

# Multiplier Effect: High Performance Construction Assemblies and Urban Density in US Housing

Eero Puurunen and Alan Organschi

**Abstract** The suburban house—an emblem of the 20th century American Dream—has come to symbolize unsustainable excess in the new millennium. For the homeowner, the single family home is increasingly burdensome to finance and maintain; for planners and policy makers, suburban sprawl has undermined efforts to limit land consumption and mitigate anthropogenic greenhouse gas (GHG) emissions. While the link between sprawl and transportation emissions is well-established, the atmospheric impacts in the construction and operation of single-family houses are acknowledged but not as well understood. Using a readily available lifecycle assessment tool and building modeling software, this study compares the carbon emissions of low- and high-density housing morphologies and weighs the lifecycle *embodied energy costs* against the *operational energy benefits* of increasing thermal performance in the building envelopes of each housing type. The assessment shows that in spite of increasing energy demands embedded in the materially and technically intensive construction of high performance assemblies, the adoption of these techniques in both the house and multi-unit apartment dramatically reduces lifetime GHG emissions. However, the initial toll of building high performance houses—measured in emissions and extrapolated as construction costs—is burdensome to the environment and homeowner alike. As an alternative, high performance apartments can be built at a carbon and dollar cost only marginally higher than that of conventionally-constructed multi-unit dwellings, with a per-unit lifetime GHG footprint that is one quarter of that of a standard house. The economic and land-use efficiencies of enhanced construction assemblies deployed in dense urban residential development create a multiplier effect in potential GHG reduction; a critical factor for contemporary environmental planning and policy.

**Keywords** Housing · Urban density · Passive house · Building assemblies · Life-cycle assessment

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E. Puurunen (✉) · A. Organschi  
Yale University, New Haven, USA  
e-mail: eero@grayorganschi.com

## 1 Introduction

The built environment—individual buildings and, by extension, large scale aggregations of buildings and their infrastructural systems—may be understood as a man-made thermodynamic system through which energy is directed to provide shelter and sustain human settlement. A building harnesses that energy through the organization of physical material in two primary stages of its lifecycle: (1) As embodied energy expended in the extraction, processing and transport of materials; the manufacture of building assemblies; in the construction and maintenance of the building and its necessary infrastructure; and, at the end of its lifecycle in demolition and disposal or recycling of material. (2) In the direct energy consumed in a building's operation as it works to manage environmental heat loss or gain (insulation, heating and cooling), maintain tolerable and healthy interior air quality (ventilation), and to provide safe and convenient interior conditions (artificial illumination and electrification). From a thermodynamic standpoint, the efficiency of this constructed environment might be understood as the relationship between the initial energy the system harvests from the environment and the useful work this energy is able to accomplish.

In creating some of the most sublime artifacts of our technological culture, the processes of building and urbanization have also produced physical by-products and engendered human behavior that has contributed significantly—both directly or indirectly—to the degradation of land, wetlands and oceans, and the atmosphere through the increase in impermeable surface and the resulting heat absorption and disruption of the hydrologic cycle, habitat destruction and loss of biodiversity, solid waste production, the dissemination of toxins and pollutants and, our primary concern here, climate change driven by anthropogenic greenhouse gas (GHG) emissions. The built environment is a significant contributor to these emissions. The global building sector is estimated to be responsible for approximately one-third of global energy related GHG emissions (Levine et al. 2007). The Intergovernmental Panel on Climate Change also estimates that the building sector has the highest potential of all sectors to reduce GHG emissions cost-effectively, with lifetime cost savings (Levine et al. 2007).

Housing construction practice in the U.S. since World War II has been defined principally by the development of the suburban single-family house (Sarkar 2011). This approach to housing production, made possible by significant timber stocks, relatively cheap and efficient construction techniques, and wide availability of inexpensive land has also been supported by indirect subsidies provided by a Federal arterial highway system and artificially suppressed U.S. fuel costs (Graetz 2011). The development pattern based on the detached house has hardened into conventions ingrained in current regulatory structures, land-use policies, and demographic patterns. By defining the spatial structure of American housing, these conventions have inflected U.S. transportation policy, and transformed the American landscape.

In the foreseeable future, however, certain pressures might suggest a reconfiguration of planning policy and land use. As heightened ecological concerns constrain greenfield and open-space development, rising energy costs burden the operation of the single family home and the use of the automobile. Additionally, stricter performance requirements in US building codes will call for more materially and technologically intensive construction techniques. In the near future, the freestanding home, the icon of American domestic privilege, will become increasingly costly to build and maintain and may prove to be—for much of the US residential market—an unbearable means of housing.

Although U.S. building codes currently lag far behind their European counterparts in their energy performance standards, it is likely that American energy regulations, based on recent historical trends in the residential construction sector, will become stricter (see: <http://www.energycodes.gov/adoption/states>). Within a 50-year time-frame, as regulatory requirements evolve to demand greater energy efficiency in building assemblies and mechanical systems, nearing current Passive House standards (see Sect. 3.2 for definition), the role of embodied energy consumption will increase as both a critical percentage of the life-cycle GHG impact of the housing stock and as an implication for “first costs” in housing production. Although per-square-foot energy consumption in newly constructed homes will decrease as a result of the increased efficiency of the building envelope, the initial costs of building, as both a percentage of a building’s life-cycle costs and as absolute per-square-foot construction costs, will rise.

