# 2 Counting Urban Carbon: Baseline and Boundaries of Current Findings

## Chapter Summary

**This chapter describes the baseline of findings from current research and identifies relevant boundaries. Particular attention is given to the inherent complexity and uncertainty of urban systems. Nonetheless, consistent factors are identified for further refinement and incorporation into a decision support tool.**

*This chapter incorporates the first half of the peer-reviewed publication "Counting Urban Carbon" (Mehaffy, 2014) as well as additional material from the paper "Prospects for scenario-modelling urban design methodologies to achieve significant greenhouse gas emissions reductions" (Mehaffy, 2013). This material covers the boundaries and methodology for gathering and assessing current research findings. The second half of the paper "Counting Urban Carbon" deals with the methodology behind the decision support tool discussed later, and it appears as part of Chapter 6, Modelling Methodologies.*

As noted in the introductory chapter, the dynamics of urban systems are among the most complex of any system we know. They include myriad factors and interactions, including perhaps the most complex of all factors: those of human behaviour. If we are to make headway in the stated aim of mitigating greenhouse gas emissions with new urban design decision-making tools, we need to be able to analyse the urban systems in question, and clearly identify, in a useful way, the factors that can be varied by design to produce the preferred results. We must also identify, to the extent they will substantially change the results, how those factors interact, possibly producing unintended consequences.

This in turn will require a very clear understanding of current emissions and their trends; evidence for the urban factors that account for emissions reductions (on conversely, increases); their potential interactions; the methodologies that can model potential reductions or increases with useful accuracy; the factors that introduce uncertainty into current measurements; and the strategies to deal with inherent uncertainty, in both the current measurements and the evidence-based models of future emissions.

In short, we need a clear "road map" of the current state of knowledge about greenhouse gas emissions, and the complexities and uncertainties that must be accounted for in development and application of our ultimate goal, an effective design decision support tool. That is the goal of this chapter.

One significant problem is that there are well-documented complexities and ambiguities in the way we measure emissions, as this chapter will discuss in more detail. In greenhouse gas emissions as in other scientific subject areas, there are characteristic phenomena of uncertainty in measurement which must be accounted for. Moreover, there are potential problems of confusion between kinds of measurements, such as production-based emissions and consumption-based emissions (Hoornweg, Sugar and Gomez, 2011; Satterthwaite, 2008).

Moreover, there is inherent uncertainty and even randomness in the way these emissions will actually occur, which makes prediction a problematic, possibly even self-deceptive exercise (Taleb, 2005; Kahneman, 2011). In part this is because the systems themselves are not static but are self-modifying, posing a fundamental challenge to both science and policy (Mayumi and Giampietro, 2006). We will discuss this particular challenge in more detail in a later chapter (Chapter 6, Modelling Methodologies).

## § 2.1 Inventory data sources and boundaries

Before we consider these deeper complexities, the first task is to identify the sources of emissions data and their relevant boundary conditions, so that we may draw usefully reliable findings. There are in fact many distinct inventories of GHG emissions, including local inventories gathered for specific purposes. (Examples include corporate inventories used to measure progress against goals, inventories developed for specific research projects (an example of which is the Vulcan Project) and inventories generated by specific measurement technologies (such as NASA's Orbiting Carbon Observatory 2, or the Japanese Aerospace Exploration Agency's Greenhouse Gases Observing Satellite, or GOSAT).

However, we must be careful not to mix data from different sources, which may be measured under different protocols or boundary definitions. We must also be careful to describe the boundaries of our own analysis, and what is being measured and what is not. Chapter 1 set out the boundary conditions of the research. For the work reported in this chapter we must further define the boundaries of measurement as follows:

