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Multicriteria evaluation of heating choices for a new sustainable residential area

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ABSTRACT

The city of Loviisa in Finland is planning a new sustainable residential area with a total of 240,000 m^2 of residential houses and apartment buildings with services. The city wants to promote sustainable energy solutions in the area, considering various renewable energy forms for heating. The aim of this research is to evaluate which heating system would be best for a new single-family house when different technical, economic, environmental and usability criteria are considered. A group of experts evaluated the alternative heating systems with respect to the criteria. The citizens were involved with a questionnaire to provide preference information for different criteria. Altogether 11 alternative heating systems were evaluated in terms of 15 criteria. The Stochastic Multicriteria Acceptability Analysis (SMAA) method was used to analyze this problem. The SMAA method was extended to handle a hierarchy of criteria and sub-criteria. The problem was analyzed in two phases based on expert evaluation for the criteria measurements first without the preference information from citizens and after this with the information. The results show that district heating produced by biomass based CHP is the most widely acceptable heating alternative followed by ground source heat pump both without and with preference information.

1. Introduction

In northern countries such as Finland, heating of residential buildings is one of the biggest energy consumers. In Finland, the heating of residential buildings constituted 19% (211 PJ) from the end-use of energy (1107 PJ) in year 2012 [1]. From energy consumption in residential buildings in total in 2012, approximately 86% was consumed in heating [1]. For all the residential, commercial and public buildings the four most used energy sources for heating were district heating (DH, share 46%), electricity (share 18.6%), wood (share 13.1%) and heat pumps (includes the electricity needed, share 11.6%) [2]. For detached houses built during the past few years, ground source heat pumps are increasing their popularity with a market share of 49% in 2013 [3].

The idea behind sustainable development is to satisfy the present needs without jeopardizing the future generations' needs [4]. In sustainable energy planning there is a balance between the energy production and consumption and the environmental impacts are in minimum (or no impact at all) but still there is an opportunity for a country or municipality to employ its social and economic activities [5–7]. In municipal planning, choosing an energy system has long-standing impacts on energy consumption, emission level as well as costs. This makes sustainable energy planning a complicated multicriteria decision problem.

Multicriteria decision analysis (MCDA) has been applied widely in various sustainable planning problems. Most of the studies concern large scale energy systems [7–12], electricity systems [9,13–16], community level heating systems [17–19], and renewable energy systems [20–24]. The criteria are mostly defined case-specifically as there is no standardized methodology or criteria set for evaluating energy sector sustainability [5,8,11,16,25–27]. However, it is obvious that many MCDA studies concerning sustainable energy planning use the traditional three pillar construction which includes economic, environmental and social criteria. Examples of economic criteria are costs, return on investment, and payback period. Environmental criteria include typically emissions (CO_2, NO_x, SO_x, particulates), renewable energy fraction and energy efficiency. Social aspect of sustainable development is more intangible and hard to model and it covers themes such as employment, poverty alleviation, health and safety, empowerment and participation [28]. Since energy systems include technology, some of the MCDA studies have also taken

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many technical components as criteria (such as [5,11]). None of the studies found contained criteria concerning the usability issues of different energy production technologies.

Several MCDA methods have been developed and used for sustainable energy planning. Choosing a suitable method for a certain problem depends on its characteristics. Broad reviews have collected MCDA methods used in sustainable energy planning (see [5,8,16,25–27]). MCDA studies of energy systems in residential buildings have stayed in lesser attention in sustainable energy research. Catalina et al. [29] studied the most suitable renewable energy sources for a detached house. The ELECTRE III method was used with three criteria: energy reduction as primary energy savings, payback time on the investment and CO_2 emission reduction. Alanne et al. [30] compared micro-CHP with traditional heating systems (altogether 10 heating system options) in a single-family house with the PAIRS multicriteria method. The criteria covered only economic and environmental issues. Vučićević et al. [6,31] used the ASPID multicriteria method to examine the sustainability in residential buildings. In both case studies, similar criteria were used in economic, environmental and social themes. Beside these studies, space heating options were studied in industrial buildings with technical criteria using the Analytic Hierarchy Process (AHP) method [32].

Even though these studies present interesting cases of sustainable energy systems in residential buildings with broad criteria settings, they lack usability criteria. We consider usability as an important criterion when choosing a heating system for residential buildings since the users play a key role in choosing, procuring and using the heating systems. Also, most of the previously presented studies include the group of experts ranking the energy systems according to different criteria. We expand this and involve a group of citizens and possible new residents in the target area to the case study evaluation.