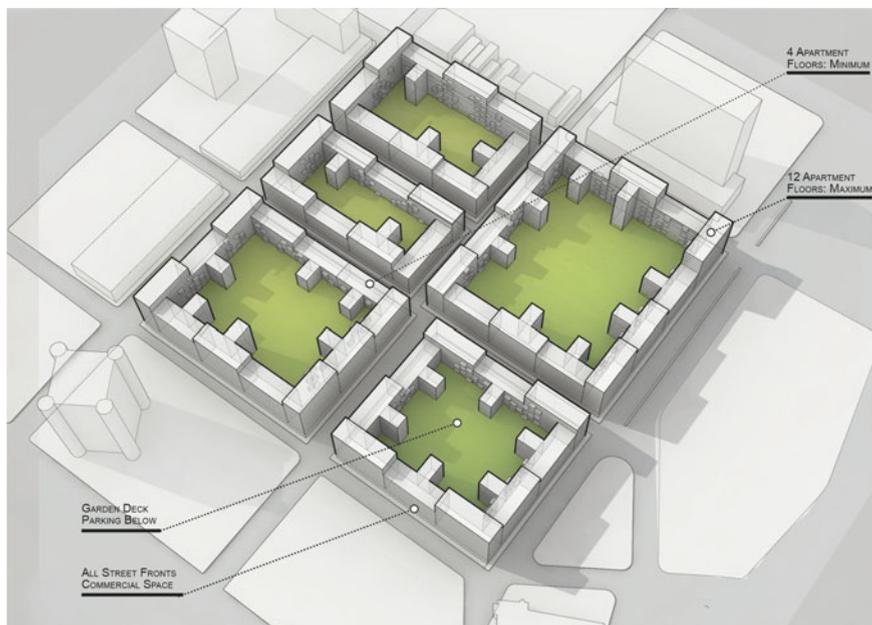
This chapter compares the environmental impacts—in the form of direct and embodied emissions and associated land-use impacts—of two opposing US housing types: the low-rise, low-density suburban single family house and mid-rise urban multi-family housing. By isolating and modeling construction assemblies of both conventional and high performance building envelopes for each housing type, our study seeks to illuminate the relationship between new, more materially intensive construction systems and the associated potential lifetime environmental benefits of density. Figure 1 presents a proposed model for residential neighborhood.

## 2 Overview of Related Research

It is well known that the residential sector plays a large role in energy use and emissions of greenhouse gas (GHG). In the United States, 23 % of primary energy<sup>1</sup> use is directly related to heating (including cooking and hot water) and to electricity use in dwellings (EIA 2011). In terms of GHG emissions, this direct residential energy use accounts for 17 % of total U.S. GHG output (EPA 2012). In addition to the direct emissions required for heating and electricity, the

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<sup>1</sup> Energy contained by unprocessed “raw” fuels, such as coal, oil, or natural gas.



**Fig. 1** Future of American housing? Proposed model for residential neighborhood

construction and maintenance of dwellings requires a large carbon expenditure. For demand-side GHG control, emissions associated with buildings are thus one of the most important targets alongside transportation emissions.

## ***2.1 Factors Driving Residential GHG Emissions***

Methodologies for studying the GHG impacts of buildings, and the factors driving these impacts, can be divided into two categories. The first consists of statistical methods, which look at data from large national surveys or local household surveys. The second consists of more detailed life-cycle assessments (LCAs) of individual buildings.

Statistical studies encapsulate characteristics of a large number of buildings or households and, in so doing, isolate driving factors behind residential GHG emissions. A statistical study can, for example, control for income while looking at the impact of housing type. A number of recent statistical studies have studied the driving forces behind residential GHG emissions. Some of the causal relations are more obvious. Increased dwelling floor area, which needs to be heated and cooled, leads to higher household emissions (Andrews 2008; Holden and Norland 2005). Living in extreme climates (cold or hot, rather than moderate) has a similar effect (Ewing and Rong 2008). Higher household income and lower energy prices are

also associated with increased direct residential consumption (Ewing and Rong 2008). Statistical studies from cold climates (comparable to the Connecticut case study presented later in this chapter) indicate that well-insulated homes perform better than poorly insulated ones and that multi-family dwellings are more energy and carbon efficient than their single-family counterparts (Andrews 2008; Ewing and Rong 2008; Holden and Norland 2005; Randolph 2008). Statistical studies, however, typically ignore the embodied portion of emissions, hence leaving the lifetime analysis incomplete.

A life-cycle assessment (LCA) which analyzes every stage of the lifetime of a building can quantify both embodied and operational emissions. On the downside, LCAs are labor intensive and LCA studies generally assess only a handful of buildings at most. Due to the inherent specificity of LCA results, some caution is necessary when extrapolating larger scale impacts. With this in mind, the following are some LCA results particularly relevant to this chapter. A rare example of a LCA study that directly compares a single family house to a multi-family building (Norman et al. 2006) indicates that on a per-capita basis single-family houses are 2.5 times more GHG intensive than apartments over their lifetime. When measured on a per square meter basis, this factor shrinks to 1.5. This study includes emissions embodied in infrastructure along with the buildings. When comparing conventional buildings to buildings of high-energy performance, the overwhelming result is that high-performance buildings have lower emissions over their lifetime (Gustavsson et al. 2010; Ramesh et al. 2010; Sartori and Hestnes 2007). Many studies compare buildings in terms of energy use, rather than GHG emissions because the choice of energy source (coal, oil, biomass etc.) has such a large impact on operational GHG emissions. According to Gustavsson et al. (2010), the embodied energy share of the total lifecycle energy demand is 6–13 % for a conventional residential building and 25–30 % for a high-performance building. This indicates that with increasing energy efficiency, the relative importance of embodied energy grows. Sartori and Hestnes (2007) put the respective shares at 3–30 % (conventional) and 14–100 % (high performance).<sup>2</sup> One of the interesting findings of this study is that a zero energy building, which satisfies all of its annual operational energy needs on site (such a building has an embodied energy share of 100 %), is not as energy efficient over its lifetime as alternates that rely solely on better insulation and other passive measures. In other words: increasing energy-efficiency during construction is GHG-efficient only up to a tipping point beyond which the initial embodied GHG burden cannot be off-set by decreased operational emissions over the building lifetime.

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<sup>2</sup> This meta-analysis of existing studies includes some office buildings alongside with residential buildings.

### 3 Case Study: Impact of Dwelling Type and Envelope Energy Performance on Lifetime Greenhouse Gas Emissions

As the preceding section indicates, the current norm of American housing, the single-family house, is a rather inefficient dwelling unit in terms of its lifetime energy use and its GHG impact. The study presented here looks at alternatives to the typical American house and aims at describing the GHG reduction potential of these alternatives.

