GREEN RESIDENTIAL BUILDING TOOLS AND EFFICIENCY METRICS

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ABSTRACT
Residential buildings have the function of providing shelter, comfort, and a host of other amenities to their occupants, yet they are responsible for a large share of global negative environmental impacts. Understanding the need to reduce the negative impacts of buildings has led to an increase in both the quantity and popularity of green building rating schemes in recent years. Within most green building schemes, the common goal generally consists of an attempt at increasing aspects of the efficiency of resource use or environmental damage. Impact quantification is often reduced to modeled operational energy consumption, while the actual function is less simple to define or assess quantitatively. In many green building schemes, consideration of function is basically omitted from the assessment, except for the inclusion of a simple proxy metric. The dominant "function" metric that has emerged is floor area, carried over from commercial building assessments. Not only is floor area not a useful proxy for function provided by residential buildings, but placing it in the denominator of an eco-intensity metric results in a perverse ratio of two impacts. All else equal, increasing floor area gives the impression of increased efficiency, while masking the increased embodied and use-phase energy, GHG emissions, and materials use. This paper provides a review and initial inquiry into environmental assessment of residential buildings, addressing the utility of common metrics.

KEYWORDS
green building, energy, metrics

1 INTRODUCTION

The effects and limits of exponential growth in resource consumption and waste production have been exposed, explored, and contested for decades (Meadows et al. 1972; Kreijger 1973; G. M. Turner 2008; Pelletier 2010). Responding to these concerns, sustainable development and sustainability have become crucial issues globally, specifically since the terms were highlighted in the report *Our Common Future* over 25 years ago (WCED 1987). The report defined sustainable development as "…development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987, 54). Calls

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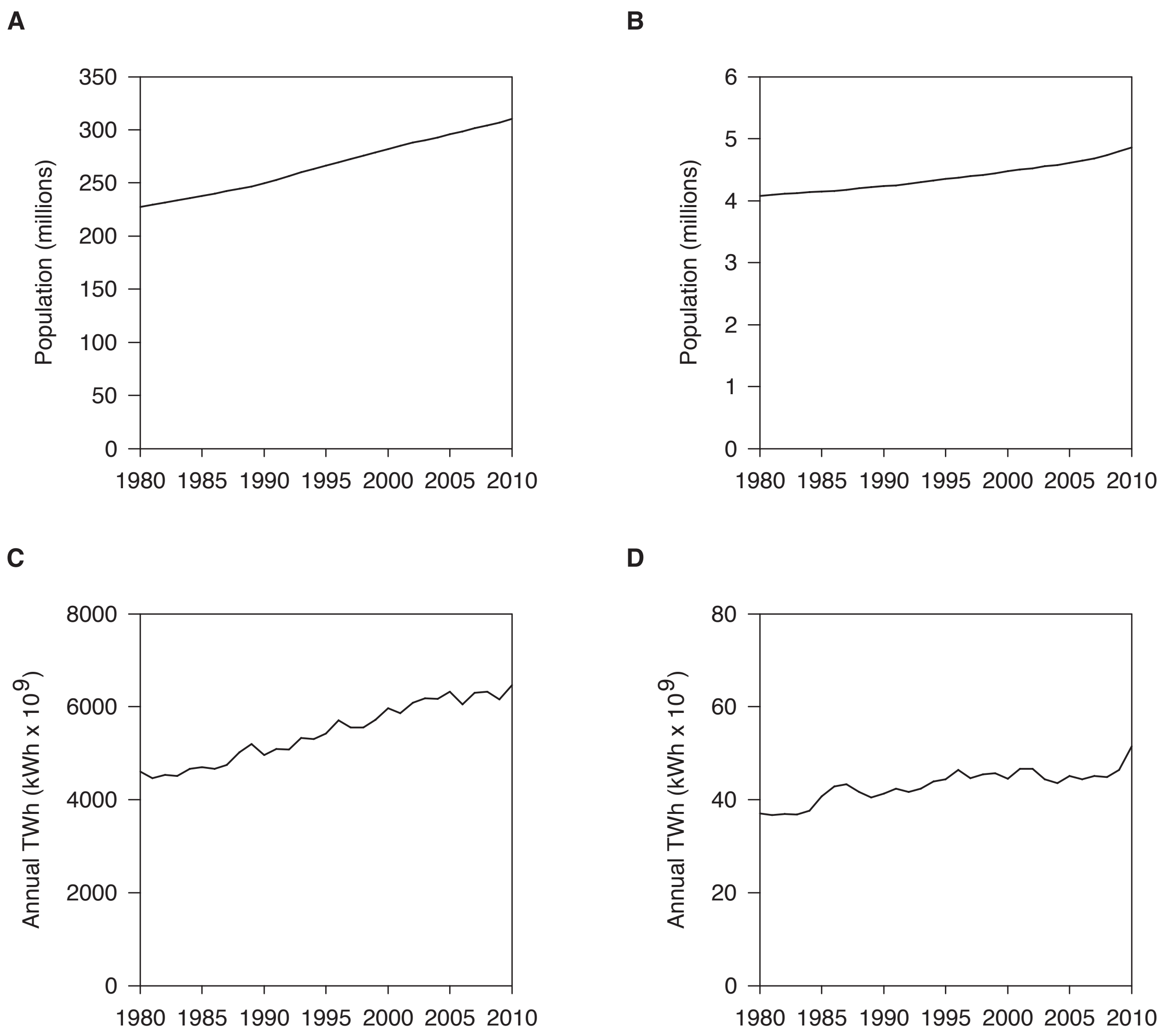
to define and implement sustainable practices are becoming more frequent and more definite as evidence of peak oil (Aleklett et al. 2010; Kerr 2011; Murphy and Hall 2011; Hall and Klitgaard 2012), peak coal (Mohr and Evans 2009; EWG 2007), and anthropogenic climate change builds (IPCC 2007). According to the Fourth Assessment of the Intergovernmental Panel on Climate Change (IPCC) "Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations" (IPCC 2007, 10).

