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High resolution performance analysis of micro-trigeneration in an energy-efficient residential building

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ABSTRACT

Trigeneration has long been proposed as a means to improve energy-efficiency for large and medium sized buildings. To curb increasing energy demand in the residential sector, researchers are now focusing their attention on adapting trigeneration to residential buildings. Literature is full of examples pertaining to the performance of trigeneration in large and medium sized commercial buildings, however little is known on the performance of micro-trigeneration inside residential buildings, particularly under a range of operating conditions. To understand the influence that parameters such as changes in thermal and electrical loading or different plant configurations have on the performance of micro-trigeneration, this research makes use of a detailed model of a Maltese apartment building, and associated micro-trigeneration system. The performance of the model is simulated using a whole building simulation tool run at high-resolution minute time frequency over a number of different operating conditions and scenarios. Each scenario was then assessed on the basis of the system's energetic, environmental and economic performance. The results show that, compared to separate generation the use of a residential micro-trigeneration system reduces primary energy consumption by about 40%, but also that the system's financial performance is highly susceptible to the operating conditions.

1. Introduction

Trigeneration is viewed as the natural extension to Combined Heat and Power (CHP) in countries where significant cooling of buildings is required ([1,2]). Unlike separate generation in which energy requirements are satisfied independently through different energy flows, trigeneration makes use of an energy cascading process where the waste heat from electrical power production is utilised to satisfy either a heating or cooling demand in a single energy flow process [3]. In the latter case use is made of a thermally activated chiller (TAC). This re-utilisation of the waste heat to supply a cooling load could be useful in reducing the increased energy demand arising from the increased use of vapour compression-based air conditioning [4].

Various studies have shown the feasibility of trigeneration particularly when used with large and medium scale loads such as industry [5], hotels [6], schools [7] and supermarkets [8]. The stable demand for energy in these sectors ensures that trigeneration systems offer attractive rates of return on investment. Research interest (*e.g.* IEA's Annex 42 [9] and Annex 54 [10]), has now shifted towards using micro-trigeneration in residential buildings. Micro-scale generation is defined as a system with an electrical capacity typically of not more than 15 kW_{el} [11]).

1.1. *Assessing the performance of micro-trigeneration in residential buildings*

An important aspect in determining the feasibility of micro-trigeneration in residential buildings is the assessment of its energetic, environmental and economic performance. Research has so far mostly focused on the documentation of results obtained from experimental test rigs [12–16] or demonstration projects such as that by Henning et al. [17]. The results from these experimental systems give an indication of what micro-trigeneration system performance should be for specific conditions. These studies however, stop short of indicating how a micro-trigeneration system would perform under more realistic operating conditions. Moreover, other operating factors such as building load, occupancy patterns and plant configuration will also dictate the micro-trigeneration system's ultimate performance. A final factor, which to-date has been under-explored, is the performance and feasibility of micro-trigeneration systems in future, energy efficient residential buildings.

To assess the influence of different operating conditions for large, medium and small scale trigeneration researchers have used

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Nomenclature

Variables
CF cash flow (€)
E energy product (kWh)
e specific emissions ($kgCO_2$/kWh)
FIT feed-in tariff (€/kWh)
I investment cost (€)
MARR minimum attractive rate of return (%)
MC maintenance cost (€/kWh)
PE primary energy (kWh)
PES primary energy savings (%)
PW present worth (€)
Y expected lifetime (years)

