Applied Energy 87 (2010) 1231–1238

Contents lists available at ScienceDirect

Applied Energy

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

Energy efficiency analysis and impact evaluation of the application of thermoelectric power cycle to today's CHP systems

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ARTICLE INFO

Article history:
Received 18 December 2008
Received in revised form 13 May 2009
Accepted 9 June 2009

Keywords:
CHP power system
TEG
Energy system analysis

ABSTRACT

High efficiency thermoelectric generators (TEG) can recover waste heat from both industrial and private sectors. Thus, the development and deployment of TEG may represent one of the main drives for technological change and fuel substitution. This paper will present an analysis of system efficiency related to the integration of TEG into thermal energy systems, especially Combined Heat and Power production (CHP). Representative implementations of installing TEG in CHP plants to utilize waste heat, wherein electricity can be generated in situ as a by-product, will be described to show advantageous configurations for combustion systems. The feasible deployment of TEG in various CHP plants will be examined in terms of heat source temperature range, influences on CHP power specification and thermal environment, as well as potential benefits. The overall conversion efficiency improvements and economic benefits, together with the environmental impact of this deployment, will then be estimated. By using the Danish thermal energy system as a paradigm, this paper will consider the TEG application to district heating systems and power plants through the EnergyPLAN model, which has been created to design suitable energy strategies for the integration of electricity production into the overall energy system.

1. Introduction

Thermoelectric technology, which converts heat energy to electric power by means of semiconductor charge carriers, is expected to contribute to meeting today's needs for increased fuel efficiency and reduced harmful emissions. Worldwide, a race has started with the aim of commercializing TEG-based energy saving systems for real life applications. The Japanese national project "The Development for Advanced Thermoelectric Conversion Systems", supported by the New Energy and Industrial Technology Development Organization (NEDO), was initiated in 2002 to create mass production lines and commercial production of TEG systems. A reduction in carbon dioxide emissions of 73,000 tons is prospected and 213 GWh of electric power is generated in 2010 with thermoelectric power generation systems developed in this project [1]. The US Department of Energy recently also initiated a programme on TEG waste heat recovery in relation to automotive and diesel engines, which is one of the sub programmes of the "Advanced Combustion Engines" research plan [2]. The waste heat recovery research focuses on technologies that can recover and convert engine waste heat to electrical energy to improve the overall thermal efficiency of diesel engines to a level higher than 55% towards 60% while reducing emissions to near-zero levels. Fairbanks and Yang spoke about the ambitious plans for practical, industrial-scale thermoelectric waste heat recovery systems [3–5].

In the application of TEG, a frequently asked question is that "how can TEG with a lower conversion efficiency compete with various generators with higher conversion efficiencies?", where Vining shows his insightful but pessimistic concern [6,7]. In our opinion, in the scope of energy harvesting, this is actually not a real barrier, as the TEG will utilize what would otherwise be waste heat, and will not consume fresh fuel for electricity production. Rather than competing with conventional generators, the purpose of most TEG applications is to exploit the low grade heat, cheap or free, and to obtain additional benefits in terms of an improved overall efficiency. Consequently, even for currently used TEG devices with a low conversion efficiency of around 5–10%, they are still strongly advantageous as compared to conventional energy technologies, not only for their well-known merits such as high reliability, silence, low environmental impact, and purely DC electrical power sources, but also because of their capability of utilizing huge amounts of industrial and private waste heat as an energy source in a simple and easy manner. More applications can thus be envisaged, and the development of TEG is expected to become more explosive in the future.

The performance of TEG systems is improved not only due to the elevation of Z-values of the materials but also the progress of the application technique. Excellent review articles have been published on thermoelectric material and technology [6–15], but the

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doi:10.1016/j.apenergy.2009.06.009

application of up-to-date TEG power generation to CHP energy systems has attracted much less attention so far. Matsuura analysed a heat pump/TEG system to identify the best use of the cogeneration rather than only to produce electricity, and proposed to apply TEG to the steam turbine of the power station for superconducting synchronous power source, in which part of the steam heat from the turbine is transformed into power by TEG for field excitation [16]. Yodovard et al. assessed the potential of waste heat recovery from the stack exhaust of around 200 °C for diesel engine and gas turbine cogeneration in the manufacturing industrial sector in Thailand [17]. Kyono et al. considered the feasibility of recovering the energy loss at the vapor condensers in the steam-based power plants, utilizing the small temperature difference between the vapor and the coolant, corresponding to around 40 °C and 15–19 °C, respectively [18]. Kametani et al. assumed that TEG modules were mounted between the high temperature exhaust gas heat exchanger (around 600 °C) and cooling water (around 90 °C) of gas engines and gas turbines, respectively, and then examined the effects [19]. However, a systematic analysis of technical pros and cons of these ideas, i.e., the incorporation of TEG into existing CHP energy systems, and especially a comprehensive description on the overall impact of this incorporation, are still absent.