1. ***Emissions per capita.*** The research will not look at emissions per geographical unit, per economic sector, or other kinds of units. Per-capita emissions data has the advantage of focussing on a global standard unit – one human individual – and the effects on emissions from that unit as the urban form and other conditions around it vary.
2. ***Consumption activities.*** The research will not look at emissions from production activities per se, but will account for them as the consequence of demand and consumption originating with individual consumers. This too helps to focus on the influences on activities of individual consumers from varying urban forms. There are of course significant factors that lie outside of this boundary: for example, policy decisions to shift to non-emitting production sources, changes to regulatory policies or technologies limiting production emissions, and the like. Though potentially very important elements of a wider GHG mitigation strategy, these factors will not be considered in this research.
3. ***Emissions measured according to a single global standard protocol.*** The research will not consider local inventories that define their own methodologies, since they may not be commensurable with other inventories. A single standard, regardless of flaws it may embody, does at least have the ability to reveal significant variations in emissions in response to other variables, including urban form.
4. ***Emissions measured as "CO2 Equivalent" in metric tonnes.*** This methodology accounts for the varying greenhouse effect and atmospheric persistence of different gases such as methane and chlorofluorocarbons, and expresses them as equivalent units in carbon dioxide of their "global warming potential" (GWP). It uses the measurement unit of "metric tonnes" which is widely accepted.

For this purpose, perhaps the most comprehensive set of inventories, and the most useful, is the set of national inventories that are provided under standardised technical specifications according to the

United Nations Framework Convention on Climate Change (UNFCCC). In turn this framework uses the ISO 14064 standard for measuring, quantifying, reporting and verifying emissions. From this set of inventories, this research will draw on the CO2 Equivalent per capita reports.

## § 2.2 Inventory uncertainties

If we are seeking to develop a useful predictive model for design decision support, we must also assess whether the data on which we rely to develop the model and to measure its effectiveness is accurate enough to provide the basis for usefully accurate prediction. To the extent the data is unreliable, our predictions will also likely become unreliable. In this regard, there are several well-recognized problems to take into account.

Many authors have documented inherent uncertainties with current greenhouse gas inventories, which may result in errors as high as 20% (Rypdal and Winiwarter, 2001). These errors are even more significant when distinctions are not kept clear between production-based and consumption-based values. Hoornweg, Sugar and Gomez (2011) demonstrate that per-capita emissions can vary significantly for the same resident of a city or country depending on whether these are production- or consumption-based values. Such distinctions are often confused, or comparisons are not made between consistently defined values.

Satterthwaite (2008) presents evidence that the emissions generated by residents within cities are overstated in current methodologies, relative to residents of other regions. Moreover, he notes, it is important to tease out the different kinds of residents within cities and their consumption habits, in order to get an accurate understanding of emissions sources. Dodman (2009) makes a similar finding, showing that the factors accounting for emissions are complex and not well understood at present.

Jonas and Nilsson (2007) find that scientific uncertainties are inherent in greenhouse gas accounting, and that (particularly under treaties such as the Kyoto Protocol) a verification framework is essential, but to date does not exist. Lieberman et al. (2007) observe that recognising high levels of uncertainty is necessary to improve inventories and manage risk in policy actions, such as carbon emissions trading schemes.

Many of these authors make the point that uncertainty cannot be removed, but it can be recognised and accounted for so as to produce more usefully reliable inventory measurements. Indeed, to that end the Intergovernmental Panel on Climate Change has produced practice guidance on uncertainty management in national inventories (Moss and Schneider, 2000). Rypdal and Flugsrud (2001) are among investigators who have developed methodologies to reduce or manage uncertainty in inventories. Moss and Schneider (2000) also have issued guidance to IPCC lead authors to reduce uncertainties through more consistent assessment and reporting procedures.

All of these investigators point out an inherent component of uncertainty in greenhouse gas data, illustrating the need for models that are sufficiently robust to be useful in spite of this uncertainty. What is critical, then, is that the basis for comparison is equivalent, and that it has a logical relation to the opportunities for reduction. For example, the allocation of GHG emissions per capita, and to the activities of individuals as they generate varying levels of demand, may provide better access to the behaviours that actually generate emissions in manufacturing, agriculture, energy generation and other sectors. Of course, it is in urban settings of varying kinds and intensities that most of these activities occur.

## § 2.3 Uncertainty regarding urban form as a factor in greenhouse gas emissions

Among the factors that influence human-generated emissions of greenhouse gases, the evidence gathered for this research indicates that urban morphology may be one of the most significant – and yet paradoxically, one of the least well recognized and understood. This state of affairs has profound consequences for present-day policy and best practice (Ewing et al., 2007).