#### 3.1 Assessed Dwelling Units

To investigate the influence of dwelling type and envelope performance on lifetime GHG emissions, this study creates a four-way comparison that includes two houses and two apartments. For each dwelling type (house and apartment) a version built according to current construction standards and a version built according to a high performance standard is considered. Figure 2 shows exterior wall assemblies for each of these dwelling types. A more detailed description of the building assemblies can be found in the appendix.

The case study dwellings are located in the southern part of the state of Connecticut in the northeastern United States. This factor has importance only as it relates to climatic conditions and some of the specific characteristics of the

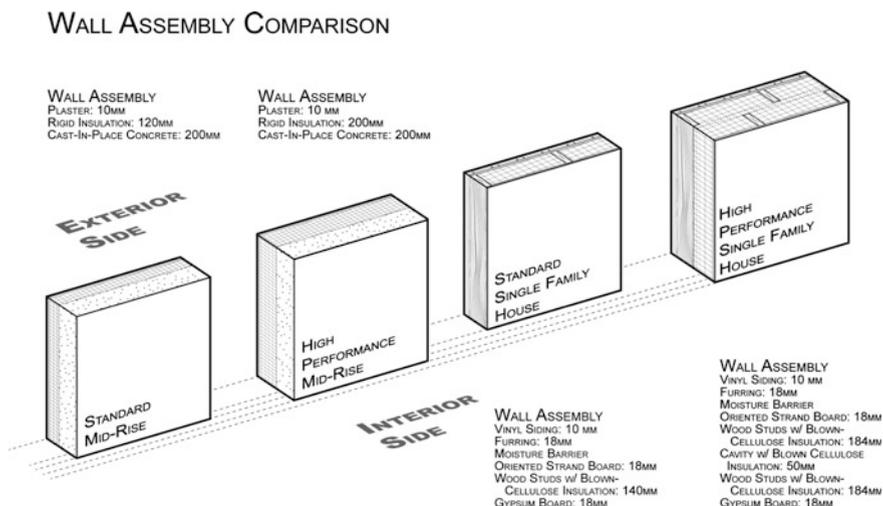
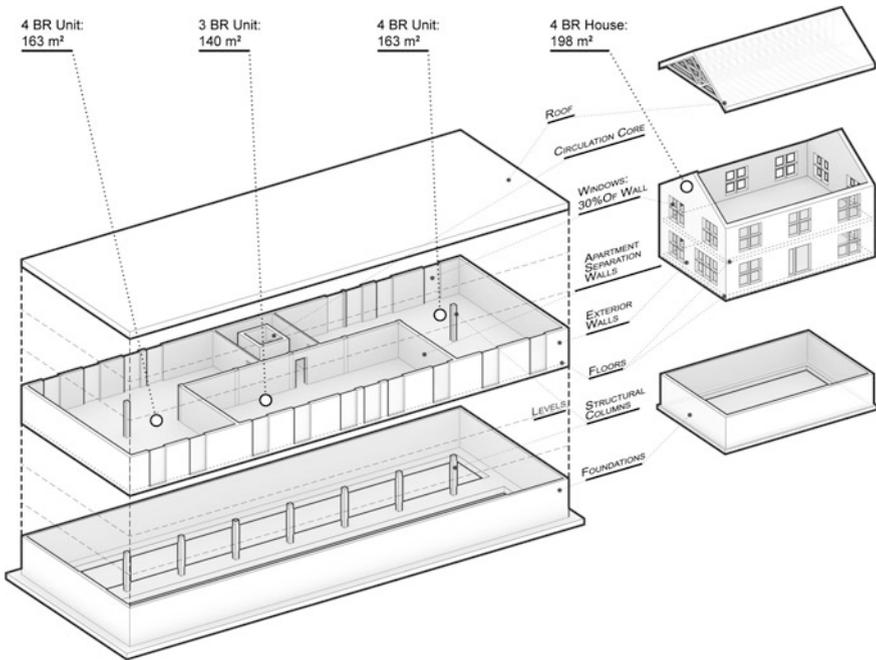


Fig. 2 Exterior wall assemblies for the four case study dwelling types

construction industry in the region (the latter factor influences emissions embodied in the construction process).

The case study house, a gable-roofed, two-story house shown in Fig. 3 is a simplified approximation of a typical suburban house in Connecticut. This house has 198 m<sup>2</sup> of living space (not including basement or attic)—a number adopted from the median size for a single-family house in Connecticut.

The characteristics of the case study apartment unit represent an average taken from apartments shown in Fig. 3. The apartment building type chosen is not typical for the U.S., but a model of urban living more common in Europe. Current U.S. regulations and practices have led to the dominance of “double-loaded corridor” type in the mid-rise (4–12 stories) housing market. In this building type apartments are lined on two sides of a long, central corridor. Elevators and fire stairs are located at certain intervals along this corridor. Only the end apartments can reach through the building (a requirement for effective cross-ventilation) in a double-loaded corridor building. In the apartment building type presented here, most units reach through the building and all of the units have a somewhat direct connection with the exterior through an elevator and stair core serving groups of three or four units per floor. The average size of an apartment unit in this layout is 150 m<sup>2</sup>. While smaller than the case-study house, these three or four bedroom



**Fig. 3** Building elements included in the embodied GHG assessment. Calculations for the apartment were based on the complete neighborhood shown in Fig. 1

apartments are considerably larger than the U.S. average for apartments (EIA 2005), making the comparison against the case study house more even based.

### **3.2 LCA Methodology**

The lifetime GHG impact of each dwelling type was estimated for a 50-year lifetime. The assessment was limited to emissions associated with building construction and operation: site, infrastructure, or transportation emissions were not considered.

Embodied GHG emissions were assessed with the Athena Impact Estimator. This free life-cycle assessment tool, which is developed by the Canadian Athena Sustainable Materials Institute, estimates environmental impacts of typical construction materials and assemblies in North America. The assessment includes life-cycle stages of material extraction and manufacturing, transportation and on-site construction, as well as maintenance and replacement. At the end of life, Athena Impact Estimator takes account of demolition and removal and disposal for those structural materials that are currently land filled.