Building and construction form the basis for many of the largest anthropogenic impacts on the environment. The building and construction sector is the largest consumer of natural resources in terms of both land use and materials extraction (Huovila et al. 2007). Buildings are responsible for 30-40% of primary energy use and greenhouse gas (GHG) emissions worldwide (Huovila et al. 2007), and currently represent "the single largest final end-use consumer" of energy (IEA 2012, 61).

FIGURE 1. Similar trends 1980–2010: Population growth in the US (A) and Norway (B); Increases in total residential energy consumption in the US (C) and Norway (D). Data from (DOE 2012; Bøeng et al. 2011; SSB 2012a, 2012b).



Residential buildings operations in the US accounted for 22% of total primary energy consumption in 2009 (DOE 2012). The inclusion of indirect consumption from other life-cycle phases (construction and disposal) into the calculation increases total consumption to 26% of total primary energy use, as well as 38% of total electricity use and 24% of GHG emissions (Ochoa, Hendrickson, and Matthews 2002). Globally, 14% of final delivered energy and 17.5% of total global primary energy in 2008 was consumed in residential buildings (IEA 2012). The contribution of residential buildings to total energy consumption has remained relatively stable, but the actual quantity of energy used in residential building operations continues to increase in line with population (Figure 1).

2 GREEN BUILDING

2.1 Residential Green Building Certification Systems and Evaluation Tools

Understanding the need to reduce the negative impacts of buildings has led to increased interest in green building and growth in evaluation tools, and rating or certification systems in recent years (BSC 2008; EPA 2008; Wang, Fowler, and Sullivan 2012). The US Environmental Protection Agency (EPA) defines green building as:

> …maximizing the efficiency with which buildings and their sites use resources—energy, water, and materials—while minimizing building impacts on human health and the environment, throughout the complete building life cycle—from siting, design, and construction to operation, renovation, and reuse (EPA 2008, 1).

A wide variety of often overlapping green building tools and systems have been introduced to influence or assess the environmental impact of buildings (Haapio and Viitaniemi 2008; Mehdizadeh and Fischer 2012; Wang, Fowler, and Sullivan 2012), which generally involve prescriptive or descriptive elements.

Prescriptive elements require or reward criteria that are expected to promote efficiency or sustainability, with the focus on influencing or steering the design process towards the goals of the program. Descriptive elements attempt to assess the system as built or designed. While the descriptive approach requires an initial design, there is a presumed underlying influence through iterative or feedback processes.