On the one hand, we have compelling phenomenological observations that cities with significant differences in urban morphology also have significant differences in per-capita GHG emissions (World Resources Institute, 2009, Energy Information Administration, USA, 2010). We can generally account for "apples to oranges" factors such as climate, culture, economy and the like, and yet it is difficult to account for more than perhaps half of the significant observed difference in emissions rates. Yet our current models are unable to account for such a large difference from urban morphology alone (Mehaffy, 2009).

This research lacuna is in contrast to the much more mature body of research on the effects of building systems and their components, which do provide useful guidance for policy and best practice in the form of energy codes, tax policy and the like. At the other end of the urban scale, there is an equally mature body of research on transport-related emissions and their variables, with applications to policy strategies such as transportation planning and pricing. But there is at present a weak understanding of the connection between the two scales – the region with its transport system (and other emissions sources) on the one hand, and the building with its resource-using systems on the other.

This gap in understanding is likely because the effects of urban form can appear modest when looked at in isolation, even if they may be significant when aggregated, or especially, when interacting within a dynamic, synergetic system. Moreover, these factors often interact in exceedingly complex, systemic and sometimes subtle ways, and they are "masked" by other variables, such as variations of climate, income and behaviour. It is therefore difficult to tease out the various local factors that may be attributable to urban form (such as end consumption) from more global ones (such as initial production) and to recognize them as variable factors in their own right (Dodman, 2009; Wilbanks and Kates, 1999). As discussed previously, the picture is further obscured by incompatible variations in the boundaries of different measurements and inventories, creating inconclusive "apples to oranges" comparisons (Mackay, 2009; Brown, Southworth and Sarzynski, 2008).

Nonetheless, the literature contains a growing body of work that examines the detailed contributions from urban morphology, and as a result, some specific elements of the system are slowly becoming clearer. For example – and as we discuss in more detail below - a number of investigators have examined causative relationships between urban form and specific emissions sources, such as personal automobile use and housing energy use (Ewing et al., 2007; Brown, Southworth and Sarzynski, 2008).



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But it is fair to say that there is still no comprehensive assessment of the full set of causative factors, their relative magnitudes, and their relation to other influencing factors (Satterthwaite, 2008; Kates et al., 1998). This uncertainty within the research community translates into uncertainty and inaction in mitigation policy. Indeed, real doubt has been expressed in leading professional publications about whether overall greenhouse gas emissions levels can be altered significantly through feasible changes in urban form at all (Technology Review, 2009).

However, the incomplete research discussed here does strongly suggest that the cumulative and systemic effects of urban form may well be major contributors to greenhouse gas emissions; that there is reason to conclude that feasible changes in urban form can and must play a central role in effective mitigation strategies (especially so for the developing world); and that there remain important gaps in knowledge that will need to be filled by ongoing research to guide effective policy and best practice (Intergovernmental Panel on Climate Change, 2007). This paper is an early effort to assess the opportunities within this subject area.

More specifically, as we will discuss later in this dissertation, the research suggests an important opportunity to develop very useful new scenario-planning tools to guide the specific features of urban design at the neighbourhood and district scale. If successful, these tools might do more than simply identify static quantities of reductions that could then be achieved. They might, by providing a dynamic feedback capability, be able to make incremental improvement in the efficacy of the design strategies, and over time, through empirical evaluations, contribute useful research data leading to improvements in their own effectiveness (Hopkins, Lewis and Zapata, 2007).

## § 2.4 The specific challenges of analysing urban systems

As noted, it is in the nature of analysis that we have a much better picture of the behaviour of individual components of urban systems acting in isolation, than we do of their behaviour as part of a complex, dynamic urban system (Condon, Cavens and Miller, 2009). Yet it is clear that this systemic context is an essential parameter of performance, without which we may achieve emissions reductions in one component, but find those reductions offset or even exceeded by increases in systems overall.

This "Whack-a-Mole" phenomenon (so named for the children's game, which solves one problem only to see another one pop up elsewhere) can often be seen at work when individual urban components such as buildings and automobiles are treated as isolated variables. Gains from the efficiency of a component in isolation are often erased when that component is examined within its larger urban system. For example, there are notable cases of "green buildings" in more remote locations that require significantly higher transport energy for their users, erasing gains from building technology. (Environmental Building News, 2007)

It is certainly true that it is more difficult to quantify these systemic impacts, and our potential leverage over them, than to quantify the impacts of individual components. Urban systems by definition contain myriad factors that interact in exceedingly complex ways – and they can be greatly affected by human behaviour, one of the most complex of all factors. Furthermore, it is difficult to quantify the impact of relative trade-offs in "apples-to-apples" fashion, because they are often masked by other variables – for example, the effects of climate or demographic variables.

