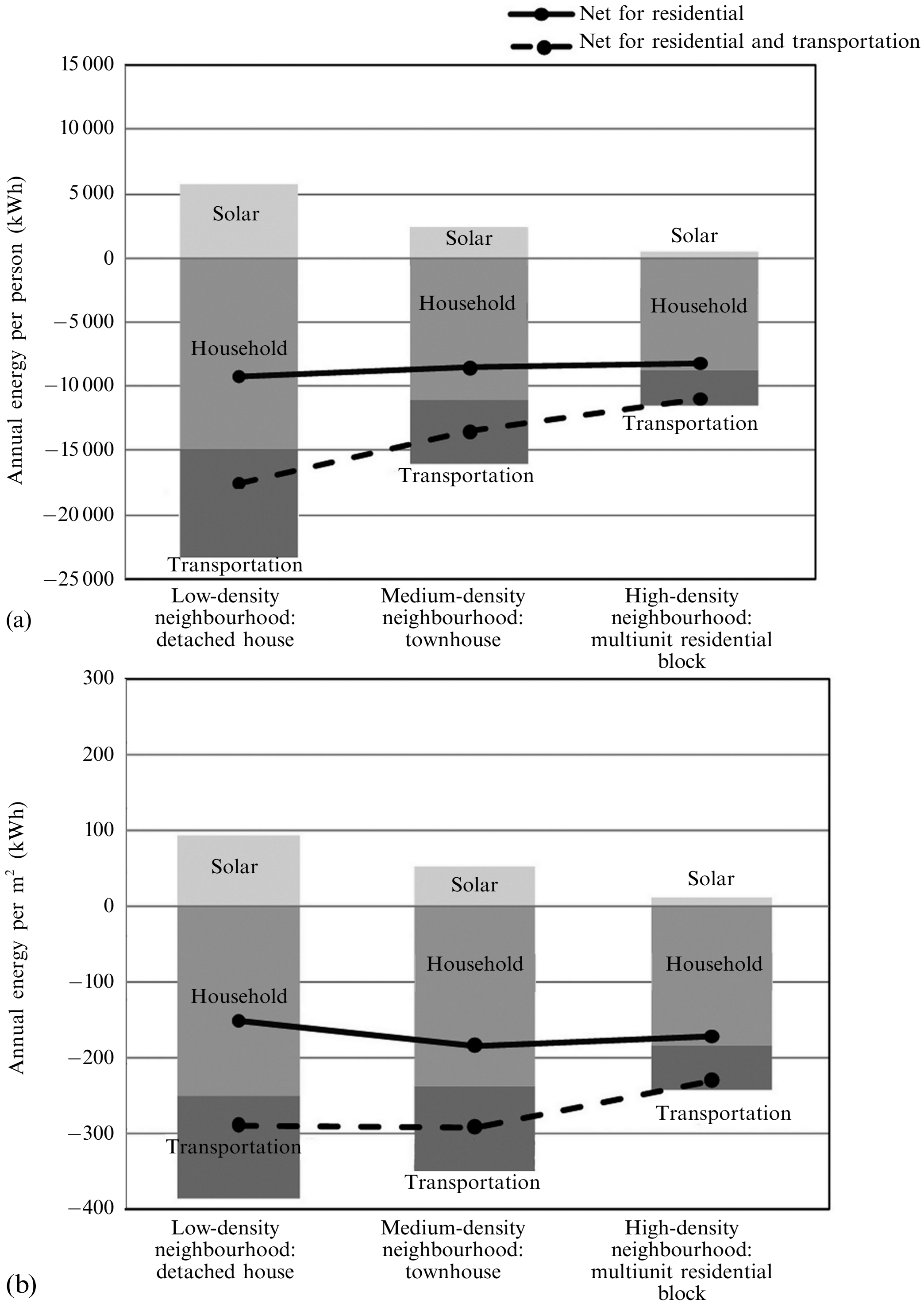

Figure 4. Net energy for base case: (a) energy per person; (b) energy per m^2. Note: 'net for residential' excludes transportation, while 'net for residential and transportation' includes all energy facilities considered.

4.3 Scenario: above plus EVs

When the entire personal vehicle fleet is upgraded to PHEVs, the trend begins to reverse, as shown in figure 6. Because of the vast reduction in transportation energy, the major determining factor of the optimal density is the amount of solar energy available. Thus, detached houses appear to be superior—but only if the strict energy-efficiency measures are implemented. The trends are similar for both functional units.