Estimates for operational energy (heating and electricity) use were based on a statistical analysis of data from recent U.S. residential buildings (for standard house and apartment) and requirements set by the Passive House standard (for high performance house and apartment). This voluntary standard which originates in Germany aims at creating buildings that minimize heating energy use, relying primarily on the heating effect of human bodies and electrical appliances. The standard sets limits also for electrical consumption. Details on this standard can be found on websites of Passive House organizations ([www.passiv.de](http://www.passiv.de) and [www.passivehouse.us](http://www.passivehouse.us)).

The LCA methodology for estimating both embodied and operational emissions is explained in greater detail in the Appendix.

#### **3.2.1 Building Elements Included in the Assessment**

Figure 3 indicates building elements that were included in the embodied GHG assessment. Structural and envelope systems for the two dwelling types are approximations of techniques typical for each building type in the American North–East. The house is built with a technique that dominates the U.S. housing market, a light wood framing and sheathing system composed of slender timber “studs” and engineered wood sheathing. The apartment building has a cast-in-place concrete frame. The amount of thermal insulation assumed for the standard dwellings was derived from examples of buildings built according to recent code requirements. The amount of insulation for the high performance dwellings was derived from Passive House certified buildings. Due to a lack of American examples of appropriate multi-family buildings, our study made use of examples

of Passive House apartment building construction in Germany.<sup>3</sup> Impacts of elements that were omitted in the assessment are discussed in the appendix.

### ***3.3 A Bi-product: Land Use Comparison***

To illustrate the land use impact of single-family housing, we created the comparison shown in Fig. 4. A small section in the town of Hamden was chosen to represent a typical Connecticut suburban neighborhood of single-family houses. Both house and property sizes in this neighborhood are very close to Connecticut median sizes (192 and 1,442 m<sup>2</sup> respectively). The counterpart to this sprawling neighborhood is a fictional mid-rise neighborhood developed in the blocks of the historic 9th Square neighborhood in New Haven, Connecticut—a small city of approximately 140,000 inhabitants, 70 miles northeast of Manhattan. Figure 1 shows this proposed development in its downtown New Haven context. It must be mentioned, for clarity's sake, that we are not advocating the total erasure of current urban fabric in the historic 9th Square neighborhood. Rather, we aim to merely illustrate a residential density appropriate for a small American city. Storefront spaces indicated in Fig. 1 were not included in the land use comparison.

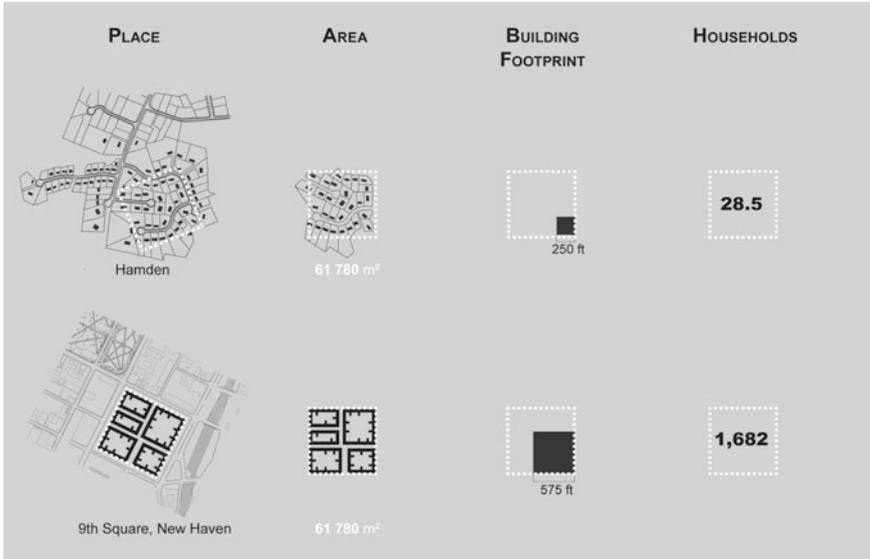
## **4 Results**

As Fig. 5 indicates, a standard house is by far the highest polluting option in the four-way comparison. Its emissions over a 50 year lifetime are 1.6 times larger than those of a standard apartment, 2.6 times larger than those of a high performance house, and 3.9 times larger than the emissions of a high performance apartment. In terms of embodied emissions, the jump from the standard house to the high performance house is dramatic. Over the lifetime, a high performance house embodies 1.5 times the emissions of a standard house. The standard apartment, on the other hand, has 18 % lower embodied emissions than the standard house. The difference in embodied emissions between the two apartment types is negligible. This is due to the fact that a large majority of the embodied emissions of the apartment stem from the concrete frame of the building. Hence some added insulation does not have a large impact on the total embodied emissions.

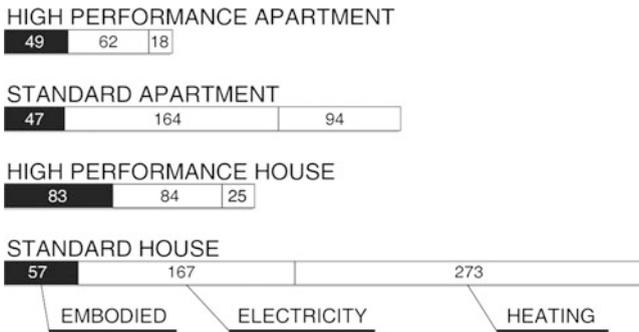
As shown in Fig. 6, the ranking of dwelling types in terms of their overall GHG footprint does not change if the comparison is done on a per square meter basis.

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<sup>3</sup> According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard, Germany and Connecticut belong to the same climate zone.



**Fig. 4** Comparison of typical sprawling Connecticut neighborhood and a high-density mid-rise neighborhood



**Fig. 5** Total emissions per household in CO<sub>2</sub> equivalent metric tons

GHG emissions for the apartments would hence be lower than their counterpart houses even if all the dwellings had the same floor area. Because operational energy for the high performance dwellings was adopted directly from the Passive House standard, there is no difference in heating and electricity emissions between the high performance dwellings.