The simple operation of TEG technology as well as its other features make it a feasible supplement to CHP performance improvement. This paper will focus on the technical and economic aspects of the state of the art of large scale TEG applications, using CHP systems in Denmark as a special energy niche. The objective is to describe the technological change represented by the integration of TEG into CHP energy systems and its role as a special kind of fuel substitution. Furthermore, the paper describes how the technological change affects energy consumption by promoting efficiency improvements. The descriptions will begin with an analysis of feasible solutions as well as the technical barriers and challenges for the integration of TEG into thermal energy systems. The representative TEG applications to generic CHP technology are presented sequentially. Following the analysis, the economic and environmental impacts of TEG application are evaluated by use of the EnergyPLAN model [20–25].

2. Applications of TEG to CHP systems

The structure scheme of a typical CHP system is shown in Fig. 1. In general, TEG can be integrated into a CHP in three modes. The first is to place the TEG between the generator and the waste heat boiler, using the temperature difference between the high temperature exhaust gas from the generator and the coolant to produce electricity [19]. The second is to place the TEG at the outlet of the waste heat boiler, using the temperature difference between the final exhaust gas from the boiler and the ambient to produce electricity [17]. The third is to place the TEG at the condenser [18], between the inlet fluid to be warmed and the outlet fluid to be used for heating demand, or in any other place to substitute the traditional heat exchangers, using small temperature differences to produce electricity. The three modes are highlighted in Fig. 1.

2.1. Modelling

In modelling TEG energy systems, an important factor is the dependency of the TEG efficiency on the temperature range. The objective of the aforementioned Japanese national project is to develop high efficiency thermoelectric modules and power generation systems to convert thermal energy of wide and various temperature ranges into electricity. The final goal is to establish a 15% energy conversion efficiency with a temperature difference of 550 K [1]. The interim goal of 12.1% efficiency has already been cleared by Komatsu's bulk material module with a hot side of 580 °C and a cold side of 30 °C [26]. Within the same project framework, another Japanese company YAMAHA proffered Bi–Te based modules for lower temperature applications with a conversion efficiency of 5.6% with around 200 °C as for high temperature side and around 50 °C at low temperature electrode [27]. Other commercially available power modules also display a similar maximum efficiency of about 5% when the operation is in the temperature range of about 200 °C [28]. In [28], it is also shown that the conversion efficiency of the TEG modules can only reach around 1% when the temperature difference is below 50 °C.

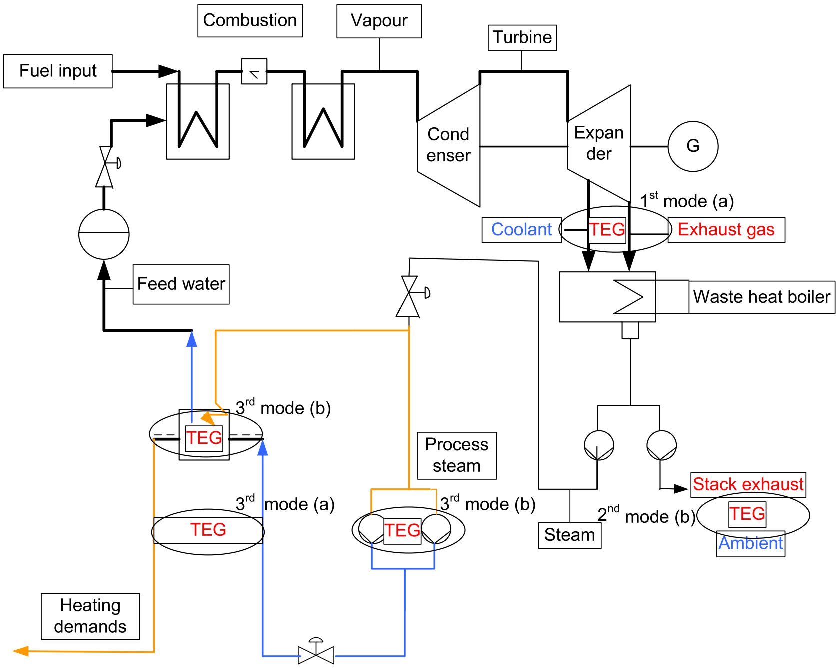

Fig. 1. Schematic representation of a typical CHP system and locations of TEG.