Greek letters
η efficiency

Indices
DHW domestic hot water
el electrical power
Gas Heater variables which refer to the gas heater
Grid variables which refer to the grid
LPG variables which refer to LPG
μTRIGEN micro-trigeneration system
Net Demand μTRIGEN electrical energy demand satisfied by the micro-trigeneration system
Net Export electrical energy exported to the grid
Net Import net electrical energy imported from the Grid
SEPARATE separate generation
SC space cooling
SH space heating
th thermal power
Water variables which refer to water heating

optimisation modelling techniques [18] whereby a 'cost function' (*e.g.* capacity, storage size, *etc.*) is optimised for various boundary conditions. For example Wang et al. [18] and Carvalho et al. [19] use optimisation to assess the performance of small scale trigeneration under different climatic conditions and in different buildings (*e.g.* hotels, hospitals, *etc.*). Kavvadias et al. [20], use an optimisation process to understand the influence of system sizing and other parameters on the project investment. A common aspect is that, the number of variables investigated was limited to a selected few (*e.g.* the CHP electrical power rating) and could perhaps best be described as constrained optimisations. To optimise a complete micro-trigeneration system model (including the building it serves) against a large number of different operating conditions would be a substantial undertaking, as the number of variables involved is huge.

A more pragmatic approach adopted in this paper makes use of a combined deterministic and sensitivity analysis methodology suggested by Dorer and Weber in [21]. The whole building simulation tool ESP-r [22] is used to assess the performance of a grid-connected micro-trigeneration system under a number of realistic operational scenarios. The micro-trigeneration performance can be compared for the different scenarios, whilst the effect that key parameters will have on a specific scenario can be assessed using a sensitivity analysis. According to Dorer and Weber [21], this approach permits a high degree of flexibility vis-à-vis the type and number of operating conditions studied, and provides a comprehensive picture of performance. Further, the use of a whole building simulation tool such as ESP-r ensures that the complexities arising from the coupling between the trigeneration plant system and the building are taken into account. As discussed by Stokes in [23] the use of a time resolution of 1-min ensures that the simulations are modelled with enough temporal precision to characterise the highly varying nature of residential energy demands, particularly electricity. Also, high resolution modelling is required to obtain an accurate picture of electrical import and export [24].

Table 1
Factors influencing performance investigated in this study.

Factors	Possible effect on micro-trigeneration system
Improvement in building fabric	Changes the thermal demand – heat load and operating time
Building size and number of occupants	Changes the thermal demand – heat load and operating time
Improvement in household appliances' electrical efficiency	Changes the electrical demand – reduced electrical demand
Addition of a chilled water storage tank	Changes operating mode
Sensitivity to grid network improvements	Changes the comparison with separate generation
Sensitivity to fuel prices	Changes the system's running costs
Sensitivity to electricity tariffs	Changes the comparison with separate generation

The model used in these simulations represents a micro-trigeneration system supplying both the electrical and the thermal demands of a multi-family residential building in the island of Malta. Given its location in the middle of the Mediterranean sea, Malta is a good example of the sub-tropical *Csa* Köppen Climate Classification (moderate rainy winters and hot dry summers) [25], prevailing in substantial parts of southern Europe.

1.2. Factors investigated

The number of variables which can influence the performance of a residential micro-trigeneration system is vast. So, for this study to be tractable, a select range of factors most likely to affect the viability of micro-trigeneration in housing were investigated, particularly factors relating to improved energy performance in housing and the wider energy network; these are summarised in Table 1.

2. Modelling

The following sections describe the modelling approach employed in this paper.

2.1. Modelling the building

2.1.1. Geometrical features

Fig. 1 shows the geometrical features of a typical Maltese building [26] modelled in ESP-r, which is representative of new Maltese residential buildings; it reflects the shift from traditional single-family terraced housing to apartment blocks. The model represents a building block abutting an adjacent building on the east and north sides. Compared to traditional buildings in Malta (where decentralised HVAC systems would be the preferred choice), these type of buildings are more suitable for a micro-trigeneration system, with a high occupancy density (large number of apartments) and the fact that some already have a centralised HVAC system. The building has a total floor space of about 360 m^2, 120 m^2 per floor, which is typical for Malta [27].

Each floor was modelled explicitly and represents an individual apartment housing a single household. The ground floor apartment houses a 2 person household, the middle floor houses a 3