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# Performance assessment of cogeneration and trigeneration systems for small scale applications

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ABSTRACT

Cogeneration and trigeneration systems can contribute to the reduction of primary energy consumption and greenhouse gas emissions in residential and tertiary sectors, by reducing fossil fuels demand and grid losses with respect to conventional systems. To evaluate the performance of these systems, several indices and assessment methodologies can be used, due to the high complexity of such systems, which can consist of several energy conversion devices and can perform bidirectional interactions with external electric and thermal grids. In this paper, a review of the available indices and methodologies to assess the performances of polygeneration systems is provided. An index ($TSS_{tri}$) aimed to assess the economic feasibility of a trigeneration system is also introduced and discussed. This activity started in the framework of the International Energy Agency Annex 54 project ("Integration of Micro-Generation and Related Energy Technologies in Buildings"), where research groups shared their expertise about methods applied in each Country to evaluate the performance of polygeneration systems. It was concluded that a thermo-economic analysis comparing the performance of a polygeneration system with those of a reference benchmark scenario, is a very suitable assessment method. Some of the reviewed methodologies are then applied to small scale commercial cogenerators. The sensitivity analysis is performed considering different reference average values of electric efficiency, unitary natural gas and electricity prices, and emission factors for some European Countries.



## 1. Introduction

In the period 2011–2013, the energy consumption in the civil sector with respect to the total final energy use increased from 37.4% [1] to 40.6% in European Union, surpassing other energy consumption sectors such as industry, which reaches only the 25.1% in 2013, [2]. This trend has determined an increasing interest in the reduction of primary energy consumption and greenhouse gas emissions in the residential and tertiary sectors. Such purpose requires a strong effort to increase energy efficiency and penetration of renewable energies.

In particular, small-scale applications of Combined Heating and Power (CHP) and Combined Cooling Heating and Power (CCHP) systems can help to achieve this purpose on the supply side. These technologies can reduce the use of non-renewable energy sources and transmission and distribution losses along the grid. They could also decrease the summer high electric peak loads and black-outs risks due to the wide diffusion of air conditioning units in the last two decades.

Therefore a general trend of recent years is the transition from centralized to decentralized or distributed generation, supported by both research activities and new applications [3]. At the same time, the size reduction of energy conversion devices led to the commercialization of small scale power, refrigeration and heat pump systems. Thanks to their advantages these systems are also largely applied in residential and office buildings. In 2014 residential cogenerators, based on fuel cells and internal combustion engines, was in Japan about 223,542 for a total installed capacity of about 201 MW. In Europe, more than 20,000 units of internal combustion engine based cogenerators have been sold, mainly considering two models, with 4.7 and 5 kW rated electric output. Moreover, about 3000 units of Stirling engine based cogenerators have been also installed [4]. Due to the diffusion of these devices, specific indices have been studied and adopted to assess CHP and CCHP performance. In this work, a review of those indices and methodologies to evaluate the performance of cogeneration and trigeneration systems is proposed. This research activity started in the framework of the International Energy Agency Annex 54