Prescriptive elements are generally found in green building rating systems and usually encompass a checkbox approach with necessary and optional criteria, where successful completion is rewarded with credits toward a label or rating. The rating systems that have garnered the most attention are the Building Research Establishment Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED). Originally developed in the UK in 1990, BREEAM has expanded with country specific variants in Europe and internationally to become the "world's foremost environmental assessment method and rating system for buildings" (BRE Global 2012); while LEED emerged 10 years later but dominates the U.S. market. BREEAM and LEED began as certification systems for commercial buildings only, but both have since developed schemes for residential homes as well, yielding LEED for homes, and BREEAM EcoHomes - which in the UK has since evolved into the Code for Sustainable Homes (CSH).

Descriptive methodologies include life cycle assessment (LCA) and LCA-based software designed to assess buildings. While some of these tools assess materials and assemblies only, some consider the building as a whole. The Athena Impact Estimator for Buildings, for example, takes input data in the form of quantities or areas of building assemblies, and then outputs a record of impacts from the characteristics of the embodied materials (Athena SMI 2013). Use phase energy consumption is not modeled implicitly, but must be input from assumed or modeled values. The result is an estimate of life-cycle impacts, with comparisons between life-cycle stages.

Two approaches that blur the line between prescriptive and prescriptive approaches are the Passive House concept and the Norwegian TEK10 building standard. Both approaches include mandatory prescriptive elements relating to efficiency and airtightness, yet also include maximum allowable values for modeled heating and cooling demand, as well as total primary energy demand (KRD 2010; PHI 2012).

2.2 Energy

The environmental impacts of buildings are not limited to energy consumption, but energy remains one of the most important factors affecting sustainability. With regards to green building, the EPA states that “energy efficiency is the place to start” (EPA 2012).

Energy use is already a common proxy or indicator metric used to represent much more than just energy. The high correlation between fossil energy consumption and overall environmental impact (e.g. GHG and aerosol emissions and associated acidification and eutrophication impacts) makes energy consumption a common focus of building sustainability assessments and LCAs (Borg 2001; Huijbregts et al. 2010; Nemry et al. 2010; Ortiz, Castells, and Sonnemann 2009).

2.3 Post-Occupancy Evaluation

Once a building is put into service, a post-occupancy evaluation (POE) can be made under actual conditions (Meir et al. 2009). Instead of attempting to address the broader goals of green rating schemes, this approach is usually focused on a limited number of metrics such as use-phase energy consumption or indoor environmental quality (IEQ).

With the exception of Passive Houses, there is a dearth of published large-scale quantitative research into real-world energy effectiveness of green residential buildings from which to draw meaningful conclusions (Beauregard, Berkland, and Hoque 2011; Schnieders and Hermelink 2006; Schnieders 2003). Commercial building assessments are more mature, and energy POEs have been used to bridge the gap between systems and their intended results, or prove the effectiveness of green building programs, with mixed results (Bordass et al. 2001; C. Turner and Frankel 2008; Newsham, Mancini, and Birt 2009; Scofield 2009; Hendrickson and Wittman 2010). The USGBC, for example, commissioned an energy analysis comparing LEED commercial buildings to Commercial Buildings Energy Consumption Survey (CBECS) data, that has since been used as evidence of LEED’s effectiveness (C. Turner and Frankel 2008). Several researchers have pointed out perceived methodological flaws or inconsistencies in the analysis, including the comparison of medians to means, comparison of size-weighted to non size-weighted averages, comparison of new LEED buildings to existing CBECS buildings, and use of a small self-selected convenience sample (Gifford 2009; Hinge and Winston 2009; Scofield 2009). Upon reexamination of the original data, one author found “no evidence that LEED certification has collectively lowered either site or source energy for office buildings” (Scofield 2009, 1386). Other researchers applied different statistical methods to the data (e.g. pair-matching similar buildings for comparison) to conclude that, on average, LEED buildings do save energy, but that 28–35% of LEED buildings have higher energy consumption than their matched CBECS counterpart (Newsham, Mancini, and Birt 2009).

The one clear conclusion that can be drawn from research, discussions, and POEs regarding energy is that savings are difficult to prove or disprove. Buildings are generally custom structures with different users and usage patterns, making direct comparisons difficult or impossible. The samples are confounded by user behavior and self-selection (green clients choosing green homes) and the impossibility of proving what would have happened otherwise. In fact all energy efficiency savings claims are counterfactual statements that cannot be observed in order to be proven or disproven (Sorrell 2010). Several authors have recommended that final ratings should be based on demonstrated performance using utility bills or POE of energy and water consumption, and measured IEQ (Gifford 2009; Newsham, Mancini, and Birt 2009; Trusty 2008). The message seems to be that the goal of green building should be to create buildings that clearly and measurably achieve performance targets, not simply to follow a criteria set that may enable or simplify their attainment. Though only addressing energy, the US Energy Star label (for commercial buildings) follows this approach, with certification of existing buildings based solely on comparisons of energy use to similar buildings in the existing building stock (Hicks and Von Neida 2003; EPA 2011a).