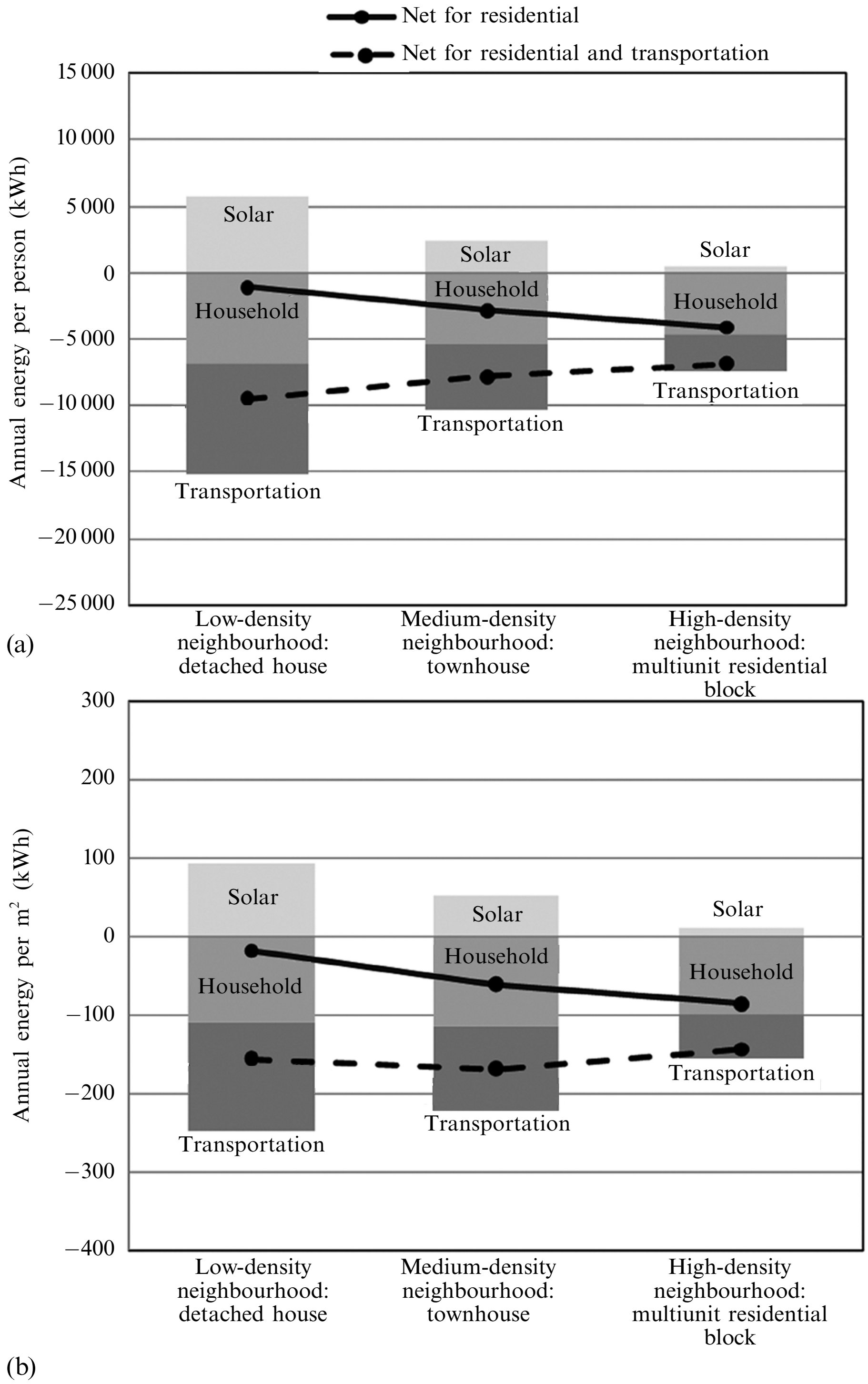

Figure 5. Net energy for efficient homes scenario: (a) energy per person; (b) energy per m^2.

It is critical to note that these conclusions only apply if the entire vehicle fleet is upgraded. If only a select sample upgrade, they themselves may achieve net-zero energy, but at the cost of pushing development of inefficient neighbourhoods outward, away from the CBD.