Lastly, we are discussing greenhouse gas emissions as they are driven by activities within urban systems, but often the emissions are actually generated in remote power generation facilities or manufacturing plants. These emissions vary by type of fuel, and, in the case of hydro, wind and nuclear, emissions are very low (but not zero, because of concrete used in manufacturing, etc).

In addition, resource use driven by urban activities can drive emissions in other complex ways. The shipping of goods is itself a remote generator of emissions. High consumption of meat can result in wood-burning for clearing that is not replaced with new growth, and higher release of methane from livestock. The process of concrete production is an emissions source in its own right. (MacKay, 2009)

Thus we must distinguish firstly between those sources of emissions that occur within the urban system itself (like gas-fired boilers, say), and those that are driven by consumption activities within the urban system, but occur remotely. Secondly, we must distinguish between the metrics of energy and resource use, which is a major driver of GHG emissions, and the metrics of GHG emissions per se. These generally correspond closely, but can have important variations. In this dissertation we will refer occasionally to the combined concept of "energy use and GHG emissions" while understanding this implicit distinction.

In spite of these systemic challenges, research is beginning to establish a much clearer understanding of the important ways that the dynamics of urban systems, with buildings as their sub-systems, affect energy use and GHG emissions (Ewing et al., 2007). Indeed, as this paper will summarize, the research indicates that important conclusions can be drawn, and that they point the way to dramatic reductions in emissions, through feasible changes to urban form.

## § 2.5 Current understanding of the urban morphology factors in GHG reductions

As we have noted, in spite of the weaknesses in this area of research, a number of contributing factors to GHG emissions from urban form have been previously identified (U.S. Environmental Protection Agency, 2010). Significant ones have been clearly identified, while other, lesser ones are more poorly understood.

Another remaining problem is that there has been little work to assess their aggregate effects in combination, or the systemic interactions between them. Nonetheless, there is sufficient data to begin putting together the factors of urban form, as elements of an eventual modelling tool.

A first step for our assessment is to summarize these factors, and what is known about them at present. From there, we can begin to identify the specific, coordinated guidance that an urban scenario planning tool would provide to achieve likely reductions.

### Residential density

Many authors have found a close correspondence between lowered residential density (usually corresponding to detached single-family residential buildings, and low ground cover) and increased GHG reductions. Most of the conclusive work in this area relates to personal transportation by car, which is relatively easy to translate into GHG reductions. For example, Holtzclaw et al. found a striking correspondence between residential density and "vehicle miles traveled per household" within parts of three American cities (Holtzclaw et al, 2002).

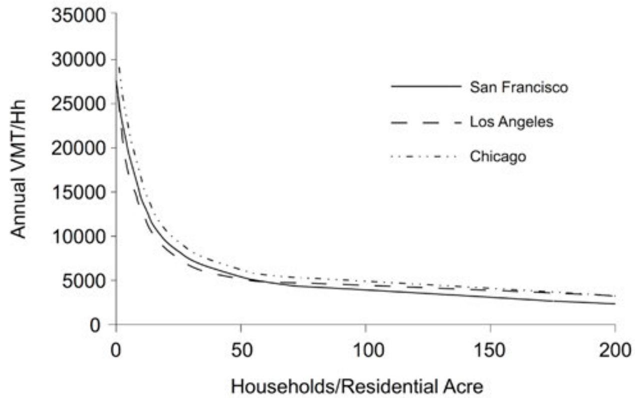


FIGURE 2.1 Driving versus residential density. Source: Holtzclaw et al. (2002)

Kenworthy and Laube found very similar results when looking at the evidence from many cities internationally. Their metrics were different (motor spirit consumption per person instead of distance driven, and urban density per person instead of per household); nonetheless their results were almost identical. Indeed, their research showed a doubling of density is associated with a reduction in energy use per capita of approximately 30% (Kenworthy and Laube, 1999).