3 EFFICIENCY, GOALS, AND PERFORMANCE METRICS

3.1 Eco-efficiency

While green building practices and assessment methodologies may imply progress toward sustainability, there is relatively little pertaining to promoting the actual overall reductions in energy and resource consumption, waste and emissions production necessary for progress toward a sustainable global society. What is promoted is more efficient consumption and production, or eco-efficiency (EE).

Production and use of buildings (and most products) represents a trade-off between function and environmental impact. The goal of EE programs is generally to get more for less, which can be interpreted as more function at lower levels of impact (Brattebø 2005; Ehrenfeld 2005; EC 2005; Pérez-Lombard et al. 2009). The alternate interpretation, which is the one that seems to be most implemented, is increasing functionality while increasing impact less (or less than would have been expected). While mathematically both approaches may reduce to ratios that show some achievement of increased "efficiency" they are entirely different in their effect on overall impact. Regardless of vagueness in definition and interpretation, EE "has been accepted as the key strategic theme for global business in relation to commitments and activities directed at sustainable development" (Ehrenfeld 2005, 6).

A valid approach to EE then requires accepted goals on what is being optimized; designation of the function that is being increased and the impact that is being decreased. The choice of numerator and denominator in the EE ratio may seem obvious or trivial, but they present a myriad of challenges in definition and quantification (Brattebø 2005; Ehrenfeld 2005; Pérez-Lombard et al. 2009). Eco-intensity, as commonly used in building metrics, is simply the inverse of eco-efficiency, but the problematic choices of numerator and denominator remain (Brattebø 2005; Ehrenfeld 2005).

3.2 Building energy use intensity

3.2.1 Background in Commercial Buildings

Building energy use intensity (EUI), defined as annual energy use per floor area (btu/ft^2 or kWh/m^2), emerged as the most common metric for assessing the energy performance of commercial buildings (Sharp 1996; Chung, Hui, and Lam 2006), and has recently found its way into considerations of residential energy consumption as well. Here energy use is likely a proxy for overall environmental impact (see section 2.2), and floor area is likely intended to represent the function or utility provided. This implies that the function of the building (the purpose for which it is built, or being used) is measurable in terms of floor area.

In commercial buildings, space and energy are used to pursue the goals of business, industry, government and other organizations. Commercial buildings comprise a widely varied range of activities, where direct comparisons are difficult owing to the variety of uses. EUI emerged from the realm of engineering and process efficiencies, where the function is taken as a given. The concept of process efficiencies is well understood and is an easy carryover for engineers wishing to understand efficiencies in other systems. While process efficiencies and intensities have transferred to the building sector, they do not adapt well. As opposed to process efficiencies, "intensities reflect behavior, choice, capacity or system utilization, and other factors" (Schipper et al. 2001, 55). A "simple normalized EUI" is not reliable enough for credible ratings, and must be tempered with explanatory variables to be meaningful (Chung, Hui, and Lam 2006, 2; Sharp 1996). The US Energy Star label for commercial buildings (EPA 2011a; LBNL 2011), as well as many research and modeling projects (Chung, Hui, and Lam 2006; Yu et al. 2010) utilize regression modeling to predict EUIs; the result is a prediction or a comparison to a similar hypothetical building. By normalizing to other primary determinants of energy use (e.g. workers per area, number of personal computers, operating hours, and whether the building is owner-occupied), EUIs can be a useful tool for benchmarking and comparing buildings (Sharp 1996).

3.2.2 Application to Green Residential Buildings

Unlike commercial buildings, people use energy in residential buildings mainly to provide shelter and comfort services for people. In designing and assessing buildings, it is easy to forget that it is the human element that is the main factor. Buildings can be designed to make it easier for people to use less energy, but currently the ultimate decision rests with the person. Regarding commercial buildings, a US Department of Energy (DOE) sponsored report concluded that "building occupants are the most significant factor in sustainable building operations" (Fowler, Solana, and Spees 2005, 19). This is likely even more true for residential property, where occupants have a higher level of individual control over most aspects of energy consumption.