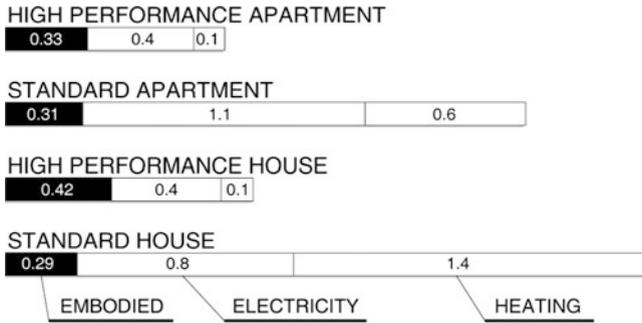


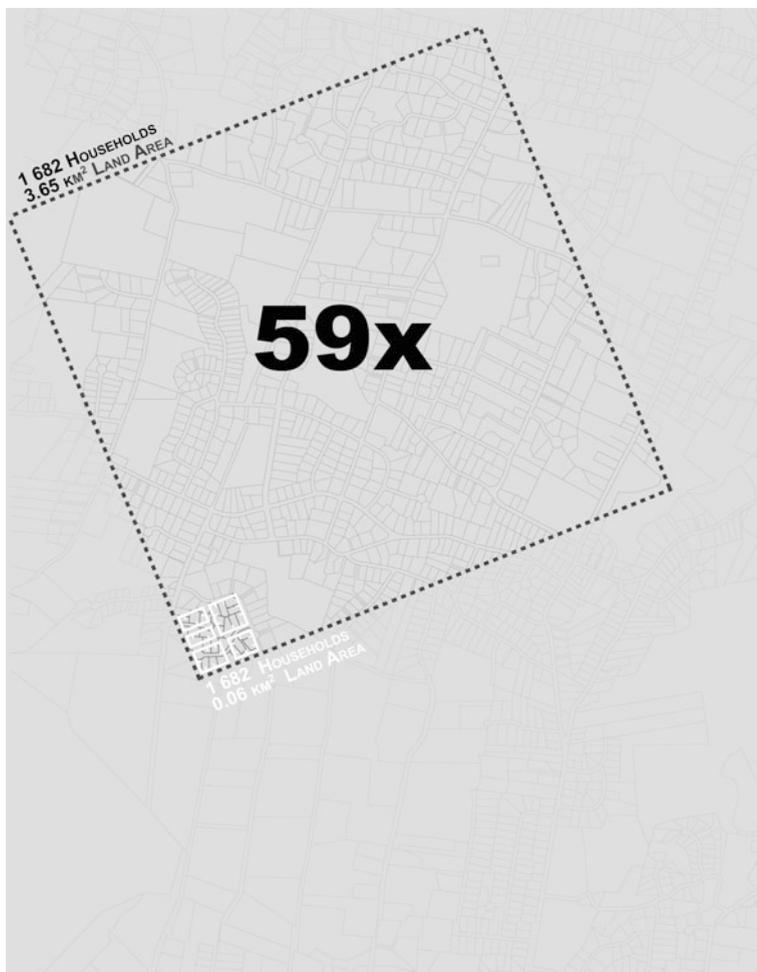
Fig. 6 Total emissions per square meter in CO<sub>2</sub> equivalent metric tons

### 4.1 Land Use Comparison

If one takes the physical footprint of the 9th square and lays it over the Hamden neighborhood, one can conclude that 28.5 households fit within this area (as indicated in Fig. 4). As designed, the 9th Square mid-rise neighborhood houses 1,682 families. If you take the household density of the Hamden example and calculate how much land area is needed to house 1,682 families at this density, you arrive at the comparison shown in Fig. 7. The land area necessary to house 1,682 families within a sprawling district is 59 times the size of the 9th Square.

## 5 Discussion

The results of our assessment of lifecycle GHG emissions in both the suburban single family house and its higher density urban counterpart corroborate similar findings that show a dramatic lifetime benefit in switching from standard building envelopes to those with high thermal performance (see Sect. 2.1). It would be easy to conclude on the basis of our findings that the current strategy of choice for designers, engineers, and builders who are concerned with the impacts of buildings on climate change—to ratchet up the performance of the materials and assemblies they employ—is a common sense approach to carbon reduction in the built environment. However, the highest performing enclosure systems, as deployed in Passive House design, which for the purposes of this analysis was used as a reasonable approximation of building regulatory requirements for thermal performance in an energy-scarce building environment of the future, come with notable embodied energy costs and GHG emissions.



**Fig. 7** Land area required to house 1,682 families in the case study sprawling neighborhood is 59 times the size of proposed high-density neighborhood

### ***5.1 Costs of High Performance in the Single Family House***

As we turn to the increased performance of materially and technically intensive building systems as a solution to residential emissions, we shift the balance between embodied and operational emissions within the lifecycle GHG equation. Put plainly, the use of more material, and the associated emissions of its extraction, transport, processing, assembly, maintenance, and ultimately, disposal or reuse, will demand a greater share of all of the emissions associated with dwelling. Although our study substantiates the assumption that a single-family-house, constructed with the material intensive assemblies of the Passive House system, still

outperforms the conventionally built house in overall energy consumption and GHG emissions, the increase in performance exacts a significant upfront penalty for the homeowner and darkens the broader global carbon outlook. At the level of the housing unit, with embodied emissions serving as a fair proxy for construction costs, the financial burden of building a high performance, energy and carbon efficient single-family house may be unbearable for average American incomes. At the global scale, at a time when the immediate mitigation of atmospheric carbon is an increasingly critical priority, concentrating emissions at the beginning of the building lifecycle during construction—in essence what the high performance house does—is counterproductive to efforts to limit anthropogenic global warming.