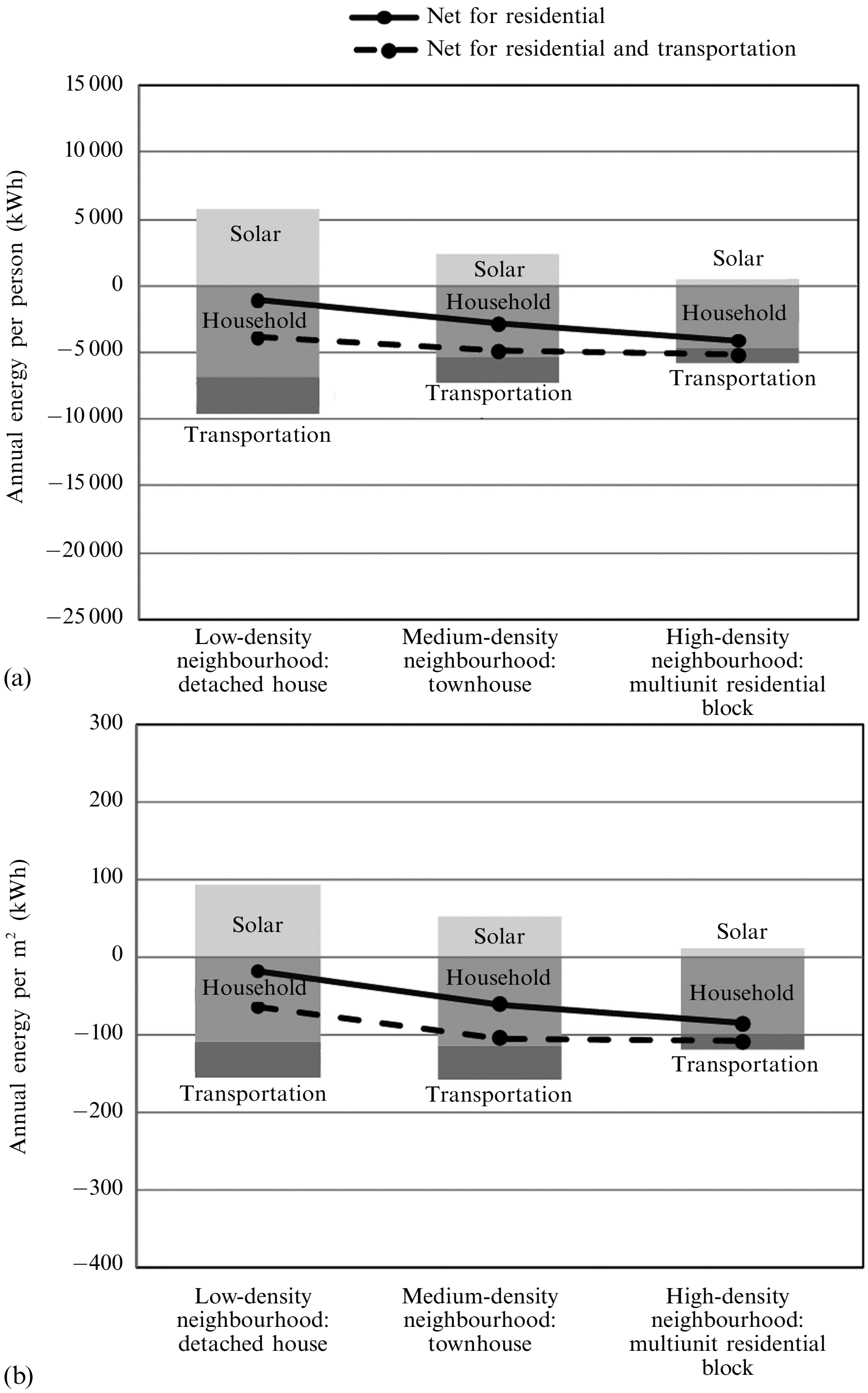

Figure 6. Net energy for efficient vehicles scenario: (a) energy per person; (b) energy per m^2.

4.4 Scenario: above plus ECs

Figure 7 merely exaggerates the trends of the previous scenario. Furthermore, this is the first scenario under which any of the cases performs at net-zero energy or better. 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.

