Sustainable Cities and Society 20 (2016) 96–108

Contents lists available at ScienceDirect

Sustainable Cities and Society

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

Environmental performance of energy systems of residential buildings: Toward sustainable communities

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ARTICLE INFO

Article history:
Received 30 August 2015
Received in revised form 17 October 2015
Accepted 20 October 2015
Available online 23 October 2015

Keywords:
Environmental performance
Energy systems
Life cycle analysis
Residential buildings
Decision support system

ABSTRACT

The evaluation of the environmental performance of energy systems used in residential buildings by applying the principles of the Life Cycle Analysis is an established methodological approach. Applying it in practice presents, however, significant interest, as a lack of available data has to be overcome. The research results presented in this paper include the analysis of the production, disposal and transportation of the materials used for the manufacturing processes of the building's energy systems, which include an oil and a gas fired boiler, split unit air conditioners, mono-Si and poly-Si PV arrays, flat plate and evacuated tube solar thermal collectors and their auxiliaries. The data needed for the analysis were taken from audits in the industries producing those systems, from related studies already published and from publicly available databases, when no other source was available. In this way, a comprehensive and fully adjustable database of the systems' environmental impact has been created. This database can be a part of an integrated dynamic decision support tool, or it can be used in combination with tools commercially available. It can therefore assist prospective users in the selection of the appropriate energy systems that will lead to the minimization of the total environmental impact of new and existing buildings. The results are applied to a representative residential building and its systems are evaluated and analyzed for several scenarios.

1. Introduction

The depletion of natural resources, the degradation of the environment and the emissions of pollutants to the atmosphere are issues that are leading to an increasing environmental awareness. Manufacturing companies have already begun researching control methods of their processes to reduce the environmental impacts, while standards, guidelines and evaluation tools are continually being developed and applied to improve the environmental performance of the energy systems and therefore the buildings. The first step to improve it is to determine and quantify the current environmental impact of the materials, services and production processes. Life Cycle Analysis (LCA) is a useful tool in order to evaluate the environmental impact of different processes from the extraction of raw materials to the disposal of products at the end of their useful lifetime. This study focuses on the environmental performance of energy systems used in residential buildings to provide heating, cooling, domestic hot water (DHW) and also RES based electricity generation systems. The impact of all those systems on the overall environmental impact of a building is significant; they have therefore to be assessed thoroughly.

Furthermore, one has also to keep the broader picture in mind: buildings are the nuclei of the urban built environment, it is only therefore reasonable to consider buildings with the highest possible energy efficiency and the lowest possible environmental impact as a prerequisite for achieving sustainability on the level of the community. This has been expressed by national and international legislation, starting with the European Directive in the Energy Performance of Buildings and the goal for the Zero Energy Building, with a significant further step being the European "Smart Cities & Communities Initiative" of the Strategic Energy Technology Plan (SET-Plan), which supports cities and regions in taking ambitious measures to progress by 2020 toward a 40% reduction of greenhouse gas emissions (Kylili & Fokaides, 2015).

However, and despite the significant achievements over the last two decades, mainly in Europe and in North America, combined efforts are necessary to foster the propagation of sustainable

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http://dx.doi.org/10.1016/j.scs.2015.10.006
2210-6707/

technologies and their projection from a single project's scale to a community level. The European experience has shown that broader synergies amongst all stakeholders are needed, as the challenge is a truly horizontal, cross-cutting one (Karkanias, Boemi, Papadopoulos, Tsoutsos, & Karagiannidis, 2010). Despite the fact that most of the involved stakeholders appreciate the necessity to adopt effective policies, and also accept most of the goals set, there are quite some barriers to overcome, including significant differences in the distribution of the means and resources necessary for promoting sustainability, but also addressing established attitudes in the decision making process (Martin et al., 2014). A much more effective dissemination of knowledge and information is needed, combined with a participatory decision making process, in order to incorporate the environmental design of buildings in the development on an urban or community level, but also in order to be able to produce effective guidelines for the development of new urban areas reflecting economic, aesthetic and eventually societal aspects.

The integrated environmental performance evaluation of several energy systems that are used in buildings, the combination of the resulting LCA performance of the energy systems in a joint approach and the development of an extensive and fully adaptive database that can be embedded into dynamic decision support tools that are used to assist engineers and architects in selecting the optimal energy system toward the minimization of a building's overall environmental impact and the main goals of the present study.