Other studies showed a similar pattern. In US research (Holtzclaw et al., 2002) the reduction is from about 15,000 miles per year (9,000 kilometres) at a residential density of 12 units to the acre (5 to the hectare) down to about 5,000 miles per year (3,000 kilometres) at 75 units to the acre (30 to the hectare). A frequently cited study in the field (Kenworthy and Laube, 1999) also demonstrated that transportation fuel consumption per capita declines by one-half to two-thirds as urban densities rise from four to twelve persons per acre (1.6 to 4.8 persons per hectare).

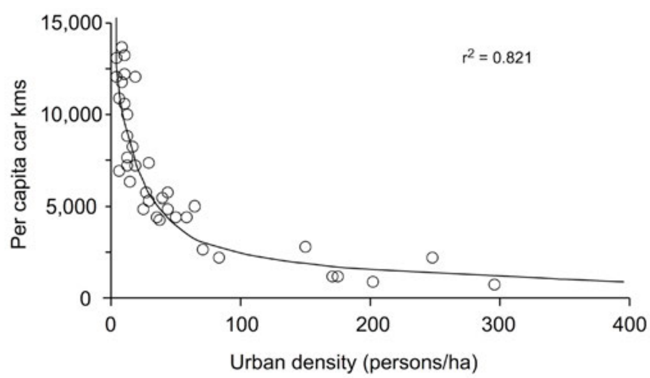


FIGURE 2.2 Urban density (persons/HA). Source: Kenworthy and Laube (1999)

A similar pattern is observable from non-transportation sources of GHG emissions (e.g. Norman, MacLean and Kennedy, 2006; Ewing and Rong, 2008). The components studied include infrastructure, transmission distribution and losses, characteristic housing stock and its heating and cooling demands, and heat island effects, among others. While transportation factors are easier to analyse, and therefore tend to dominate the literature, a growing body of work is already establishing a clear association between residential density and greenhouse gas emissions from non-transportation sources.

These findings are compelling, providing strong evidence that an effective urban design path to lower greenhouse gas emissions is to increase residential density. Nonetheless, of course, "density" is an aggregate variable that includes a number of other factors, and these must be teased out if we are to have more accurate design guidance for effective reductions (Norman, MacLean and Kennedy, 2006). Among them, as identified by the research, are:

## Proximity of daily needs and activities

An optimum mix and distribution of workplaces, retail, offices and other daily destinations results in significantly shorter trips per day on average. The most optimum pattern follows a "power law," e.g. many small and close, few large and distant, and a range between." A mature body of literature demonstrates this association with proximity to daily needs and activities through "jobs-housing balance" and "retail-housing mixing" (e.g. Kenworthy and Laube, 1999, Cervero and Duncan, 2006.) This criterion is associated with typological diversity (a mix of different building types allowing different uses).

An urban morphology meeting this criterion would feature an optimally distributed pattern of uses, with "neighbourhood center" uses (such as limited groceries and everyday conveniences) tightly distributed (e.g. 400m to 800m or ¼ to ½ mile), "town center" uses (general groceries and shopping, other regular services and employment centres) distributed somewhat less tightly (e.g. 800m to 3200m or ½ mile to 2 miles), and "urban center" uses (specialty shopping and services) distributed in fewer and more centralized locations (e.g. 3km-7km or 2 miles-5 miles). (Mehaffy et al., 2009.)

## Walkable neighbourhood design

Research is confirming the many important benefits of a neighbourhood structure that accommodates high rates of walking, including the energy efficiency and GHG emissions reductions from walking, which consumes approximately 150 kilojoules per passenger-kilometer, compared to 4,200 kilojoules per passenger-kilometer for an average single-occupancy passenger sedan (Hydro-Québec, 2005.) (It is worth noting that walking trips fuelled by a significant meat diet can be somewhat higher.) Moreover, the beginning or end segment of a public transport trip is almost always a walking segment. Therefore a neighbourhood morphology that obstructs walkability is likely to obstruct transit use as well.

