Energy Conversion and Management 103 (2015) 991–1007

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Ground source heat pumps as high efficient solutions for building space conditioning and for integration in smart grids

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ARTICLE INFO

Article history:
Received 23 March 2015
Accepted 12 July 2015
Available online 25 July 2015

Keywords:
Ground source heat pumps
Thermal storage
Demand response
Demand side management
Smart grids
Renewable heating and cooling

ABSTRACT

Buildings space conditioning is a key sector with a high potential for cost effective energy and carbon savings, in which high efficient heat pumps can have a significant contribution. Besides consuming electricity increasingly produced by renewable energies, heat pumps can also have an important role to balance supply and demand, allowing the integration of intermittent renewable generation in smart grids. The aim of this paper is to demonstrate that ground source heat pumps are a very high efficiency technology for buildings space conditioning, and present a high potential for electric load management as a flexible load, when combined with the thermal storage capacity of the building.

The very high efficiency of an advanced ground source heat pump system, which integrates state of art components in an optimal manner, was assessed considering the seasonal performance factors for one complete heating season and one complete cooling season, calculated based on the monitored data of an experimental site installed in a service building in Portugal. Innovative load management strategies to control the heat pump coupled with the thermal mass of the building were tested and its associated benefits, including integration for intermittent generation, were evaluated.

The thermal response of the building was analyzed applying a model based on the lumped capacitance method, and it was validated with experimental data. A load shifting strategy by preheating the building and avoiding peak periods is proposed to allow the use of lower electricity rates leading to a reduction of electricity costs of 34%. Additionally preheating the buildings also contributes a larger integration of the renewable generation surplus (19–30% of the surplus generation). The implementation of Demand Response actions by switching off heating loads, during some periods of time, to compensate the variations and forecasting errors of wind power is also evaluated with positive impacts.
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1. Introduction

1.1. Context and motivation

The buildings sector, represents about 40% of the final energy consumption and 36% of the total Greenhouse Gases (GHG) emissions in the European Union (EU) [1], and due to its high savings potential, is considered one of the key sectors to reach the energy policy EU targets [2]. Buildings space heating at EU level is the end use which presents the highest energy consumption. Moreover, in the EU, space heating accounted for 43% of the final energy in service buildings and 67% of the final energy consumption in residential buildings in 2012 [3]. Two-thirds of the supplied heat is generated with fossil fuels and it is mostly dominated by natural gas boilers [4]. In the particular case of Portugal, due to its moderate climate conditions, space heating is not so significant, but together with space cooling, they already represent one of the most significant end-uses energy consumption in buildings [3].

In a context where large investments should be done at the buildings level to increase its energy efficiency as required by EU legislation (Energy Performance Building Directive [5] and Energy Efficiency Directive [6]), and with the electricity becoming less carbon intensive due to the massive increase of renewable energies in the last decade [7], there is a huge opportunity for replacing fossil fuels by low-carbon efficient technologies. Electric Heat Pumps (HPs) can play a major role in this transformation as demonstrated in [3] where a large scale replacement of natural gas boilers by HPs

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http://dx.doi.org/10.1016/j.enconman.2015.07.032
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for space heating was assessed at the EU level and by [8] where HP implementation scenarios until 2030 were assessed both for new and existent buildings in eight European countries in terms of primary energy and carbon emissions savings and increase of Renewable Energy Resources (RES).

Although Ground Source Heat Pump (GSHP) technology and market are developed in countries of Central Europe, the corresponding market in South Europe is at early developing [9]. There is also the potential to significantly improve the efficiency of GSHP, using state of the art developments of key components (namely motors, compressors, circulators, heat exchangers and optimized controls).

Another significant challenge associated to the energy sector is the high penetration levels of intermittent energy resources in the electricity generation. Most of the energy generation by renewable resources (wind and solar) are dependent on weather conditions and presents a high variability being its generation profile very different from the energy demand profile [10]. Nowadays, wind power already covers a large part of the demand for electricity in many areas of EU and in the particular case of Portugal it represents 26% of the total installed power and ensured 24% of the generation in 2014 [11]. Wind power often presents large variations of generation with extreme ramp rates and large forecasting errors [12]. Additionally, during the nights in rainy and windy winters, the electricity generation from renewable sources may exceed the electricity demand in Portugal [11].

Therefore, it is essential to increase the system flexibility in order to ensure the integration of intermittent renewable resources. This can be ensured mainly by introducing decentralized energy storage systems and by increasing demand elasticity using Demand Response (DR). The Demand Response concept refers to changes in electricity consumption in response to supply conditions [13]. In the context of Smart Grids the consumers will evolve from a passive to an active role, providing services to the grid to shape electricity demand according to the available capacity of generation [14].

