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Review

Current status of fuel cell based combined heat and power systems for residential sector

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HIGHLIGHTS

- Status of micro FC-CHP system activities in different countries is described.
- Technical potential of PEMFC and SOFC technology is presented.
- FC-CHP system main components are characterised and analysed.
- By doubling the production 25% price reduction of micro FC-CHP system is possible.
- LT-PEMFC and SOFC is dominant but HT-PEMFC has potential for FC-CHP application.

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ABSTRACT

Combined Heat and Power (CHP) is the sequential or simultaneous generation of multiple forms of useful energy, usually electrical and thermal, in a single and integrated system. Implementing CHP systems in the current energy sector may solve energy shortages, climate change and energy conservation issues. This review paper is divided into six sections: the first part defines and classifies the types of fuel cell used in CHP systems; the second part discusses the current status of fuel cell CHP (FC-CHP) around the world and highlights the benefits and drawbacks of CHP systems; the third part focuses on techniques for modelling CHP systems. The fourth section gives a thorough comparison and discussion of the two main fuel cell technologies used in FC-CHP (PEMFC and SOFC), characterising their technical performance and recent developments from the major manufacturers. The fifth section describes all the main components of FC-CHP systems and explains the issues connected with their practical application. The last part summarises the above, and reflects on micro FC-CHP system technology and its future prospects.

1. Introduction

Electric power and heat are the most important driving forces in energy in the modern world. World primary energy consumption is increasing with a growth rate of 1.8% and coal consumption is increasing at a rate of 2.5%. In 2012 coal reached its highest share of global primary energy consumption since 1970 at 29.9%. Meanwhile, global nuclear power output has decreased by 6.9%, Japanese output has dropped by 89%, accounting for 82% of the global decline in 2012 [1]. Currently conventional coal-fired power plants are not able to meet present energy demands and reduce emissions; moreover the average efficiency of these plants is quite low at around 41%. Almost 60% of the primary energy of the fuel used in these power plants becomes waste heat. Heat loss from power generation in the USA is equal to the total yearly energy use in Japan.

The world average split in residential energy consumption is about 27% electrical energy and 38% thermal energy [2]. The division of residential energy consumption in different countries is shown in Fig. 1 [3]. Countries in colder climates, for example Germany or the UK, use more than 70% of their energy for space heating and 9% of their energy for water heating. On the contrary,

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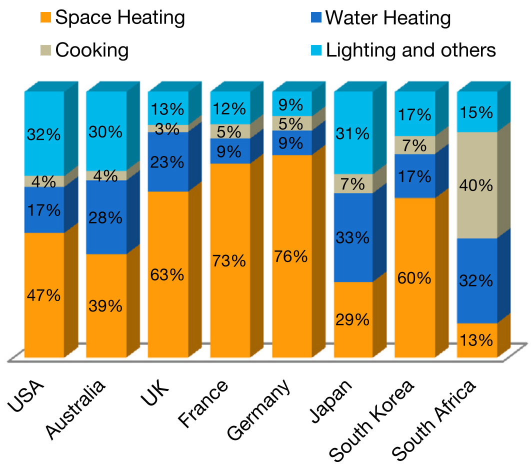

Fig. 1. Energy usage of typical household in different countries worldwide.

the Republic of South Africa uses only 13% of its energy for space heating and 32% of its energy for hot water. Most of the countries do not use co-generated heat energy from power plants for other purposes such as space heating and water heating. Finland's residential energy consumption data published in 2012 shows that 29% of household energy consumption is from district heat and the remaining energy is from various sources, as shown in Fig. 2. Overall, almost 64% of total end-used electrical energy is used for space heating and the remaining 36% is an electrical energy supplied for household appliances [4].