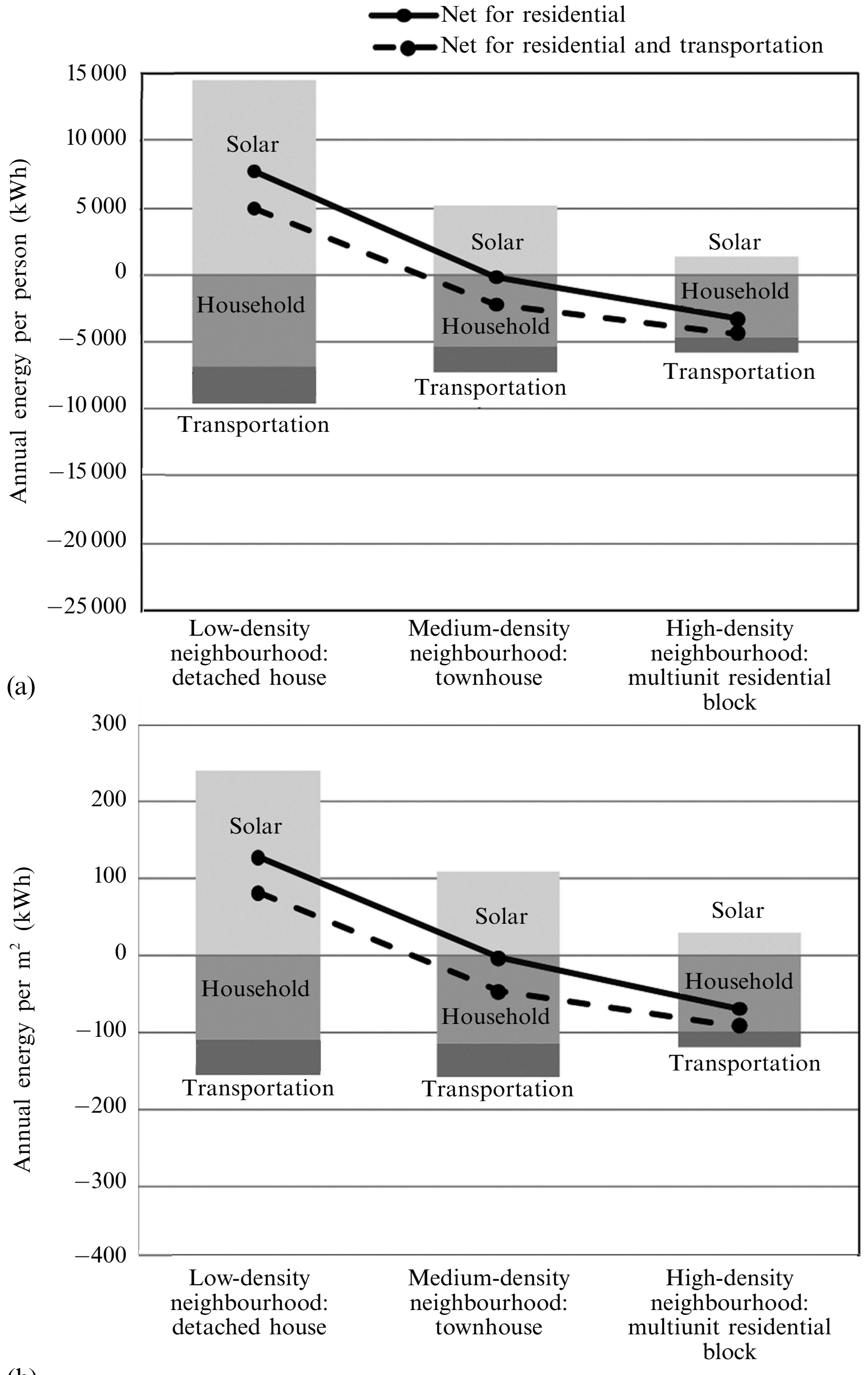

Figure 7. Net energy for efficient solar collectors scenario: (a) energy per person; (b) energy per m^2.