The problem of frontloading carbon emissions in the lifecycle of the single-family house is compounded by other significant factors when we consider the ongoing proliferation of the individual house across the American landscape. By looking beyond the boundaries of the energy system analyzed in this chapter—the building envelope and lifecycle building emissions—we find that any potential long-term benefits of increasing performance in the freestanding house are quickly offset by other important carbon impacts that attend sprawl: the continued degradation of greenfield land and the loss of carbon stocks in plants and soils; reduced efficiencies in electrical power due to transmission losses (Andrews 2008) and in heating fuel due to the expenditure of energy in its transport within an attenuated distribution network; the embodied emissions of roadway, bridge, and tunnel construction and repair and the operational emissions of unabated daily vehicular travel. The current low residential density of typical U.S. cities creates local transportation systems that are almost solely based on the private car and makes the daily commute of a typical American the longest in the world (Kenworthy 2008). These impacts, best assessed quantitatively in other past (and hopefully future) studies, begin to suggest that the benefits of increased performance in the construction of the individual house may be outweighed by the societal and environmental impacts, as well as the costs to homeowners, of sustained suburbanization.

## ***5.2 Building Performance Benefits in High-Density Housing***

Our study shows that, in terms of operational GHG emissions per housing unit, an apartment building clearly outperforms a house. That operational GHG emission reductions are achieved through the aggregation of housing units under one roof in a cold climate can be readily predicted with basic volume to surface area calculations: with its reduced surface of exterior envelope required to enclose it, an apartment tends to be more thermally efficient than a house. A more noteworthy finding is the relatively low GHG cost of upgrading an apartment building from standard envelope assemblies to high performance assemblies. Our study indicates that while the cost of these upgrades is negligible over the lifetime of an apartment

building, it is very significant for a house—nearly doubling embodied emissions. Our lifecycle assessment of high performing building enclosures deployed in a dense urban development demonstrates a multiplier effect, in which the performance benefits are amplified by the inherent thermal efficiency of multi-unit housing. Just as increased energy efficiency is most effective at higher residential densities, embodied emissions reductions are compounded when less surface area of high performance building envelope is used to house more people.

As we look for paths toward significant GHG reductions in the residential sector, high performance apartment buildings are an appealing option. They can deliver low household GHG emissions at a low initial cost, making the shift to high performance construction techniques more financially tolerable and, as a result, more likely.

### ***5.3 Other GHG Emissions Benefits in High-Density Housing***

Other benefits of residential density and urbanized housing lie outside the scope of this study but parallel the advantages found in the material and performance efficiencies of the shared building envelope. Several studies identify economies of scale found in more concentrated human settlement and confirm the reduction of emissions derived from them. Urban density allows for the development of more contained, efficient, and sustainable infrastructure. The employment of efficient energy supply and transportation systems, such as district heating and cooling and rail-based public transportation only becomes affordable once critical density thresholds have been surpassed (see e.g. Cervero 2004).

One perceived disadvantage of concentrating buildings and roadways as urban developments—the Urban Heat Island (UHI) Effect—may actually provide passive benefit during the heating season in cold climates. The UHI effect raises ambient temperatures around buildings, shrinking the thermal gradient between unheated exterior surfaces and heated interiors (Ewing and Rong 2008). These potential benefits of condensing housing are all based on the same principles of optimizing the built environment as a system that considers the overall balance of embodied and operational emissions; material investment and operational return.

### ***5.4 Questioning Density***

Concerns about the GHG reduction strategy of increasing urban density range from the quantitative to the qualitative and seek to assess negative effects or offsets as density reaches thresholds of tolerability—the attendant impacts on health, sanitation, air quality, and the atmospheric and hydrologic effects of large continuous surface areas of heat-absorbing, impervious material.

Some studies have questioned the effectiveness of carbon reduction strategies in the face of human behavior. A Norwegian study by Holden and Norland (2005) shows that if long-distance leisure travel by car and plane is added to everyday travel, inner city households have just as high carbon footprints as suburban residents. In effect, lower local travel needs are off-set by much higher long distance travel needs. Heinonen et al. (2011) discuss a related finding in a Finnish study: inner city residents have the highest carbon footprints, when consumption of all consumer goods is taken into account. Rather than calling into question the GHG benefits of urban density, these studies appear to confirm the consistent finding that increasing wealth tends to increase individuals' carbon footprints (as discussed also in Lenzen et al. 2008).

It is difficult to account for the variations in occupant behavior in the lifetime operational emissions of a house. Obviously, our quantitative assessments and the policies and plans that rely on them must assume some amount of human transgression of our models, measurements, and predictions. The agency of designers and policy makers lies to some degree in their ability to modify lifestyle through design and to a much greater degree in their implementation of energy efficient assemblies and mechanical systems (Salat 2009). Occupant behavior within or outside the home may ultimately determine individual carbon footprints. As one American energy consultant Andy Shapiro quipped, "There are no zero-energy houses...only zero energy families." (Solomon and Malin 2011).

## ***5.5 Impact of Carbon Sequestered in Buildings***

Another important point relates to the carbon sequestration potential of buildings. Our life-cycle assessment did not include the immediate benefit of the carbon storage capacity of the wood products used in the typical construction of the suburban house. Had it been accounted for, the suburban house would have fared somewhat better in the assessment, taking advantage of the carbon offset. The exact duration and magnitude of this sequestration effect depends on assumptions made about the building lifespan and end-of-life disposal or reuse of materials. Even in the worst case scenario, where the sequestered carbon is released by burning the wood after a short lifetime, a timber framed building is typically more carbon efficient than a concrete or steel framed building (O'Connor and Dangerfield 2004; Petersen and Solberg 2002; Upton et al. 2008). That the built environment might become, in its material and structure, a carbon sink drawn from a renewable source (timber) is a significant observation that bears more research, experimentation, and assessment (Oliver and Mesznik 2006). At the moment, the use of light wood framing in the U.S. is limited by regulatory codes to four stories. Mid-rise buildings like those modeled for the urban housing blocks in our assessment, are typically structured in steel or concrete. New heavy timber construction systems like laminated wood veneer and cross-laminated timber (CLT) panels, currently in use in Europe and Canada, have the capacity to bear the significantly higher structural loads of mid-rise buildings, resist failure in fire, and,

most relevant here, sequester carbon throughout the lifespan of the building. Had our studies analyzed mid-rise wall assemblies using CLT, the emissions advantage would have tipped even further toward the mid-rise high density-housing alternative. The introduction of CLT construction techniques to the American mid-rise construction industry promises notable benefit in the mitigation of atmospheric carbon. Further engineering and regulatory analysis and life cycle assessment of GHG emissions in mid-rise timber wall assemblies should be undertaken.