"Walkability" must be defined in precise morphological terms in order to be sufficiently specific for an urban design methodology. A growing body of research demonstrates a strong correlation between walkable neighbourhoods and such factors as high intersection density and short blocks, and diversity of close-by destinations (e.g. Leslie et al., 2005, Berrigan, Pickle and Dill, 2010), and walking infrastructure and aesthetics (e.g. Cerin et al., 2006). That is, a walkable neighbourhood will offer attractive, comfortable, well-connected pathways on short blocks (no more than 120 meters or about 400 feet per side, 360 meters or about 1200 feet total perimeter) to a mix of nearby destinations.

## Bikable neighbourhood design

Biking is also a low-energy (and low GHG emissions) form of transport, just 60 kilojoules per passenger-kilometre when fuelled by a vegetarian diet, and somewhat higher when fuelled by meat (Hydro-Québec, 2005).

A small but growing body of literature shows that the morphological characteristics of a bikable neighbourhood are similar to those of a walkable neighbourhood: close-by destinations, connectivity, intersection density, adequate infrastructure and attractive aesthetics. In addition, there is evidence that bikability requires a pathway safe from vehicles, close to buildings and "eyes on the street," and generally free from major grade changes (generally above 5% for more than 90m or 300 feet). Typically this requires a set of quieter secondary through streets that are closely spaced, with attractive aesthetics such as vegetation and detailed building architecture (Saelens, Sallis and Frank, 2003, Wahlgren and Schantz, 2010).

## Availability of effective, safe and convenient public transport

An average single-occupancy passenger sedan consumes 4,200 kilojoules per passenger-kilometer, while a 40% occupied subway consumes 280 kilojoules per passenger-kilometer (just 6.7%). A 50% occupied diesel bus consumes 800 kilojoules per passenger-kilometre. (Hydro-Québec, 2005.) The urban morphology to support this reduction must be sufficiently dense, typologically diverse, and (as noted above) supportive of walking to stops.

The vehicles themselves contain embodied energy and resources (Welbanks et al., 1999). Thus a greater number of cars per capita will translate into greater embodied energy and resources, and greater emissions. A younger fleet (vehicles replaced more often) will also increase the embodied energy and resources as well as emissions per capita, other things being equal. (However, an example of the complexity of such an analysis is that at present a younger fleet is also likely to have higher fuel efficiency, lowering emissions.)

The urban morphological characteristics of effective public transport systems are the subject of a mature body of literature. Generally, a minimum residential density of 8 units per acre, or 20 units per hectare (translating to about 50 persons per hectare) is accepted, and stops must be no more than 800 m or ½ mile apart, and must form a well-connected network with minimal detour requirements. Service must also be frequent, convenient and comfortable. (Berrigan et al., 2010; 37. McNally and Kulkarni, 1997; Johnston and de la Barra, 2000.)

## Urban network

An integrated rather than fragmented urban network results in shorter trips on average, and proportionately lower energy use and emissions per trip. It also promotes walking, as average walking trips are also shorter. (Pushkar, Hollingworth and Miller, 2000, Dill, 2004). There is also evidence that the dynamics of networks allow for resource efficiencies from combined and synergetic interactions, resulting in additional efficiencies and reductions of GHGs. (This phenomenon, which has been termed the "resource spillover," is one that I have identified for future research.)

This factor also requires a morphology with a small-grained, interconnected street pattern (Berrigan et al., 2010).

## Neighbourhood Vehicle Infrastructure

Neighbourhoods that have a low demand for only occasional automobile use (e.g. for transporting large purchases) can support reduced numbers of shared automobiles. The result of reduced fleets will be a reduction of embodied emissions and energy from manufacture per person (Sullivan , Costic and Han, 1998). Neighbourhoods whose morphologies allow an efficient distribution of daily destinations without the need for high-speed automobiles (e.g. freeway travel) can support fleets of low-impact vehicles, such as Neighbourhood Electric Vehicles (NEVs) (Marshall, 2009). This is a synergetic benefit from the other urban morphologies discussed above (density, typological diversity, interconnected street pattern).

Beyond the effects associated with transportation, there are many other lesser but also evident factors of urban form that directly influence greenhouse gas emissions. Some of these factors are only poorly understood at present – particularly as they may aggregate and interact with other factors. Therefore the magnitudes of their contributions to emissions, both in aggregation and in interaction, present a ripe area for further exploration. Following is a brief review.

