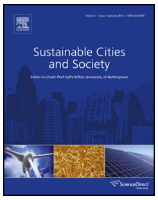
Sustainable Cities and Society 16 (2015) 24–38

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs



A novel hybrid methodology to evaluate sustainable retrofitting in existing Swedish residential buildings

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ARTICLE INFO

Article history:
Available online 23 February 2015

Keyword:
Retrofitting
Embodied energy
Sustainability

ABSTRACT

Energy and environmental issues are increasingly important in existing building service and energy systems around the world. Despite great efforts to implement retrofit techniques in Sweden, no stringent evaluation of the benefits of these techniques or their systematic design has been completed. Traditional evaluations have not taken into account the embodied energy and greenhouse gases emissions of different retrofit options. This omission leads to underestimation of the potential environmental benefits of modern retrofit techniques. In this study a novel hybrid modeling approach to quantify the sustainability of retrofit options is developed to fill these knowledge gaps. The compatibility of environmental and energy-saving modeling of various energy-saving techniques for future transition of Swedish residential building stock is analyzed. Consolis Retro and the life cycle assessment (LCA) techniques are employed and further coupled to simulate retrofit options. The model integrates both energy demand (net operational energy), primary energy (operational energy from energy mix to buildings) into evaluation criteria. Embodied energy (energy required to produce materials of retrofitting options) and embodied greenhouse gas emissions (upstream CO_2 equivalent) are introduced as new measures in the evaluation criteria. The results showed that low-temperature heating retrofitting was the most effective option from both a primary and embodied energy perspective in the studied building types. Combining circulation pump renovations could further contribute to the efficiency of low-temperature heating for energy-demand savings. High operational energy-saving measures may not always lead to larger reduction in both embodied energy and greenhouse gas emissions, particularly for building envelope retrofitting. Neglecting the embodied energy of retrofit options will increase the risk of overrepresenting their energy-saving contributions. The sustainability improvements of retrofitting, particularly large-scale measures, should take into account the embodied energy and greenhouse gas emissions from the material productions.

1. Introduction

Energy utilization and the mitigation of environmental impacts are increasingly important in building stock around the world. Among all end users, existing residential buildings represent a large part of total energy use and greenhouse gas (GHG) emissions. In 2010 to adapt to established climate targets, European Union launched the “20–20–20” sustainability target, representing a decrease in EU GHG emissions to 20% below 1990 levels, and 20% energy efficiency improvements to be achieved by 2020 and 2050, respectively (Energimyndigheten, 2012).

In response to tightening EU energy and environment directives, Sweden is actively engaged in sustainable transition of national building stock, targeting at least 50% of the total energy use, 49% share of renewable energy sources, and 40% reduction of GHG emissions compared with 1990 levels by 2020 (Energimyndigheten, 2011). Specifically for existing residential buildings, the Swedish government has established the ambitious energy efficiency target of 50% (per heated floor area) by 2050 compared with the 1995 level (Swedish Environmental Protection Agency, 2011). As an effective technique, building industry considers retrofitting an efficient means to accelerate the transition of existing housing stock (Företagen, 2009). In line with these goals, the Swedish Building

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http://dx.doi.org/10.1016/j.scs.2015.02.002

Nomenclatures

Acronyms

ACH	air changes rate, h^{-1}
AHU	air handing unit
BBR	Swedish building regulation
CHP	combined heat and power
DHW	domestic hot water
GHG	greenhouse gas
LCA	life cycle assessment
LTH	low temperature heating
MP	miljonprogrammet (million program)
RO	retrofit option

Symbols

A_h	heated floor area, m^2
A_l	effective air leakage area, m^2
A_{pipe}	piping area of district heating grids, m^2
C_{D}	discharge coefficient
I_{rad}	average for horizontal radiation
f_{PE}	primary energy factor
$f_{\mathrm{PE,DH}}$	primary energy factor for district heating
f_{PEl}	primary energy factor for electricity
$f_{\mathrm{PH},i}$	primary energy factor of energy carrier *i*
Δp_r	reference pressure difference, Pa
q	flow in the hydraulic system, *kg/s*
$\mathrm{Q}_{\mathrm{DH,piping\ loss}}$	heat loss through district heating grids
t	monthly basis
t_g	ground temperature
t_r	return temperature of the district heating
t_s	supply temperature of the district heating
T_{ave}	monthly averages for local outdoor temperature
T_e	outside temperature variation
U	heat transfer coefficient of building parameter
U_{pipe}	heat transfer coefficient of district heating pipes
ρ_{air}	air density, kg/m^3
ρ_{material}	density of the building material, kg/m^3
$\Phi_{\mathrm{Delivered}}$	delivered energy of energy supply systems
Φ_{DHW}	energy usage of domestic hot water
Φ_{ED}	total net energy demand
Φ_{EL}	electricity usage of the building
Φ_{H}	energy usage for space heating
$\Phi_{H,T}$	transmission heat loss through building envelope
$\Phi_{I\cdot S}$	solar heat gains
Φ_{Ven}	ventilation heat loss
Φ_{PE}	total operational primary energy usage of the building
Φ_{PEl}	cogenerated electricity
$\Phi_{\mathrm{PH},i}$	input heat in energy carrier *i*