### ***5.6 Cultural Arguments Against Urban Housing***

Finally, it is beyond the capacity of this chapter to address the philosophical and cultural arguments that have been made against the urbanization of housing in the United States. These reactions are bound inextricably to the history of a nation with abundant land resources and reinforced by long accepted American planning practices and commercial real estate interests. We acknowledge that for many Americans accustomed to the wide availability of relatively inexpensive land and acculturated to the notion that a sense of domestic well-being and safety can only be guaranteed by a buffer of private exterior territory, city life may seem distasteful. This has, of course, important implications for American policy makers considering the viability of new planning strategies and development mechanisms. But problems of political and economic feasibility must be weighed against the mounting empirical and quantitative evidence that the sprawl of human settlement causes both global and regional environmental impacts such as soil and fresh water acidification and ozone depletion. According to a recent multi-national study the threat on the global ecosystem caused by biodiversity loss associated with ever expanding human settlements is on par with the threat of global warming (Hooper et al. 2012). One of most startling results of our study was a by-product of our methodology, the comparative mapping of the land areas required to house families in the suburb and the mid-rise city (Fig. 7). Architects, builders, planners and policy makers might consider the land resources exploited in the platting of cities and suburbs as part of the overall embodied emissions equation of the built environment. Our stark graphic analysis simply depicts, in quantitative terms, the voracious consumption of greenfield land areas under the current suburban planning and development regime, the equivalent, in terms of ecological resources—habitat, soil quality, and biomass—of fouling potable water in a drought.

## **6 Conclusion**

With the puncture in 2008 of the huge “housing bubble” in the U.S. economy and a growing realization that the freestanding house is, for most parts of the country, no longer a secure personal investment and commercial finance instrument; with

the spreading structural fragility of an extensive infrastructure that now barely—and at great cost—supports existing sprawl; and with the slow thawing of American’s historically chilly relationship with cities, a critical opportunity for planners and policymakers, as well as individual homeowners, has arisen in the United States. Once a major exporter and consumer of the building morphologies, development practices and investment models of invasive sprawl, Americans must now reassess the once shrinking city as a source of higher living standards, a site for new lifestyles, and a means to mitigate anthropogenic climate change.

In 2013, as the U.S. economy begins its “post-bubble” recovery, described in the familiar parlance and economic metric of “increased housing starts”, Americans face a critical choice and a formidable challenge: whether to treat their smaller, shrinking cities as just one more (albeit large) material possession to be ignored and discarded or, alternatively, to recognize their endowment of *embodied* potential. We can choose to understand our undervalued and underutilized urban centers as land area to build on intensively, avoiding further destruction of habitat, carbon bearing soils and plants, and complex natural hydrologic systems. We can exploit urban infrastructure as an existing system for the delivery of services: energy in the form of heat and electrification, potable water supply and waste removal and treatment, and transport. By focusing only on the increased enhancement of our own homes’ thermal performance, we fail to understand the overall system of energy consumption and carbon emissions in the construction and operation of the buildings we occupy and the land we consume. We are missing a vital chance to rebalance our use of land and material in our quest for shelter and comfort.

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## 7 Appendix: Study Methodology in Detail

### 7.1 *Embodied Emissions*

Embodied GHG emissions were assessed with the Athena Impact Estimator (from here on: Athena). This life-cycle assessment (LCA) tool has a built-in life-cycle inventory (LCI) of different construction materials and assemblies that respond to regional differences in construction practices in North America. The LCI for New York City was used in this study because it is the closest geographic match. Athena GHG assessment does not account for carbon sequestered in any material. More detailed assumptions of Athena as well as LCI reports can be found at <http://www.athenasmi.org/our-software-data/impact-estimator/>.

The assessment was done for a 50-year lifespan and all dwelling units were assumed to be owner occupied (this decision has an impact on assumptions that Athena makes about building maintenance).

## ***7.2 Building Assemblies***

Table 1 shows building assemblies used in the LCA.

## ***7.3 Omitted Building Elements***

The most notable omission in the embodied GHG calculation is the impact of gravel fill at foundations. While an important factor when looking at an individual building, the effect is small when comparing two or more structures. An apartment building is likely to need more fill but its impacts are divided between a large number of apartments. Other omissions include the mechanical and plumbing systems, and elevators. Since a full basement was included for both dwelling types, it can however be assumed that there is ample space for mechanical rooms. The GHG impact of building systems can be presumed to be negligible. In a LCA of a concrete apartment building Pasanen et al. (2011) estimate that elevators and mechanical equipment represent 0.2 % of the total weight of the building. Partitions (except the ones dividing apartments) were also excluded since they would have close to a matching GHG impact in both the apartment building and the house.

## ***7.4 Operational Emissions***

Operational emissions for the standard house and the apartment were estimated on the basis of U.S. data found in the Residential Energy Consumption Survey (RECS) 2005 (EIA).<sup>4</sup> Average per square meter annual energy consumption was first derived for each dwelling type and this figure was then multiplied by the size of each dwelling. Basement or garage floor areas were not included for either dwelling but stair halls were included in the apartment building. Data included from RECS was narrowed to dwellings in cold climates (at least 6,000 heating degree days per year) and dwellings built since year 2000.<sup>5</sup> Calculated in this manner, annual per-square-foot heating energy consumption for the house and the

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<sup>4</sup> RECS 2009 energy data was not available at the time of writing.

<sup>5</sup> RECS does not have enough data to warrant the use of New England data alone.