### Infrastructure efficiency

It is intuitively obvious, and confirmed by research, that higher density reduces the allocation of required infrastructure per person:

- ***Infrastructure construction and maintenance.*** A one-block street segment that embodies a typical 100 million BTUs (approx. 100 gigajoules) will be allocated across 8 households at 12 million BTUs (approx. 12 gigajoules) per household. But the same street segment serving 20 households will be allocated at only 5 million BTUs (5 gigajoules) per household (Allen, Bruce and Benfield, 2004).

- ***Operating energy.*** This includes lighting, pumping, signals, irrigation, and other urban infrastructure energy systems. Higher density neighbourhoods require proportionately less operating energy per capita (Hydro-Québec, 2005).

- ***Transmission efficiency and loss***. Losses from transmission can be as high as 7% or more, and there is a clear association with urban form. Higher density means shorter distances and more efficient distribution (Dong, 2006; Suresh and Elachola, 2000).

- ***Cogeneration and district energy opportunities.*** These can be much more efficient than individual building systems – over 25% more efficient – and they can also significantly reduce transmission losses (Allen, Bruce, and Benfield, 2004).

In addition to higher residential density, infrastructure efficiency is increased with an urban morphology that includes other intensive activities, diverse and complementary uses (e.g. demand occurs at different times of day), and dense spacing of network nodes for greater efficiency (Dong, 2006; Ewing and Rong, 2008).

### Ecosystem Assets

Approaches to infrastructure which replace GHG intensive engineered solutions with ecosystem services show great promise in a wide variety of socioeconomic settings:

- ***Protection and restoration of ecosystem services.*** Urban form can be designed to maintain or restore natural systems that are performing water filtration, carbon sequestration, air purification and other valuable services. These eliminate the need for engineered equivalents which would generate high energy use and emissions (Knapp et al., 2005, Bolund and Hunhammar, 1999).

- ***Local and urban agriculture.*** Other factors being equal (e.g. requirements for greenhouse heating), local and organic food systems appear to offer the ability to reduce energy, petrochemical use and GHG emissions associated with food growing, storage, and transportation. Urban form can be used to support adjacent extra-urban agricultural lands and to promote urban agriculture on rooftops, in greenhouses, in yards and open spaces, and in underutilized areas (Knapp et al., 2005).

- ***Sustainable water systems.*** Urban form can be designed to facilitate systems approaches to water catchment, purification, and distribution, as well as to stormwater, graywater, and wastewater treatment, re-use, and infiltration. These approaches can greatly reduce GHG emissions associated with conventional water purification and wastewater treatment plants, including pumps and mechanical filtration systems (Hellstrom, Jeppsson and Kärrman, 2000).

- ***Heat island/albedo/vegetative cover per person***. Low-density auto-dominated development is typically associated with relatively high loss of vegetative cover per person. Areas of extensive pavement and hard surfaces tend to increase heat island effects, with an increased demand on cooling equipment in warm areas and seasons. In addition, low albedo in pavement and roofing increases warming, and loss of vegetative cover reduces $CO_2$ absorption – both of which aggravate warming effects over time, and increase cooling demands yet further. These can be mitigated with a more compact urban form that reduces such surfaces per person, and preserves surrounding ecosystems. The urban environment can also be supplemented with "cool roofs" or green roofs, and greater levels of urban vegetation (Akbari and Levinson, 2008; Akbari, Menon and Rosenfeld, 2009).

  Clearly, urban morphologies that are more compact are likely to consume less of the surrounding land that would otherwise perform ecosystem services. In addition, urban morphologies that afford places for on-site water reinfiltration, green roofs, urban agriculture and mitigations of heat island/albedo effects (reduced paving areas, lighter paving, roofs and buildings, etc) can improve performance by measurable percentages.

