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Energy performance assessment of a complex district heating system which uses gas-driven combined heat and power, heat pumps and high temperature aquifer thermal energy storage

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A B S T R A C T

The large industrialization in 70s and 80s provoked a transfer of population from the rural areas to cities. Especially in the communist countries, massive multi-storey buildings were erected, supplied by a district heating grid with big power plants. Nowadays the maintenance of such big systems is big-energy consuming and refurbishment is very hard to accomplish and therefore, in many situations, district heating is no longer profitable. We present in this paper an integrated system for local district heating, aiming to substitute the old and inefficient district system for a condominium, located in the city of Bucharest, Romania. The main paper objective is to demonstrate that the energy performance of the connected buildings could be significantly improved by changing the heat source. With CHP–HP–HT-ATES technology, initially D-energy class buildings (according to the Romanian methodology of calculation of buildings performance-Mc 001/2006) can switch to B-energy class. Moreover, the refurbishment of the buildings envelopes will help the envisaged condominium to approach the nZEB characteristics of energy consumption. A comparison between several heat production systems, in terms of primary energy and CO_2 emissions is also provided.

Contents

1. Introduction

The trend towards decentralization of the electricity supply market will influence the speed of the potential introduction of what has become known as “distributed generation”. Distributed generation is a revolutionary concept, which consists in local generation of electric, thermal or mechanical energy [1]. Micro-turbines in combined heat and power (CHP) applications may take an increasing share of this market. Europe has a substantial share in

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the gas turbine market, with manufacturer machines that produce over 400 MW_{el} on a single shaft.

The electricity obtained from co-generation has the second best price after that obtained from hydro-power systems. Co-generation proves to be effective for high values of the ratio between the CO_2 emission per unit of electricity produced and the CO_2 emission per unit of chemical energy stored in the fuel, respectively [2]. In particular the concentration of pollutants in exhaust gases, except for NO_x and CO_2, strongly increases by reducing the electrical power output [3].

CHP plants typically achieve high efficiencies, leading to fuel savings compared to independent supply of heat and electricity. However, CHP is not a new technology and its global efficiency depends on the ambient temperature (for combustion engines and gas turbines). The experimental results in a cold area show that when ambient temperature increases, electrical efficiency of the micro-turbine decreases but the exhaust heat recovery increases [4]. Large scale and district heating systems from a few hundreds kW to MW capacities have been used for decades in process industries, hospitals and leisure centres, using gas and steam turbines, internal combustion engine systems and, more recently, micro-turbines. In literature, a large number of papers concerning the problem of necessary installed power [5,6] and control strategy (thermal power versus electric power) [7], can be found. Moreover, based on district heating plants models [8], the CO_2 emissions for residential buildings heating, connected to the district heating grid, are lower than for similar buildings with a low-energy standard and with heating based on electricity.

Micro-turbines offer new perspectives in small-scale heat and power production. However their profitability depends strongly on the annual number of running hours. It should be noted that the non-continuous heat demand in a condominium of residential buildings often leads to a reduction in running hours. Simulations on a micro-gas turbine (mGT) showed that most of the exhaust heat can be recovered through injection of heated water after the compressor, resulting in an 18% decrease in fuel consumption and an absolute increase in electrical efficiency of 7% [9]. However, their use is limited by the demand for heat and this can greatly affect the financial and environmental benefits. A solution is to use the excess heat to drive a cooling cycle [10].

Another viable solution is to store the excess heat in the underground environment (ground soil or ground water). Sensible heat storage using water is the most widely used technology of energy storage. The application of Thermal Energy Storage (TES) systems in industrial and building sectors in the European Union can provide an annual potential energy saving of 7.8%. As for the environmental impact, the utilization of these systems can reduce the emissions of CO_2 into the atmosphere by 5.5% [11]. Moreover, installing a big thermal storage at a CHP-plant makes it possible to shift the production of electricity and heat to hours when electricity unit price are higher, especially on days with low heat demand. Consequently, all these assumptions should influence the conception and design of new CHP-plants [12].