The target of this study was to identify the most suitable heating systems for new single-family houses built according to the current building regulations in Finland. The case study was done for Loviisa city, which was planning at Harmaakallio a new sustainable residential area applying wood constructions and renewable energy solutions for heating. In this study we used 15 criteria to evaluate 11 alternative heating systems. A group of experts evaluated the alternative heating systems with respect to the criteria. We also involved the citizens of the Loviisa with a questionnaire to provide preference information for different criteria.

To analyze this problem we used the Stochastic Multicriteria Acceptability Analysis (SMAA) method [33]. SMAA was developed for real-life decision problems where the criteria measurements can be uncertain, inaccurate or even partly missing. SMAA has been applied in many decision making problems (e.g. [15,34–40]). Earlier SMAA has been applied only with a single level of criteria. In this paper, the SMAA method is further extended to handle a hierarchy of criteria and sub-criteria.

This paper is organized as follows. Section 2 describes the Harmaakallio case. Section 3 describes the SMAA method. Section 4 formalizes the decision problem in terms of criteria and alternatives. Section 5 presents the analysis results. Section 6 contains discussion on the results and conclusions.

2. Case description

2.1. Residential area

The city of Loviisa is located in Southern Finland, about 90 km East from the capital Helsinki. Loviisa is planning a new sustainable residential area in the Harmaakallio region, which is located about 2 km from the city center. The area of Harmaakallio is 160 ha and it will provide residence for 3000 people. The region will contain diverse residential buildings (detached houses, row houses and apartment buildings) and service buildings with total floor space of 240,000 m^2. District heat (DH) is provided in the city center and at Loviisa harbor by Porvoon Energia, which is the municipal energy company of the city of Porvoo, located 32 km west of Loviisa [41]. DH is currently produced in heat-only-boilers (HOB) from heavy fuel oil and biomass [2]. The energy company has early stage plans to extend the central DH network to Harmaakallio, and to connect it with the harbor area. They are planning to build a new biomass based production unit, which can be either a HOB or a combined heat and power (CHP) plant.

Choosing the most suitable heating systems for Harmaakallio requires evaluating different economic, environmental, social, technical and usability criteria carefully. In this study we perform a multi-criteria analysis on the alternative heating systems for a new single-family house built according to the Finnish building regulations. The heat consumption estimates are based on an actual, recently built house with 180 m^2 floor area and three people living in it. The yearly heat demand is 14.8 MWh, of which 3 MWh is used to produce domestic hot water (normally about 10–25% of the overall heat energy is used for hot water [42], in our case 20%). Space heating is implemented as a floor heating system. The indoor temperature in the heating season is 20 °C and the heat losses are approximately 100 W/°C depending on the indoor–outdoor temperature difference. The building also has a wood-fired sauna stove with yearly combustion of 0.5–1 MWh and approximately 50% efficiency for heating.

2.2. Stakeholder participation

Stakeholders involved in the study included decision makers, experts in sustainable energy solutions, and inhabitants of Loviisa. The experts defined the alternatives and criteria in collaboration with the decision makers and planning officers of Loviisa. The experts were also responsible for evaluating the alternatives with respect to the criteria. Preference information and opinions about the development of the Harmaakallio region was collected via a survey from the inhabitants of Loviisa.

Fig. 1 presents how the case study proceeded and which parties were involved in different phases. After meetings with decision makers of Loviisa and collecting basic data, experts defined in phase 1 a large number of possible alternative heating systems for a single-family house in Harmaakallio. The alternatives consisted of different main heating systems in various combinations with supplementary heating. Both sustainable and fossil based solutions were included at this phase. The experts also defined a preliminary set of criteria that were organized in into five categories: economic, environmental, social, technical and usability. Heating options and criteria were included in the survey. Based on the results, 11 potential heating system combinations were selected for further analysis. Also, the set of criteria was reduced into 15 relevant criteria. For example, some overlapping criteria were omitted at this phase.

In phase 2, the experts evaluated the alternatives with respect to the criteria. Only a few criteria (costs and climate) were measured cardinally. The majority of the criteria were measured ordinally, i.e. the experts ranked the alternatives with respect to each ordinal criterion. The criteria measurements together with preference information extracted from the survey formed the input data for the multi-criteria analysis in phase 3.

2.3. Survey

The main goal of the survey was to find out the heating system preferences of the potential new inhabitants of Harmaakallio. The survey was implemented as an on-line questionnaire and