### Interface between urban form and building form

Urban areas that include multi-family and attached dwellings – particularly those with advantageous solar orientations – have a number of energy efficiency and GHG emissions advantages:

- ***Urban building type, exposure, and orientation.*** According to U.S. DOE data, space-heating requirements are roughly 20 percent less on a square foot basis for dwellings in multi-unit buildings, compared to detached structures. (Allen, Bruce and Benfield, 2004; Ewing and Rong, 2008)

- ***Prevailing size, and associated economic factors.*** Residential units in higher-density areas are typically smaller on average, in part because of the higher prices commanded by greater proximity to nearby employment, amenities and services. This results in a proportionate decrease in heating, cooling, and other energy loads. The increased cost of homes also may cause a shift away from other forms of energy-intensive consumer spending, toward home care and improvement. (Allen, Bruce and Benfield, 2004, Ewing and Rong, 2008)

- ***Embodied energy in building materials.*** Smaller residences will also have a proportionate decrease in embodied energy for building materials, which translates into reduced GHG emissions in manufacture and construction – assuming that the number of people per square foot is not also reduced even more. In addition, attached dwellings have an average of 5% lower embodied energy per unit of floor area than detached dwellings (Allen, Bruce and Benfield, 2004). (But it is worth noting that as buildings grow beyond about 5 stories in height, there are disproportionate increases in embodied energy per unit of net residential area due to losses to building circulation systems and non-linear changes in structural requirements (Treloar et al., 2001). The lesson is that all factors must be weighed systemically.)

Urban morphologies performing well in this category feature relatively low-rise, compact residences, with good solar characteristics (exposure, deciduous trees, etc). Other non-residential buildings are generally well-integrated into the neighbourhood structure, and also compact and well-oriented to solar exposure.

Though it is beyond the scope of this paper, we note there is evidence that tall buildings have a number of drawbacks, including relatively high embodied energy, poor exposure to wind and sun, inefficient floorplans due to egress requirements, and other factors. These do not appear to be offset by increased density, the benefits of which seem to diminish above a more moderate density. In addition, there are significant effects of tall buildings on the other buildings and environments that surround them, such as shading, wind effects, and “canyon” effects (trapping heat and pollutants). (See e.g. research cited in Mehaffy, 2011.)

## Other indirect factors

There are other topics that are more difficult to quantify, but may be critical in accounting for observed GHG emissions – and in developing new strategies for reduction:

- ***Induced demand.*** This is a well-known perverse effect of efficiency (also known as Jevon’s Paradox). As systems become more efficient, they also tend to become less expensive. The result is that people may be more likely to use them more, partially or wholly erasing the gains from efficiency. It will be critical to develop policy approaches that prevent the induced demand effect from erasing potential decreases in GHG emissions. (Allen, 2001; Johnston, 2006; McNally and Kulkarni, 1997).

- ***Cognitive and behavioural factors.*** To what extent will the quality and conviviality of the built environment and associated open spaces displace demand for forms of consumption associated with high levels of GHG emissions? How does this interact with a wide range of cultural factors? What will promote lower resource use and emissions habits and choices? Much more research is needed in this important subject, but we know that the success of neighbourhoods in attracting and retaining residents over time depends on attractive architecture, durable high-quality construction, and access to parks and natural areas (Holtzclaw, 2001; Ramaswami et al., 2008).

- ***Resilience and performance over time***. New technology that is meant to improve performance will clearly do little good if it breaks down or becomes rapidly obsolete. In such a condition the embodied energy of its production can easily exceed any savings from its introduction. So too, buildings need to be able to adapt to new uses, while remaining durable and easy to repair and maintain. There is also evidence to suggest that buildings that reflect local identity are more likely to be found appealing and worthy of care. (Allen, 2001.)

We suggest this is an important category that deserves much more investigation.  Though the significance of these factors is inherently harder to quantify, since they relate to the complexities of behaviour and perception, nonetheless they may play a major role in consumption and therefore emissions per capita.

For the moment, we note evidence suggesting that an urban morphology that is compact, connected, diverse, varied, and fractally patterned, as well as less dependent on systems that are prone to induced demand (i.e. more reliant on passive approaches) will contribute to improved performance in all these factors.  Not surprisingly, such a morphology has many of the characteristics that were well-adapted to an era prior to extensive mechanization of transport and relatively inexpensive fossil fuels: a small and flexible grain of development, permeable pedestrian networks, diversity and proximity of uses, typological diversity, complex layering of public and private realms, and other factors.

There remains the problem of how to incentivise development of these and other beneficial morphologies, aside from making clearer changes to best practice standards.  One way would be to monetize the savings from GHG reductions, as well as other resource conservation benefits.  But that again begs the question of how to quantify such reductions – and actually to capture them through changes in form once they are quantified.

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