5 Discussion and conclusions

This study looked at housing energy, building-integrated solar energy collection, and personal transportation energy, in an attempt to quantitatively compare different housing forms and densities. From the results it can be concluded that, generally, under current conditions, high-density development is superior with regards to total net energy. The extra solar energy availability associated with low-density development is not justified by the greater transportation energy. This was true even for the scenario when energy-efficiency measures were applied to the homes, as would be the case for new homes. However, once the personal vehicle fleet was converted to PHEVs, the trend reversed—the low-density development has a lower net energy than the medium-density and high-density developments. However, this requires that the entire 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 shown that this form is not justified unless two conditions are met: (1) each home maximizes solar collector coverage and (2) the entire personal vehicle fleet is upgraded to be extremely efficient.

It is not uncommon in Toronto and elsewhere to have small pockets of high-density housing forms in the suburbs. While dense development is encouraged and may lead to future densification of the surroundings, this form of development is not ideal for net energy use, unless it is supported with efficient public transit. Without public transit, this form combines low solar availability with high transportation energy. Conversely, one might argue that a low-density development in the city core minimizes energy use. If the analysis were limited to the household level, this conclusion would be correct. However, consuming high-value land with low-density developments necessarily pushes a city outwards, increasing the average transportation energy use of the remaining households. Instead, a city should aim to locate the maximum number of people where their transportation energy is at a minimum. Ontario's Places to Grow plan encourages this type of densification (Ontario Ministry of the Environment, 2007).

In general, cloudier climates would disproportionately reduce the performance of low-density development and thus favour higher density. Conversely, a sunnier climate would favour a lower density. If everything else remained the same, except for less severe temperatures (ie, cooler summers and milder winters) compact building forms would be less beneficial because heating and cooling energy would become significant. A colder climate, in particular, would favour compact building forms that preserve heat better.

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. It was based on the assumption that building energy demands be met with building-integrated solar collectors. However, that should not be extended to conclude that solar energy (or other forms of renewable energy, such as wind or biogas) should not be collected elsewhere to achieve net-zero energy on the urban scale. For instance, 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. Solar thermal collectors should be given priority as building-integrated renewables because of their relatively higher efficiency (than PV) and higher energy-transmission losses. Ultimately, there is potential to reduce transportation energy by using good planning and mixed-used neighbourhoods. 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. This study focused on a traditional grid-like street pattern, but could be expanded to consider contemporary forms. It may be advantageous to build slightly curved streets to prevent the peak solar electricity generation of all buildings from occuring at the same time (assuming facades and, thus, building-integrated collectors are tangential to the street). Also, the trend towards telecommuting should be considered, since it can reduce the correlation between transportation energy and housing density. One study indicates that telecommuter VKT is 11.5% less than non-telecommuters during a five-day workweek. However, aggregate vehicle-distance travelled has been found to be about 0.8% (equivalent to about half of that resulting from public transportation) in the US (Choo et al, 2005). Interestingly, the total potential benefit of telecommuting may be diminished by the fact that it enables people to live further from urban centres, causing their nonwork trips to increase in distance (Mokhtarian et al, 2004).

The transportation and household energy-use data for this study were obtained from measured results, and thus, while representing reality, are limited to the context from which they were taken and are consequently somewhat inflexible. Also, this means that the data are decoupled from each other and not well suited to explore the effect of different design options and the corresponding interactions. Future work on this topic could be performed with simulation tools that couple two or more of the energy quantities that were examined in this study. For example, the subdivision energy analysis tool (Christensen and Horowitz, 2008) allows the energy implications (household energy use and passive and active solar energy collection) to be quickly examined for detached houses that line virtually any street pattern. CitySim (Robinson et al, 2009) also includes transportation energy and allows nearly any building form. These tools are currently under development, but upon public release they will provide a previously unseen platform for integrated neighbourhood design.

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 the effect on the grid when a temporal mismatch between solar energy conversion and electricity demand occurs—both diurnally and seasonally. 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. The results suggest that low-energy development is possible in both low-density and high-density forms. However, low-density forms must efficiently utilize the available solar energy to achieve this status. Higher-density developments have significant potential to reduce energy use because of the shortened average distance between buildings and between trip origin and destination, which can translate to lower energy-transmission losses and transportation. The caveat to this is that proper infrastructure must be in place. New urban developments should not only contain low-energy buildings, but they should be situated in neighbourhoods of medium to high density with good access to public transportation and amenities. This study demonstrated that, where possible, it is desirable to include transportation energy in the analysis of new building developments, since transportation energy can rival household-operating energy in magnitude, and is highly dependent on geographical context.

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