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Building-integrated trigeneration system: Energy, environmental and economic dynamic performance assessment for Italian residential applications

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ABSTRACT

A trigeneration system uses only one source of primary energy, while providing power, heating and cooling simultaneously. This primary source can be represented by either fossil fuels or some appropriate renewable energy sources (biomass, biogas, solar energy, etc.).

In this paper a brief review of micro-trigeneration systems for residential applications was reported. An innovative building-integrated micro-trigeneration system was proposed. This proposed system was based on a natural gas-fueled internal combustion engine micro-cogeneration unit for heating purposes and domestic hot water production. The cogeneration device fed an electric air-cooled vapor compression water chiller for cooling purposes. The micro-trigeneration system was coupled with a multi-family house characterized by transmittance values of the building envelope compliant with those imposed by Italian Law. The considered building is representative of a typical Italian residential application. The feasibility of the proposed trigeneration system was investigated by using the dynamic simulation software TRNSYS in comparison to a traditional supply based on separate energy production. The analyses were performed by varying the climatic conditions and considering buildings located in three different Italian cities (Palermo, Naples and Milan), which are representative of the different climatic regions of Italy.

The primary energy consumption, the equivalent carbon dioxide emissions as well as the operating costs of the proposed system were evaluated based on the simulation results according to the Italian scenario and compared with those associated to a conventional system composed of a natural gas-fired boiler coupled with the same air-cooled water electric chiller fed by the electric grid. The performed analyses allowed to assess the energy, environmental and economic suitability of the proposed scheme as well as its potential benefits in comparison to the reference plant based on separate energy production.

Contents

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1. Introduction

Population growth and technological advancement over the last two decades, along with the desire for higher living standards and comfort levels, have led to an unprecedented increase in energy consumption and global energy-related carbon dioxide emissions worldwide; the contribution of buildings in the European Union is about 40% of the total energy demand and generates 40–50% of the total emissions of greenhouse gases [1,2]. In many countries, there has been an increasing demand of cooling energy during the warm season, which is generally satisfied by electrically-driven units; this trend has involved an increase of the power generation capacity of electric utilities, while contributing to electrical load peaking and subsequent network congestion as well as failure events in different power systems worldwide. This has strengthened the awareness of governments, manufacturers and communities of energy issues, pushing forward the search for innovative systems for local cooling energy generation. Wide-ranging options exist on the supply side for the provision of electricity and heat. Among these options, micro-cogeneration (combined production of electrical and thermal energy from a single fuel source with an electric output lower than 50 kW_{el}) is considered by the European Community as one of the most effective measures to both save primary energy as well as reduce greenhouse gas emissions in domestic and small-scale applications. Moreover, the high-efficiency cogeneration system and/or efficient district heating and cooling are considered by the European Community comparable to the renewable energy sources in accordance with [3].

The presence of a threefold energy demand (namely, electricity, heat and cooling) leads to the possibility of profitably combining micro-cogeneration units with various technologies currently available for cooling generation. The combination of MCHP systems to various thermally fed or electrically-driven cooling systems allows to set up a so-called micro combined cooling heat and power (MCCHP) system [4,5], with it representing the production in-situ of a threefold energy vector requested by the user from a single fuel source. The processes and technologies for micro-trigeneration that are nowadays available can lead to a number of advantages [4,5]:

- increasing the global energy efficiency together with a wider utilization of renewable sources;
- lowering the environmental impact in terms of carbon dioxide equivalent emissions;
- avoiding the huge investments needed to reinforce the electric infrastructure;
- improving the stability of the electrical grid;
- reducing the overloads and blackouts of the electrical system.

1.1. Literature review

The role of the residential sector is very important in reducing the global total energy-related CO_2 emissions [6]. This sector represents around 40% of global energy consumption. Furthermore, it has been predicted that the energy demand of buildings will continue to increase worldwide in the coming years [6,7]. In addition, the buildings sector will continue to condition the natural resources exploitation [8]. For these reasons, there are numerous studies that show an interest in energy consumption and CO_2 emissions on the residential sector [6–9] in current literature. Nejat et al. [6] reported a review of the status and current trends of energy consumption, CO_2 emissions and energy policies in the residential sector in ten countries: China, USA, India, Russia, Japan, Germany, South Korea, Canada, Iran, and United Kingdom. These countries produce two-thirds of global CO_2 emissions in the residential sector [6].The authors highlighted that the energy consumption in this sector increased by 14% over the last ten year, which was mainly due to rapid urbanization and economic development in countries as China, India and Iran. Indeed, these countries had increasing trends in CO_2 with alarming values; differently from this trend, other countries as Russia, Canada, United Kingdom and Germany presented a reduction of the CO_2 emissions with respect to the last years [6]. A hierarchical process with embedded techniques (insulations, energy efficient equipment and micro-generation) was presented in [7] as a pathway towards zero-carbon building refurbishment in order to help designers and engineers reduce complexity by prioritizing design considerations at each stage in the design and evaluation processes. Zuo and Zhao [9] reported a crucial review of existing studies related to green buildings in the world. The authors [9] showed that these studies can be categorized as follows: (i) the definition and scope of green buildings, (ii) benefits and costs of green buildings and (iii) ways to achieve green building. The paper [9] also showed that there is a greater attention at the interaction between building and its users.

In this context, trigeneration systems are a feasible solution for improving overall system efficiency and reducing the environmental impacts in residential sector [10].

Trigeneration or Combined Cooling Heating and Power (CCHP) is the simultaneous production of power, heating and cooling. CCHP uses only one source of primary energy, represented by either fossil fuels or some appropriate renewable energy sources (biomass, biogas, solar energy, etc.) [11]. Trigeneration systems therefore have the potential to increase access to the benefits achievable from on-site electrical generation and to reduce emissions and operating costs [12]. Micro scale trigeneration power plants, typically below 50 kW_{el}, are called micro combined cooling heat and power (MCCHP) systems. MCCHPs are particularly interesting not only due to their technical features and their high overall energy conversion efficiency but also because the European Community considers them equal to renewable energy sources [3,13]. A typical MCCHP system consists of three basic elements: prime mover, thermal energy storage and cooling unit.

The prime mover in a MCCHP system is the “core” of the micro-trigeneration system. The energy conversion process can be based on combustion and the subsequent conversion of heat into mechanical energy, which then drives a generator to produce electricity. Alternatively, it can be based on the direct electro-chemical conversion from chemical energy to electrical energy. Moreover, downstream of this conversion process waste heat is

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