In this context, and taking into account that GSHPs have been considered as a very promising technology for space heating when compared with other heating options as referred by [15,16], which represent one of the main loads in buildings, it is important also to assess their potential as a flexible load, when combined with the thermal inertia of buildings, to balance the consumption level to the grid supply and therefore contribute to the integration of intermittent renewable resources.

1.2. Literature review

Within the HPs technologies available in the market, GSHPs are more efficient than the more widely used Air Source Heat Pumps (ASHP) since they rely on extracting thermal energy from the ground, which behaves like an approximately constant temperature source, warmer than the air in winter and cooler than the air in summer [17]. A recent study made in the ASHRAE building in USA compared the energy consumption of the GSHP and the Variable Refrigerant Flow (VRF) systems, which one installed in two different floors of the same building. The study concluded that GSHP system exhibits a substantially higher energy performance (65% in heating mode and 70% in cooling mode) than the VRF system [18].

The HP system performance can vary significantly depending on a variety of parameters such as the local climate, the operation mode, the operation period, the heat demand of the building and the building heating system, e.g. radiators, radiant floor heating or fancoils as referred by [19]. In the case of a GSHP system, additional parameters associated to the boreholes influence its performance like the soil type, depth of borehole, water velocity in the pipes, thermal conductivity of grout, the thermal resistance and heat exchange rate, etc. [20]. For example, in an experimental study developed in Turkey, the GSHP performance increased for cooling from 3.85 to 4.26 [21] and increased for heating from 2.68 to 2.82 [22] by increasing the depth of the horizontal heat exchanger from 1 m to 2 m, respectively. Due to these reasons the HPs performance results achieved in different GSHP installations in buildings within different weather conditions (cold, mild or hot climates) are difficult to compare. For example, in Southern Germany the performance of a GSHP system installed in an office building was investigated and it was found a Seasonal Performance Factor (SPF) of 3.4 for winter and an SPF of 8.2 for summer [23]. In the Mediterranean coast of Spain the performance of a GSHP system installed in an academic building equipped with fancoils presented at the end of the heating season a SPF of 3.5 and at the end of the cooling season a SPF of 4.3 [24]. In Canada the same GSHP system was studied in different cities with different climates. The SPF for heating varied from 2.9 to 3.1, being the lower SPF achieved in the localization with the lower mean surface temperature (2.6 °C), and the SPF for cooling varied from 5.7 to 6.1, being the higher SPF achieved in the localization with the lower mean monthly temperature (16.6 °C) [25]. In Portugal, the use of GSHP systems is almost inexistent and the achievable efficiency deserves to be assessed.

Several studies have been published concerning GSHPs performance and their potential to reduce primary energy consumption and thus to reduce emissions of greenhouse gases when compared with others technologies [26]. However, the overall environmental impact of electric heat pumps depends very much on how the electricity is produced, on the HP efficiency and with which technology the comparison is done [3]. For example, in Portugal by switching natural gas boilers to electric HPs, it is possible to achieve carbon savings with a HP efficiency of 1.4, while in Germany a minimum efficiency of 2.2 is needed and higher minimum efficiencies are needed in countries with large coal contribution for electricity generation like Estonia, Malta and Poland [3]. The higher is the RES share electricity generation in countries, the higher and faster penetration of HP systems for space heating and space cooling can be expected, since higher carbon and primary energy savings can be achieved [8]. Additionally, a high RES share, generally associated to a high share of wind power, means a higher need of flexible loads to integrate this type of generation and an increasing use of HPs in space heating and cooling can give an important contribute in this area. This is the case of Portugal, where the adoption of HPs simultaneously leads to large GHG savings due to large share of renewables and there is a need for flexible loads to compensate the variability of such renewable generation.

DSM strategies have been widely applied and studied to reduce costs operations at the consumer level by shifting energy consumption from peak prices electricity periods (peak period) to lower electricity prices periods (off-peak periods) offered by utilities (typically during nights) in order to leveling electricity demand profile and to avoid new electricity generation capacity only to satisfy peak demands [27]. For decades, DSM strategies for peak demand reduction in service buildings have been a very active area of the research and development in the Heating, Ventilation and Air Conditioning (HVAC) field. However, as referred by [28], Demand Side Management (DSM) strategies are now needed to integrate intermittent renewable electricity generation, since peaks in renewable generation do not necessarily coincide with peak in demand so energy needs to be either artificially consumed or stored for later use. Therefore, new DSM strategies must be assessed on order to simultaneously provide cost reductions to the users and services to the grid (integration of the renewable generation).

The main DSM strategy used in HVAC systems is the load shifting strategy by using Thermal Energy Storage (TES) systems to be

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