In the 27 European Union (EU) member states, Norway and Croatia, the Energy Performance of Buildings Directive (EPBD) lays out an ambitious framework requiring energy certificates for new and existing buildings. Energy efficiency as interpreted by the member states is generally based on theoretical or measured annual energy consumption per area (annual kWh/m^2). The goal of the program is to "certify the buildings and not the users" (EC-EPBD 2011, II–5), but is severely limited in scope. The EPBD is a one-time certification without provision for ongoing evaluation, which is diversely implemented by the different member states (Building EQ 2010). The certification process considers only operational energy while neglecting the embodied energy from construction, materials, and components in the building being certified (Szalay 2007).

The Norwegian TEK10 standard applies to all new residential buildings, not just those seeking a "green" label. While TEK10 utilizes a prescriptive approach to energy-related building characteristics, including insulation values, airtightness, and other factors, it also includes a maximum allowable estimated total annual EUI (KRD 2010). While the TEK10 standard does not specifically address occupancy or occupant behavior, a sliding energy scale incentivizes the construction of smaller homes. Contrary to most other approaches, the TEK10 maximum allowable annual EUI increases with decreasing conditioned floor area, from 120 kWh/m^2 up to 153 kWh/m^2 (for a 30 m^2 house). Free-standing houses under 30 m^2 must only fulfill the prescriptive requirements.

The UK CSH utilizes floor area for all energy and GHG emissions calculations and targets, with no reference to the intended number of occupants, or to floor area per occupant (BRE 2010). Building energy efficiency and CO_2 emissions are estimated and normalized to floor area, using the "standard occupancy and usage pattern" found in the Standard Assessment Procedure (SAP) (BRE 2010; BRE 2011, 5). Indoor water use is not calculated per floor area but per capita, by applying fixture efficiency values to assumed consumption rates (BRE 2009). Put simply, the water efficiency calculator utilized to determine compliance "cannot be used to calculate actual use due to the impact of user behaviour" (BRE 2009, 9). The CSH does not consider building size relative to occupancy, or assess actual consumption rates post occupancy.

LEED for homes now includes post-construction tests for envelope and duct leakage, refrigerant charge, and air flow, incorporating the US EPA Energy Star for homes ratings for modeled energy consumption per floor area (USGBC 2010). While the Energy Star calculations utilize a benchmark home floor area to determine efficiency based on US residential energy services network (RESNET) ratings, the benchmark size increases with the number of bedrooms; All rooms with a closet and an egress window, including dens, libraries, and home offices count as bedrooms (EPA 2011b, 2011c). LEED for homes adjusts the points necessary to reach specific ratings through an adjustment based on floor area and the number of bedrooms, recommending any room that could legally be used as one to be counted as a bedroom (USGBC 2010). Neither LEED nor Energy Star incorporates any post-occupancy evaluation to compare modeled to real-world energy consumption.

One approach that does consider both energy use and occupancy related to floor space is the Passive House concept. While the main focus is on prescriptive means to reaching specific annual energy intensity targets (maximum 15 kWh/m^2 heating, 15 kWh/m^2 cooling, and a maximum total primary energy demand of 120 kWh/m^2), the concept also includes a mandatory occupancy characteristic of 35 m^2 per person (between 20–50 m^2 per person may be allowed) (Schnieders and Hermelink 2006; Feist 2011; PHI 2012). Passive house certification requires a post-occupancy airtightness evaluation, but no comparison of how well the in-use building energy consumption compares to that of the modeled building.

4 DISCUSSION

Green building evaluation and rating systems have emerged to meet the demand for buildings with verifiably reduced environmental impacts. The goal is to reduce the harmful impacts of buildings without a loss in functionality, but a review of the current systems and the metrics used to evaluate them reveals several issues. Most of the rating systems lack any real-world quantitative assessment. Progress is measured through a focus on efficiency ratios, obscuring understanding of the contribution to total impact. The function variable in the most common EE ratio (EUI) is not a valid representation of building function.