The Aquifer Thermal Energy Storage (ATES) systems have moved from a demonstration stage to a well-established and documented technology over the last thirty-five years. The first pilot projects were installed in the late 70s and early 80s in US, China, Switzerland and Denmark [13]. The source of heat is most commonly wasted heat from heat pumps which are being used for cooling in the summer season. Less common is wasted heat from co-generators or industrial processes [14]. The performance of the ATES system primarily depends on the thermal interference between warm and cold plumes, placed in the same aquifer. Further on, the thermal interference is affected by the distance between wells, the thermal conductivity of the aquifer and the pumping/injection rates.

In particular, the excess heat produced by co-generation turbines can be efficiently stored in a high-temperature ATES (HT-ATES) system due to high production temperatures. In such configurations, the use of the heat pump can be reduced significantly or even eliminated (reduced electricity consumption, improvement of the energy efficiency). Also, the relatively large temperature difference between the hot and the cold wells increases the thermal power of the system significantly [15].

However high temperature heat storages (>50 °C) encounters several technical problems. Clogging of wells and heat exchangers due to fines and precipitation of minerals is one of the biggest challenges so, in most of the cases, water treatment is mandatory. In addition, exposing the water to the atmosphere might accelerate the corrosion of components in the groundwater systems. To prevent that, the system should be kept permanently under pressure. Therefore the sustainable operation of HT-ATES is achieved under several conditions, in addition to the normal ATES systems, and that implies difficulties for automatic control of the ground water system. The research made over the period 1985–1995 demonstrated that all the technical problems could be solved [16].

We present in this paper the performance assessment model for a gas-driven micro-turbine and a heat pump unit, coupled to an HT-ATES system. Similar technology had been studied previously at a small scale (individual houses), providing encouraging results [17] but at bigger scales (condominiums) the results could be slightly different. Our case-study model takes into account the daily energy profiles for 13 multi-storey buildings and a kindergarten, located in Bucharest, these profiles being registered for the year 2011. The condominium is supplied by a large district heating system stated as energy- inefficient and non-sustainable. The alternative, innovative system modelled here consists in a gas driven micro-turbine (CHP), a group of compression heat pumps (HP) and a high-temperature thermal energy storage (HT-ATES) system.

The annual energy savings in terms of primary energy and CO_2 emissions, comparing to the large district heating system, are the main presented results. The original contribution of this work envisages the importance of energy supply quality for the energy performance of buildings certification. For instance, the energy performance of a building can be raised from class D to class B just by changing the heat production and supply system. Similar technologies, briefly presented in this paper, were technically and economically proved in Europe.

2. Similar CHP–HT-ATES systems

Several HT-ATES projects were made worldwide with storage temperatures >60 °C. Two of these projects are located in The Netherlands, at the Utrecht University and in De Bruggen, in Zwammerdam but now are out of use. In Germany there are two running applications, one in Berlin, working in a central heating and cooling system for the Reichstag buildings and the other in Neubrandenburg, working in a district heating network.The Reichstag complex in Berlin, Germany has a bio-fuelled co-generator that produces electricity. Waste heat is used in the winter directly to heat buildings and in summer to drive an absorption chiller (Fig. 1). The excess heat produced during fall and spring is stored in a rock aquifer located at a depth of approx. 300 m. The excessive cooling flow produced by the absorption chiller in summer is stored in another aquifer, at a depth of 40 m to 70 m. The injection/charging water temperature is set at 70 °C due to geo-chemical restrictions. During the heating season, the water is reused for direct heating until it reaches 30–35 °C. During summer time, the cold groundwater is used to cool the buildings [18].

The design heat storage capacity is 2650 MWh/yr but was varying between 1400 MWh/yr and 3100 MWh/yr. This is due to the