Regulations (BBR) was recast in May 2011 to accelerate the transition of existing housing stock nationwide. The revised building code mandates that existing buildings implement more efficient retrofitting measures for space heating, domestic hot water (DHW), and electricity usage (Boverket, 2012).

Despite the urgent need, little research is currently being done for the primary purpose of improving retrofitting efficiency through energy and GHG emission reductions. Most often retrofit options are driven by commercial or operational necessity: through conventional energy-demand savings, reducing operational costs, occupier fit-outs, or the replacement of installations at the end of their service life (Mjörnell & Werner, 2010). Based on pilot retrofitting projects, retrofitting can directly address decreased operational energy targets as evaluated by net energy demand to the end users (Cellura, Guarino, Longo, & Mistretta, 2014).

However, conserving energy demand is not the only reason for retrofitting existing buildings. More complete evaluation methods also should be investigated, such as operational primary energy that considers the energy involved in the whole supply chain from the sources/energy mix. More importantly, retrofit options that mitigate operational energy will simultaneously increase the embodied energy attributed to the energy-saving measures, as constituted in the building envelope, heating and ventilation equipment, and corresponding building installations (Famuyibo, Duffy, & Strachan, 2013). In other words, the more operational energy saved by retrofitting, the more embodied energy will be involved.

If the net-zero building concept can be achieved through future holistic housing refurbishments, the embodied energy will be a major factor to consider in a retrofitting project. Therefore, sustainable retrofitting, which is defined as considering both energy demand/primary energy savings and corresponding embodied energy/GHG emissions of different retrofit options, are critically evaluated in this study on a long lease term.

1.1. *Previous studies*

Specific to Swedish residential buildings, the Energy Europe TABULA project (TABULA, 2009) performed a sustainable retrofitting guideline based on 44 typology categories of existing Swedish residential buildings for simplified operational energy savings and corresponding GHG estimations. Brown, Olsson, and Malmqvist (2014) and Toller, Wadeskog, Finnveden, Malmqvist, and Carlsson (2011) assessed several retrofitting measures in relation to the reduction of embodied GHG emission, 50% of the operational energy savings was in line with the Swedish national energy-saving directive (Swedish Environmental Protection Agency, 2011). Mata, Kalagasidis, and Johnsson (2013) developed a bottom-up model in Simulink with plug-in models to assess several technical and nontechnical measures for improving the sustainability of Swedish building stock. Considering four major types of Swedish energy supply systems, Gustavsson et al. (Gustavsson, Dodoo, Truong, & Danielski, 2011; Truong, Dodoo, & Gustavsson, 2014) modeled the combined effects of energy supply and demand renovation. They found that the primary energy savings and CO_2 efficiencies through energy retrofitting largely dominated by the heat-producing systems and the capacities to reduce the energy supply peak loads. Paiho, Abdurafikov, and Hoang (2015) developed three strategic retrofitting concepts to implement building installation system renovations (considering both energy demand and supply) for typical Russian apartment stock and residential districts in Baltic region. This retrofitting concept was further extended to cost-effectiveness analysis over a 20-years period. Dixit et al. (Dixit, Fernández-Solís, Lavy, & Culp, 2010; Dixit, Fernández-Solís, Lavy, & Culp, 2012) reviewed the current benchmarks and methodologies to assess the environmental impacts in the building sector, and concluded that an investigation of both operational energy and embodied energy had growing significance. However, the approach is plagued by incomplete data and the lack of standardized modeling guidelines and simplified protocols from archetype perspectives. Other possible software and modeling techniques that have been employed or coupled to evaluate the benefits of operational energy and environmental contributions include IDA ICE, Design Builder/EnergyPlus, Transys, eQuest®, Simapro, GaBi LCA, and Athena Impact Estimator (Ardente, Beccali, Cellura, & Mistretta, 2011; Chen, Burnett, & Chau, 2001; Hasan, Kurnitski, & Jokiranta, 2009; Ouyang, Wang, Li, & Hokao, 2011; Russell-Smith, Lepech, Fruchter, & Meyer, 2015). These models are capable of providing relatively accurate single- or multi-zone energy demand simulations before and