EE as a means to reducing total consumption is justified, but has been challenged as a goal in itself, as increased consumption (rebound or backfire) may reduce or overcome any possible gains (Hanley et al. 2009; Huesemann and Huesemann 2008; Korhonen 2008; Rudin 2000). In casual or uncritical use EE can be mistaken as actually resolving "unsustainability" and shifting burden "away from the search for effective solutions" (Ehrenfeld 2005, 7). The success or failure of EE in reducing consumption in residential buildings depends on goals and implementation, and often relies on occupant behavior; it can be a useful approach if all other variables remain constant, but the building sector presents a constantly moving target. Home size has been increasing while occupancy per home has been decreasing. Floor space per capita has been increasing while total residential operational energy consumption per capita has been relatively stagnant. Historically, efficiency gains have been overcome by a relentless growth in both population and housing size:

> Despite better building practices and newer systems, the greater average floor space of new homes has offset their improved efficiency (DOE 2012, 63).

Efficiency touted as a means of reducing energy consumption has been repurposed as a means of providing larger homes while keeping per capita energy consumption relatively stable (Figure 2A, 2B).

Figure 3A shows the trend of decreasing EUI with increasing residential household floor space in the US and Norway. A focus on EE based on EUI is likely to distort a deeper understanding of the drivers of residential energy consumption. Based on the figure, one could conclude that the answer to the energy problem is bigger homes. If certification were based on EUI only, many of the largest houses would potentially qualify for the Passive House standard (Feist 2011). In fact, and contrary to the seeming efficiency exposed by EUI, the figure hides a much bigger truth—larger buildings use much more energy (Figure 3B) per occupant,

FIGURE 2. Similar trends 1980–2010: Slight increases in per capita residential energy consumption in the US (A) and Norway (B); (DOE 2012; Bøeng et al. 2011; SSB 2012a, 2012b).

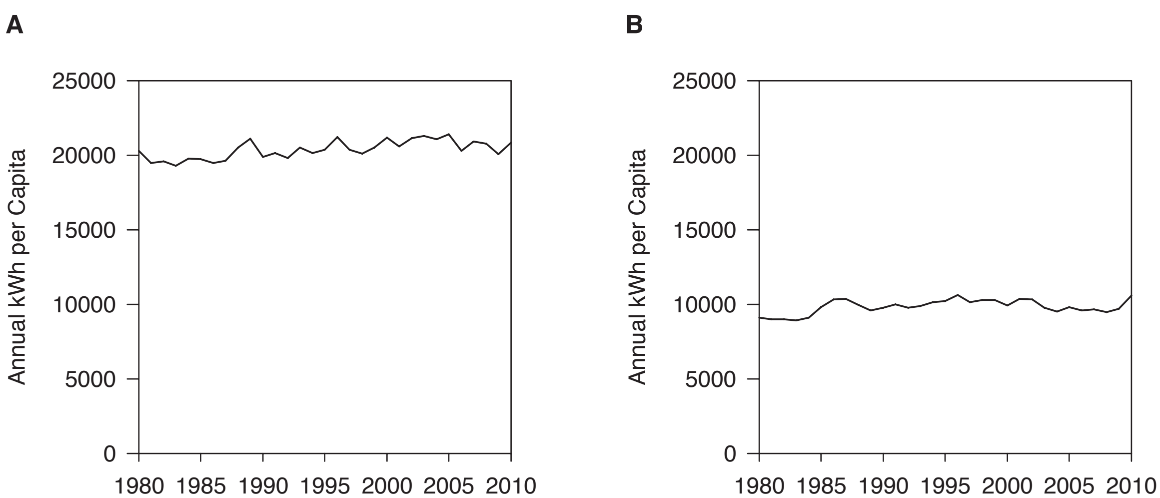
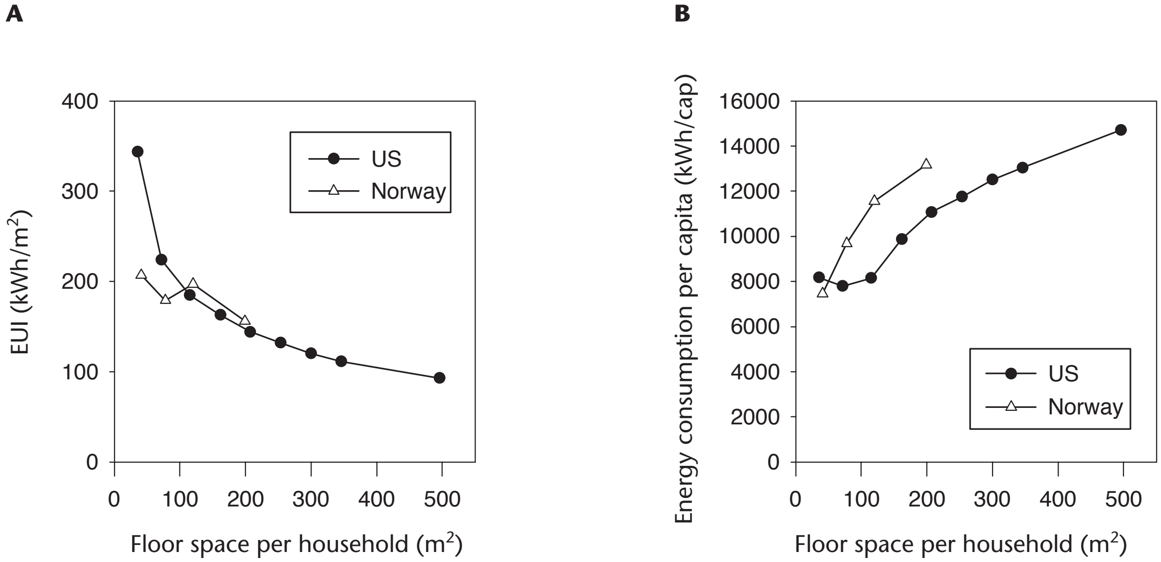