In CHP technology, the waste heat is captured during operation and can be used for space heating, preparation of domestic hot water, laundry hot water as well as providing heat for swimming pools or spas. CHP reduces the amount of wasted energy by almost half and system can deliver energy with efficiencies exceeding 90%, while significantly reducing emissions per produced kWh. CHP can be defined as the sequential or simultaneous generation of multiple forms of useful energy in a single integrated system. The total CHP system efficiency can be expressed as ratio of the sum of the net power and useful thermal energy output divided by the total energy of the consumed fuel. CHP systems can generate energy with efficiencies of up to 85–90% (combined electrical and thermal efficiency), which is much higher in comparison with the efficiency of system that is generating electricity and useful heat in separate processes. This increased energy efficiency can result in a reduction of costs and a reduction in Green House Gas (GHG) emissions when compared to the conventional methods of generating heat and electricity separately.

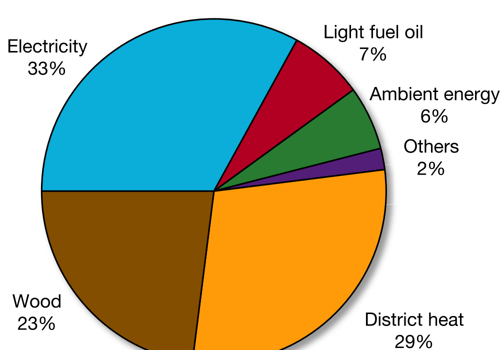

Fig. 2. Household energy consumption in Finland by energy source in 2012.

CHP technologies have higher system efficiency, higher fuel utilization efficiency, and lower emissions. They may also minimize power distribution losses because the production of energy can be decentralized. Many commercial office buildings and apartment complexes throughout the world are powered by CHP systems to save on energy costs, increase energy reliability and decrease carbon dioxide (CO_2) emissions (as well as other harmful gases) [5–7]. After the first oil crisis in 1973, many countries started to establish and/or promote an increased use of CHP systems. CHP systems gained attention in industrial/commercial as well as in institutional organizations mainly due to their high efficiencies, savings on energy bills and decreased GHG emissions [8]. The use of CHP in residential applications has increased as the systems have the ability to produce both thermal energy and electricity from a single source of fuel, yielding high overall efficiency [9]. CHP systems consist of several individual components configured into a fully integrated engineering system. The main components of the system, for instance the generator and heat recovery module, are shown in Fig. 3 (a basic system layout). The heat recovery subsystem captures the waste heat using a heat exchanger and the energy can then be utilized for heating purposes. The generator converts the chemical energy of the fuel into electrical energy. Cogeneration technologies for residential, commercial and institutional applications can be classified according to their prime mover and their energy source, as follows:

- Reciprocating Internal Combustion Engine (ICE) based cogeneration systems;
- Micro-turbine based cogeneration systems;
- Stirling engine based cogeneration systems; and
- Fuel cell based cogeneration systems.

The CHP technologies based on stirling engines and fuel cells seem to be promising for small scale cogeneration in residential buildings. The latter possess high overall efficiency and low emissions levels but currently ICEs are the only systems available offering reasonable costs. In addition, ICEs are attractive for small scale cogeneration CHP applications due to their robust nature and well-developed technologies. The other cogeneration technology that has potential for residential applications are micro-turbine based systems. However, reciprocating ICEs have higher efficiencies at lower power range and the capital cost of micro-turbines is higher compared to that of reciprocating ICE cogeneration systems [8]. A key constraint on the deployment of CHP is difficulty in distributing thermal energy over long distances. Because of this, CHP units must be located close to demand, which potentially increases the costs. The fuel cell based CHP systems have gained attention in recent decades, due to their higher achievable efficiencies over a broad range of load profiles and lower emissions without the need for additional controls.

2. Fuel cell CHP systems

A fuel cell is an electrochemical device which converts the chemical energy of a fuel and an oxidant, supplied continuously from external sources, into electrical energy in a direct process (without intermediate energy changes) with heat and water as byproducts and zero or very low harmful emissions. The fuel is typically either an alcohol, a hydrocarbon or a substance derived from it (e.g. hydrogen (H_2)), which can be supplied continuously. The principle of operation is similar to that of batteries but instead giving energy continuously, as long as the fuel and oxidant are supplied. The fuel cell can produce electricity with no or with very little emissions; it operates quietly, without generating vibrations and the need for frequent disposal of the fuel cell when its fuel is