**Table 1** Assemblies used in the LCA

	High-performance high-rise apartment		Standard performance high-rise apartment		High-performance single-family house		Standard performance single-family house	
	Material or product type	Thickness or dimensions in millimeters	Material or product type	Thickness or dimensions in millimeters	Material or product type	Thickness or dimensions in millimeters	Material or product type	Thickness or dimensions in millimeters
Exterior wall	(Exterior) Plaster	10	Plaster	10	(Exterior) Vinyl siding	10	Vinyl siding	10
	Rigid insulation	200	Rigid insulation	120	Furring	18	Furring	18
Basement wall	(Interior) Cast-in-place concrete	200	Cast-in-place concrete	200	Moisture resistant building wrap		Moisture resistant building wrap	
					OSB	18	OSB	18
					Wood studs w/blown cellulose insulation	184	Wood studs w/rock wool insulation	140
					Cavity w/blown cellulose insulation	50		
Basement wall	(Interior) Cast-in-place concrete	300	Cast-in-place concrete	300	Wood studs w/blown cellulose insulation	184	Gypsum board	18
	Rigid insulation	150	Rigid insulation	50	(Interior) Gypsum board	18		
					Rigid insulation	150	Rigid insulation	80
				Cast-in-place concrete	200	Cast-in-place concrete	200	

(continued)

Table 1 (continued)

	High-performance high-rise apartment		Standard performance high-rise apartment		High-performance single-family house		Standard performance single-family house	
	Material or product type	Thickness or dimensions in millimeters	Material or product type	Thickness or dimensions in millimeters	Material or product type	Thickness or dimensions in millimeters	Material or product type	Thickness or dimensions in millimeters
Floors	Cast-in-place concrete	200	Cast-in-place concrete	200	Plywood	18	Plywood	18
Basement slab-on-grade	(Top) Cast-in-place concrete	100	Cast-in-place concrete	100	(Top) Wood I-joist Slab-on-grade	240 100	Wood I-joist Slab-on-grade	240 100
Foundation	Rigid insulation	200	Rigid insulation	50	Rigid insulation	100	Rigid insulation	50
Footings	Cast-in-place concrete	1,500 × 500	Cast-in-place concrete	1,500 × 500	Cast-in-place concrete	600 × 300	Cast-in-place concrete	600 × 300
Roof	(Top) Ballast EPDM membrane	20	Ballast EPDM membrane	20	(Top) Asphalt roofing Underlayment		Asphalt roofing Underlayment	
	Rigid insulation	300	Rigid insulation	220	Blown cellulose insulation	800	Blown cellulose insulation	300
Windows	Cast-in-place concrete 30 % window to exterior wall ratio Aluminum frame	200	Cast-in-place concrete 30 % window to exterior wall ratio Aluminum frame	200	(Bottom) Gypsum board	18	Gypsum board	18
	Double glazing with low E silver argon fill		Standard double glazing		30 % window to exterior wall ratio Aluminum frame		30 % window to exterior wall ratio Aluminum frame	
					Double glazing with low E silver argon fill		Standard double glazing	

(continued)

**Table 1** (continued)

	High-performance high-rise apartment		Standard performance high-rise apartment		High-performance single-family house		Standard performance single-family house	
	Material or product type	Thickness or dimensions in millimeters	Material or product type	Thickness or dimensions in millimeters	Material or product type	Thickness or dimensions in millimeters	Material or product type	Thickness or dimensions in millimeters
Apartment partitions	Gypsum board	18	Gypsum board	18				
	Gypsum board	18	Gypsum board	18				
	Steel stud with rock wool insulation	92	Steel stud with rock wool insulation	92				
	Gap	20	Gap	20				
	Steel stud with rock wool insulation	92	Steel stud with rock wool insulation	92				
	Gypsum board	18	Gypsum board	18				
Elevator core	Gypsum board	18	Gypsum board	18				
	Cast-in-place concrete	200	Cast-in-place concrete	200				

apartment is 595 and 228 MJ respectively. Electricity consumption was estimated at 222 MJ for the house and 296 MJ for the apartment. With no specific data for common area energy use available for Connecticut, these same figures were used for the stair halls of the apartment building.

Energy consumption for the high-performance dwellings were taken directly from the stipulations of the Passive House standard. For both dwelling types, annual per square meter heating energy consumption was estimated at 54 MJ. Electricity consumption was estimated at 112 MJ/m<sup>2</sup>/a on the basis of the maximum total primary energy consumption (divided between heating and electricity) of 433 MJ/m<sup>2</sup>/a and estimated 30 % efficiency in electricity production.

Operational GHG emissions were estimated on the basis of the fuel mix for heating in the U.S. North–East and Connecticut electricity emission factors. Carbon equal global warming potential factors of 25 for methane and 298 for nitrous oxide were used. It was assumed that the carbon intensity of both heating fuels and electricity production would be decreasing over time: by 2.4 % annually for electricity and 0.8 % for heating over the full lifetime.

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## Author Biographies

**Eero Puurunen** has practiced as an architect and urban planner in the United States, China, and Finland. His work, ranging from single-family houses to district plans, focuses on sustainable development with a particular emphasis on environmental issues. In 2007 he won a Holcim award in sustainable construction for his urban design proposal for one of Shanghai's old neighborhoods. Mr. Puurunen has conducted research on sustainability assessment methods in urban planning and is participating in the development of an assessment tool for Finnish cities. He currently teaches environmental design at Yale School of Architecture. Mr. Puurunen carries master's degrees in architecture and urban planning (Aalto University) and environmental design (Yale University).

**Alan Organschi** is principal and partner at Gray Organschi Architecture, a design firm recognized for its innovative conception and implementation of projects that range from the adaptive re-use of

damaged buildings and neighborhoods to the development and implementation of low-impact assembly systems for ecologically delicate sites. As a member of the Yale School of Architecture faculty, he coordinates Yale's first-year graduate housing studio which culminates each spring with the student construction of an affordable house in the city of New Haven. He is also a lecturer in building technology and an area coordinator at the graduate school. He has lectured publically on architecture, technology, and sustainable urban renewal. Mr. Organschi's current research includes prototype development for high-density, high performance wood housing in the U.S., conducted under the auspices of the Hines Research Fund for Advanced Sustainability in Architectural Design.