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**Nomenclature**

| | |
|---|---|
| *a* | discount rate (–) |
| *CEE* | Comprehensive Energy Efficiency (–) |
| *COP* | Coefficient Of Performance (–) |
| *DE* | Delivered Energy (kW h/y) |
| *EC* | Extra Cost (€) |
| *EER* | Energy Efficiency Ratio (–) |
| *EIHR* | Electrical Incremental Heat Rate (–) |
| *FESR* | Fuel Energy Saving Ratio (–) |
| $F_k$ | yearly cash flow (€/y) |
| *GER* | Greenhouse Gas Emission Reduction (–) |
| *GHG* | Greenhouse Gas Emission (–) |
| *GWP* | Global Warming Potential ($kg_{CO_2,eq}/kg_{GHG}$) |
| *IRR* | Internal Rate of Return (–) |
| *K* | generic energy quantity for emissions calculation (kW h/y) |
| *LHV* | Lower Heating Value (kW h/N $m^3$) |
| *m* | mass (kg/y) |
| *NE* | Net Energy (kW h/y) |
| *NPV* | Net Present Value (€) |
| *OC* | Operating Costs (€/y) |
| *OE* | Output Energy (kW h/y) |
| *PE* | Primary Energy (kW h/y) |
| *PEF* | Primary Energy Factor (–) |
| *PER* | Primary Energy Ratio (–) |
| $PER_{VW}$ | Value-Weighted Primary Energy Ratio (–) |
| *PES* | Primary Energy Saving (–) |
| *PHR* | Power to Heat Ratio (–) |
| *PI* | Profitability Index (–) |
| *RE* | Renewable Energy generated on the building premises (kW h/y) |
| $r_e$ | share of CHP electric energy output used in electrically driven cooling equipment (–) |
| $r_t$ | share of CHP thermal energy output used in thermally driven cooling equipment (–) |
| *SPB* | Simple Pay Back period (y) |
| *SS* | Spark Spread (–) |
| *TCC* | Tolerable Capital Cost (€ or $) |
| $TCO_2ER$ | Trigeneration Emission $CO_2$ reduction (–) |
| *TIHR* | Thermal Incremental Heat Rate (–) |
| *TPES* | Trigeneration Primary Energy Saving (–) |
| *TSS* | Total Supply Spread (–) |
| *UP* | Unitary Price, €/kW h if referred to electricity or thermal energy, €/N $m^3$ if referred to fuel |
| *XE* | Exported energy (kW h/y) |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | emission factor for electricity drawn from grid ($kgCO_2$/kW $h_{El}$) |
| $\beta$ | emission factor for natural gas ($kgCO_2$/kW $h_{PE}$) |
| $\Delta CO$ | reduction of Operating Cost (€/y) |
| $\Delta CO_{2,eq}$ | avoided equivalent $CO_2$ emissions (–) |
| $\eta$ | efficiency (–) |
| $\Psi$ | surplus factor (–) |
| $\mu$ | specific emission factor ($kg_{CO_2,eq}$/kW h) |
| $\xi$ | allocation factor (–) |

*Subscripts*

| | |
|---|---|
| *a* | artificial |
| *AS* | Alternative System |
| *C* | Carnot engine |
| $CO_{2,eq}$ | equivalent carbon dioxide emission |
| *Cool* | cooling |
| *CS* | Conventional System |
| *Case Study 1* | referred to Case Study 1 |
| *Case Study 2* | referred to Case Study 2 |
| *DHW* | Domestic Hot Water |
| *El* | Electric |
| *eq* | equivalent |
| *Fuel* | related to fuel |
| *GHG* | Greenhouse Gas |
| *hs* | heating season |
| *ref* | reference value |
| *SH* | Space Heating |
| *sum* | summer season |
| *Th* | Thermal |
| *tri* | trigeneration |
| Subcase | referred to Subcase |
| *w, in* | water inlet temperature |
| *w, out* | water outlet temperature |
| *z* | generic pollutant |

*Superscripts*

| | |
|---|---|
| *AHP* | Absorption Heat Pump |
| *CH* | Chiller |
| *Case Study 1* | referred to Case Study 1 |
| *Case Study 2* | referred to Case Study 2 |
| *CHP* | Combined Heat and Power |
| *DC* | District Cooling |
| *DH* | District Heating |
| *EHP* | Electric Heat Pump |
| *Grid* | electric grid |
| *Subcase* | referred to Subcase |
| *TCS* | Thermally-activated Cooling System |

*Acronyms*

| | |
|---|---|
| AHP | Absorption Heat Pump |
| AS | Alternative System |
| CHP | Combined Heating and Power |
| CCHP | Combined Cooling Heating and Power |
| CS | Conventional System |
| DC | District Cooling |
| DH | District Heating |
| DHW | Domestic Hot Water |
| EHP | Electric Heat Pump |
| GHG | Greenhouse Gas |
| HVAC | Heating Ventilation and Air Conditioning |
| IC | Internal Combustion |
| TCS | Thermally-activated Cooling System |
| TES | Thermal Energy Storage |

project (“*Integration of Micro-Generation and Related Energy Technologies in Buildings*”) [5], where research groups shared their expertise about methods applied in each Country to evaluate the performance of polygeneration systems, in terms of energy, environmental and economic criteria. A review of microcogeneration national testing procedures can be instead found in [4]. Many studies have been carried out to assess the performance of CHP and CCHP systems from the economic, energy and environmental point of view, through some adequate indices.

Ciampi et al. [6] performed an experimental analysis of a microtrigeneration plant consisting of a 6.0 $kW_{El}$ cogenerator based on internal combustion engine interacting with a chiller delivering 7.5 kW of cooling power. This system has been compared with a conventional one based on separate energy

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