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Energy matching analysis of on-site micro-cogeneration for a single-family house with thermal and electrical tracking strategies

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ABSTRACT

This paper conducts matching analysis for micro-cogeneration products with generated electrical power (G_{elec}) range 0.5–2.0 kWe and electrical to thermal ratio (ETTR) range 0.05–0.80 for a Finnish single-family house. Using the recently defined matching indices and evolved criteria, the matching capabilities are comprehensively assessed from both electrical and thermal heat matching aspects. Furthermore, both of the thermal tracking (with electrical grid feed-in) and electrical tracking (with thermal heat grid feed-in) strategies are considered. The simulation tool is TRNSYS 17. In terms of the averaged matching index under the thermal tracking strategy without battery, the best matching happens with a fuel cell with G_{elec} of 1.5 kWe and ETTR of 0.8, whereas under the condition with battery, the best matching happens with a Stirling engine or internal combustion engine with G_{elec} of 1.0 kWe and ETTR of 0.3. Under the electrical tracking strategy, the best matching happens with a Stirling engine with G_{elec} of 1.0–2.0 kWe and ETTR of 0.25. However, by putting certain preferences on the specific aspects of the matching capability, the best matching might be altered, which can be assessed using a weighted matching index. There is no linear relation between matching and primary energy consumption.

1. Introduction

In recent years, micro combined heat and power (mCHP) has started to be implemented in domestic applications. Similar to the large-scale combined heat and power (CHP), mCHP can fully utilise the embodied fuel energy by utilising the waste heat from the electricity production process. As a result, the total fuel efficiency of mCHP can be as much as 90%, significantly enhancing the efficiency of the energy system. At present, domestic-scale, commercially available mCHPs include the Stirling engine, Organic Rankine Cycle (ORC), internal combustion engine (ICE), and fuel cell with nominal electrical outputs mainly in the range 0–2 kWe, while 1 kWe is the most common value. Table 1 lists 16 reviewed mCHP products relating to different specific technologies. Furthermore, Fig. 1 depicts the ranges of the electrical to thermal ratio (ETTR) with respect to specific mCHP technologies referring to the commercial products listed in Table 1. As shown in Fig. 1, the Stirling engine is in the ETTR range 0–0.3, the ORC is in the ETTR range 0–0.15, the ICE is in the ETTR range 0.3–0.4 and the fuel cell is in the ETTR range higher than 0.4.

Many researches have also been focused on using mCHP for domestic applications. Shaneb et al. conducted the sizing analysis of various types of mCHP technologies (Stirling engine, ICE, and fuel cell) with back-up heaters for three typical residential buildings in UK, based on a generic deterministic linear programming model [1]. They found that Stirling engine, with a recommended size of 0.85–1.25 kWe, and ICE, with a recommended size of 1.7–2.9 kWe, are feasible for the application under the optimistic current cost and typical specifications. Roselli et al. comprehensively conducted the experimental analysis for the mCHP units of Stirling engine and ICE, based on the assessment of energy, economic, and environmental impact, for residential and light commercial applications in Italy and Germany [2]. They found that both the Stirling engine and ICE technologies can help to significantly save the primary energy consumption and pollutant emissions compared to the conventional separate energy suppliers, whereas they showed that the investment cost of mCHPs is the main obstacle for their widespread in the market. Barbieri et al. analysed the feasibility of using several mCHP technologies to meet the energy demands of two different single-family houses in Italy [3]. Barbieri et al. found that by thermal tracking strategy, mCHP units can meet at least 80% of the thermal heat energy demands, whereas the ratio between the electrical production and demand is usually less than 85%. Based on the economic analysis conducted by Barbieri et al., the Stirling engine is the most feasible for the application. Bianchi et al. made guidelines for residential mCHP systems based on the thermal tracking strategy [4]. Based on their detailed analysis, Bianchi et al. highlighted that the proper sizes of mCHP and thermal storage and the self-consumption of generated electrical energy are the key factors for the profitability of mCHP. Ren et al. conducted two special