In Section 2, several LCA studies on the environmental performance of energy systems that are used in buildings are presented. The methodology adopted for the integrated environmental performance evaluation of several energy systems and the results of the analysis are presented in Sections 3 and 4, respectively. In Section 5, the methodology adopted is applied to a fairly representative multifamily building located in the Mediterranean region and the results of seven possible solutions in four scenarios implemented are analytically discussed in Section 6. Finally, the conclusions arisen from the integrated environmental analysis are presented in Section 7.

2. Literature review

Previous studies have focused on the impact of the building's envelope, during its production, construction and operational phase of buildings, using as indicators energy, emissions, and cost. Research on the environmental impacts of heating, ventilation and air conditioning (HVAC) systems is still not extent.

2.1. Heating systems

Treloar, Fay, IIozor, and Love (2001) analyzed an energy efficient two story residential house of 115 m^2, including the structural elements, space heaters, solar hot water systems and external elements such as paving and pergolas. The embodied energy was estimated at 11,100 MJ/m^2, including 870 MJ/m^2 for the construction process. Over the last 15 years there has been significant research on the building materials' environmental performance; a synoptic analysis of those points has been provided by Papadopoulos and Giama (2009) and by Giama and Papadopoulos (2015). Prek (2004) evaluated the environmental impact of manufacturing process of three residential heating systems (11.8 kW output power): hydronic radiators with metal pipes, a floor heating system with polyethylene pipes and fan coils. The heat conversion equipment and fittings were not taken into account. The study used the Eco-Indicator 95 method to aggregate various environmental impacts into one single indicator. The radiators heating system was found to have the highest environmental impact while the floor heating system had the lowest.

Yang, Zmureanu, and Rivard (2008) presented the use of expanded cumulative exergy consumption (ECExC), which combines the pre-operation and operation phases, and the abatement of greenhouse gas (GHG) emissions, as the unifying indicator of environmental impacts of hot water heating (HWH) and forced air heating (FAH) systems,. The results indicated that the HWH systems with heat recovery ventilation (HRV) using either electricity or natural gas had the lowest ECExC. It was found that the heating systems cause marginal impacts compared with the entire building in the pre-operating phase. In the operating phase, on the other hand, they caused significant environmental impacts. When life cycle energy use was the comparison criterion, HWH systems with HRV using either electricity or natural gas performed best. The HWH and FAH systems, both using electricity as energy source, had the lowest equivalent CO_2 emissions for the electricity mix of the Quebec province.

Shah, Debella, and Ries (2008) assessed three different heating systems (furnace, boiler and air to air heat pump) in four locations in USA. The boiler found to have the largest impacts associated with the production and distribution systems. However, the impact of the operational energy consumption was dominant over the entire study period. The heat pump had the maximum impact in regions where a high proportion of the electricity is derived from fossil fuels. The furnace turned out to have the best overall performance in those regions.

Gu, Gu, Lin, and Zhu (2007) assessed three basic heating systems (gas fired boiler, oil fired boiler and LiBr absorption heat pump) in a real office building in Beijing in China using the life cycle environmental load method (LCEL). The results indicated that the gas fired boiler had the lowest LCEL.

Nitkiewicz and Sekret (2014) evaluated the environmental performance of an electric water–water heat pump, an absorption water–water heat pump and a natural gas fired boiler. The heat pumps operate with low temperature geothermal water. According to the Eco Indicator 99 method that was used for the evaluation, the results of the analysis indicated that the heat pumps result in lower environmental impact compared to the natural gas boiler, whereas the absorption heat pump has the lowest environmental impact. On the contrary, the selection of the natural gas boiler turns out to have the lowest damage to human health.

Theodosiou, Koroneos, and Moussiopoulos (2005) examined five alternative scenarios concerning different type of fuels used for the coverage of the energy requirements for a typical apartment building in Thessaloniki, Greece, using LCA. The main result showed that the optimal scenario in financial and environmental terms is the one in which natural gas is used for almost all of the model's operations and for generating the electricity consumed.

2.2. Cooling systems

Few studies analyzed the environmental impact of cooling systems. Mostly these units are combined with different heating units and the system is assessed as a whole. This makes it difficult to find out particular data for the cooling systems alone. Legarth, Akesson, Ashkin, and Imrell (2000) analyzed the environmental impacts of an air conditioning unit using nine impact categories (such as global warming and ozone depletion), four waste categories, and nine natural resource categories. They concluded that air handling units are highly active products and most of the effects on the external environment and the high depletion of energy carrier stock are associated with this high level of activity.

Heikkila (2004) evaluated the environmental impact of two air conditioning units using the weighting method EPS 2000. The functional unit was an air handling unit, which distributes a constant airflow volume of 4.8 m^3/s 24 h a day for 15 years. The first system has a cooling coil with a vapor compression chiller, while the