FIGURE 3. (A) EUI decreases with increasing household floor space, while (B) per capita energy use increases with increasing household floor space. 2009 data from (EIA 2012a; SSB 2011).



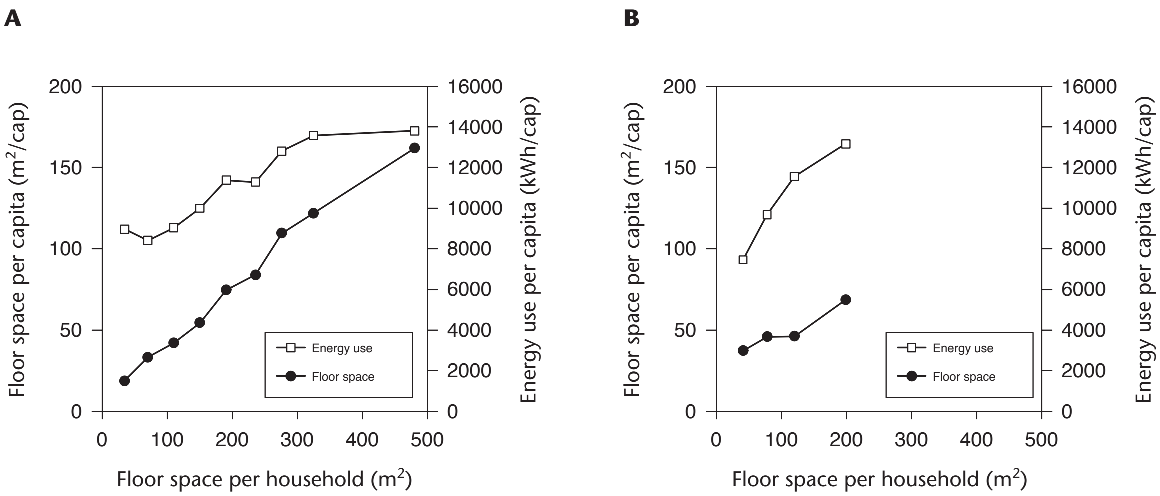
not less. In addition to direct impacts like use-phase energy consumption, every extra square foot or meter of housing per capita involves embodied and recurring energy and materials throughout its life cycle, from site preparation to construction, maintenance, refurbishment, and end-of life, not to mention the opportunity cost of removing materials and land from the stock available for use by others (Hellweg, Hofstetter, and Hungerbühler 2003). As such, EUI is a metric that could be considered to represent an "efficiency" ratio of two impacts, not impact resulting from function.

Examining the same housing statistics on a per capita basis shows the large disparity in energy and floor space based on total household size (Figure 4A, 4B). The occupants of larger homes use much more space, materials, and energy than their smaller homed counterparts. The 13.3 million households in the US larger than 325 m^2 used more total energy in 2009 than the 27.6 million households that are smaller than 94 m^2 (EIA 2012a). The smaller houses use 25% less total energy, while at the same time providing housing for 15 million more Americans (EIA 2012a).

Two problems emerge with the use of floor area as the function metric in residential buildings. One is the lack of a global definition for what spaces are included in the measurement. Second, and more important, is the same lack of functional validity that emerged with commercial assessments 20 years ago (see section 3.2.1).