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Nomenclature

AHU	air handling unit
AMI	averaged matching index
ANPE	annual net primary energy consumption (kWh/m^2 a)
CHP	combined heat and power
DHW	domestic hot water
dt	the time-step used in the research
$E_{\text{off-h}}$	off-site part of electrical power sent to electrical driven heating machines (kW)
$E_{\text{on-h}}$	on-site part of electrical power sent to electrical driven heating machines (kW)
ES_{off}	net off-site part of the electrical power sent to electrical storage, charge in ‘+’ sign, and discharge in ‘−’ sign (kW)
ES_{on}	net on-site part of the electrical power sent to electrical storage, charge in ‘+’ sign, and discharge in ‘−’ sign (kW)
ETTR	electrical to thermal ratio
F_{eg}	interacted electrical power with the electrical grid, exporting in ‘+’ sign, and importing in ‘−’ sign (kW)
F_{dh}	interacted thermal heat power with the thermal heat grid, exporting in ‘+’ sign, and importing in ‘−’ sign (kW)
FSOC	fractional state of charge
G_{elec}	electrical power generated by on-site electrical energy production system (mCHP in this paper) (kW)
$G_{\text{h\_th}}$	thermal heat power generated by on-site thermal energy production system (mCHP in this paper) (kW)
$H_{\text{eoff-h}}$	generated heat power by the electrical driven heating machines by off-site part of the electricity (kW)
$H_{\text{eon-h}}$	generated heat power by the electrical driven heating machines by on-site part of the electricity (kW)
HS_{off}	net off-site part of the thermal heat power sent to heat storage, charge in ‘+’ sign, and discharge in ‘−’ sign (kW)
HS_{on}	net on-site part of the thermal heat power sent to heat storage, charge in ‘+’ sign, and discharge in ‘−’ sign (kW)
L_{elec}	electrical load power excluding the electrical load from the electrical driven heating and cooling machines (kW)
L_{heat}	thermal heat load power excluding the thermal heat load from the thermal driven cooling machines (kW)
l_{e}	electrical losses of on-site electrical power during distribution process (kW)
l_{h}	thermal heat losses of on-site thermal heat power during distribution process (kW)
HWST	hot water storage tank
ICE	internal combustion engine
mCHP	micro combined heat and power
OEF	on-site energy fraction
OEFe	on-site electrical energy fraction
OEFh	on-site thermal heat energy fraction
OEFc	on-site thermal cooling energy fraction
OEM	on-site energy matching
OEMe	on-site electrical energy matching
OEMh	on-site thermal heat energy matching
OEMc	on-site thermal cooling energy matching
t_1	starting point of the time span
t_2	ending point of the time span
WMI	weighted matching index

operation strategies for fuel cell and gas engine (internal combustion engine) for a standard Japanese single-family house: one strategy was a minimum cost strategy and the other a minimum emission strategy [5]. In Ren et al.'s research, an ideal assumption is made that the mCHP can instantaneously operate at any percentage of the rated capacity. According to Ren et al.'s results, fuel cell is the best option for the studied house in terms of both of the operation strategies. Paepe et al. compared three different mCHP technologies (Stirling engine, ICE, and fuel cell) for a detached house, a terraced house, and a two-storey apartment in Belgium [6]. They found that the ICE seems to have the best performance, whereas all three mCHP technologies would need to reduce the installation costs by 50% before they can be economically competitive. Dong et al. reviewed various biomass based micro- and small-scale CHP systems based on various solutions, such as external biomass combustion, gasification, and bio-fuel produced from chemical/biological/mechanical processes [7]. Dong et al. emphasised that, although the application of biomass based micro and small CHP is increasingly significant from an environmental point of view, the research and development is still in the infant stage and requires urgent research efforts. Regarding the objective of creating a net zero energy building, the mCHPs based on biomass, biogas, or hydrogen are also being studied by various researchers [8,9]. Moreover, many researches have focused on testing and/or conducting numerical simulations of specific mCHP technologies, for example Stirling engine [10–12], ORC [13,14], ICE [15–17], and fuel cell [18–20], which are not introduced here in detail.

Up until now, there are several research topics which have not been done by the previous researchers: (1) no research has specifically focused on the matching analysis of various mCHP technologies from the perspective of their comprehensive thermal and electrical matching aspects; (2) most of the researches have focused on the thermal load based mCHP (thermal tracking), whereas limited research has focused on the comparison between the thermal tracking and electrical tracking strategies; (3) most researches have focused on the mCHP with an electrical grid feed-in option, but few has analysed the matching situation of mCHP with a thermal heat grid feed-in option. Recently, the thermal heat grid feed-in option has been developing quite rapidly and some EU countries have already started to implement some district heating systems that are bi-directionally connected with the distributed on-site heating units [34]. In this paper, using the recently defined matching indices, the matching analysis of mCHP is conducted for both the thermal and electrical tracking strategies with certain electrical or thermal heat grid feed-in options. All of the common mCHP technologies (Stirling engine, ORC, ICE, and fuel cell) are covered via the parametric analysis of mCHP with respect to the variable of ETTR. In Section 2, the simulation tools, the applied single-family house, and the mCHP model are briefly introduced, while Section 3 describes the operation strategies of the mCHP system. Furthermore, the matching indices and related criteria used for the matching analysis are provided in Section 4. Thereafter, Section 5 presents the results and parametric analysis based on the simulation. It should be mentioned that the relationship between matching and net primary energy consumption are also briefly introduced in Section 5. Finally, conclusions are drawn in Section 6.

2. Simulation tools, single-family house, and mCHP model

The simulation tool for this research is TRNSYS 17, which is a dynamic simulation environment for heating, cooling, air-conditioning, and energy systems [35]. The mCHP is applied to a 150 m^2, one-storey, single-family house located in Helsinki, Finland (60.2°N, 24.9°E). This house is a standard house, whose envelope, occupancy, internal gains, and building service systems follow the