There is no global consensus on the definition or calculation of floor area, which can vary between geographic entities, as well as within them depending on the goal of the calculation. Often the definition or calculation methodology is not explicitly stated along with presented data. In other cases the methodology can change between surveys or datasets, confounding efforts at benchmarking or comparison. Tax records and property listings often involve actual measurements, but "included areas differ by jurisdiction and housing unit type", while surveys such as the Residential Energy Consumption Survey (RECS) often rely on self-reported floor area estimates that are "typically much smaller" than RECS measurements (EIA 2012b). As

FIGURE 4. Per capita energy use and floor space in the US (A) and Norway (B) show similar trends with increasing household floor space. 2009 data from (EIA 2012a; SSB 2011).



RECS has moved from self-reported to measured values, comparisons between surveys and between years may be inappropriate (EIA 2012b). Standards may be expected to fill the harmonization gap, but the definitions in the relevant ISO and ASTM standards are not consistently utilized or properly referenced. The ISO standard for calculating energy performance utilizes "conditioned area" but leaves the definition open to national regulations (ISO 13790 2008).

Area alone is a poor proxy for function or functionality in residential buildings, which are expected to provide safe, comfortable shelter for their inhabitants. The use of floor area to represent service function may facilitate comparisons between buildings, but floor area does not actually define their function (Forsberg and Von Malmborg 2004). The main argument for the use of the area metric would likely be then that it simply represents a normalization factor, not an actual attempt to track function, service provision, or utility. The normalization factors commonly used are intended to be the variables that have high correlation with consumption (Sharp 1996; Chung, Hui, and Lam 2006). When considering only the contribution of heating and cooling loads to consumption, and ignoring user behavior and occupancy, floor area is but one possible metric. Internal volume, external surface area, or a ratio of the two may be more pertinent normalization factors in the consideration of energy consumption (Nemry et al. 2010; Nemry et al. 2008; Wilson and Boehland 2005; ISO 9836 2011). The correlation between floor area and overall consumption at the aggregate level may be valid, but knowledge of energy consumption per floor area provides little to no guidance toward reducing total consumption.

5 CONCLUSIONS

> A design that is better than a bad design is not necessarily a green design (Straube 2006, 7).

Metrics are chosen or created by people in order to simplify and enhance understanding. While the common area efficiency metric in use achieves the goal of being simple, it is hard to argue that it provides much useful information on its own. The utility of the metric is dependent on deeper system knowledge of other factors influencing consumption. Beyond the marketing and lifestyle rhetoric, the point of residential housing is to provide shelter for people; any chosen "function" metric for residential buildings needs to explicitly include occupancy. While theoretical and achieved efficiencies are important, they generally consist of an attempt to direct people to make certain choices that may be more sustainable. The ultimate choice is left to the consumer, and in a democratic society, the choice is generally what the consumer is willing to pay for. For a consumer that wants a bigger, warmer house, or a heated outdoor patio, or an exponential increase in appliances (Hertwich and Roux 2011) there is little that efficiency gains alone can do to control or alleviate their impact. In fact, in considering the rebound effect, efficiency gains may actually increase consumption.

The Kyoto Protocol and other approaches to limit greenhouse gas emissions take a per-nation absolute approach, while green building approaches and definitions generally utilize a per-area efficiency approach. This obvious disconnect will inherently lead to limitations in the effectiveness of green building to contribute to GHG reduction goals. Worldwide, houses keep getting bigger, as occupancy per building decreases and the population increases. Consideration of energy use per area, while overlooking occupancy and total area is a futile exercise if the goal is an overall reduction in energy use. Except for government and academic analyses related to macro-scale energy trends, there has been little if any consideration of actual energy consumption in defining green/sustainable practices for residential buildings. Considering LEED for homes, Energy Star homes, Passive House, TEK10, and the CSH, none base their rating on actual measured energy consumption, or involve any post-occupancy comparison of modeled to actual energy use.

If the goal of green building metrics is to expose and ultimately reduce total impact, then the most valuable metrics will be those that expose the relationship between efficiency and absolute impacts. The causative variables should be folded into the metric, yet remain available for consideration. If green building tools are to reduce the impact of providing residential services to people, then the metrics in use need to relate to people; communicating the relationship between their behavior and their numbers to their impacts.

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