Potentials of Fuel Cells as μ-CHP Systems for Domestic Applications in the Framework of Energy Efficient and Sustainable Districts

G. Vourliotakis[a]***, D. Giannopoulos***[b] ***and M. Founti***[c]

Laboratory of Heterogeneous Mixtures and Combustion Systems
Thermal Engineering Section, School of Mechanical Engineering
National Technical University of Athens, Greece
[a]*gvou@central.ntua.g*
[b]*digiann@central.ntua.g*
[c]*mfou@central.ntua.gr* , ***CA***

Abstract:

The present work presents an innovative energy production and distribution concept for sustainable and energy efficient refurbished and/or new "energy autonomous" districts exploiting decentralized co-generation coupled with optimized building and district heat storage and distribution networks. Centralized power stations feature a primary energy content-based efficiency of less than 35%. On the other hand, a μ-CHP SOFC (Solid Oxide Fuel Cell) based system has an overall efficiency of up to 80-90%. The present concept is based on dynamic heat exchange between the building(s) (fitted with SOFC based energy units and with improved thermal storage and insulation building systems), the distribution system (optimized piping and district heating) and the consumer (new business and service models), aiming to achieve energy balance at district level. The energy reduction will originate from improved efficiency and cost effective SOFCs, coupled with optimized energy and power distribution networks that will optimally control heat storage at building and/or district level. A micro-grid/heat network arrangement of dispersed μ-CHPs, can lead to significant reduction in power transmission and heat dissipation losses, ensuring direct energy savings (up to 60% reduction in primary energy use and CO_2 emissions) at both building and district levels.

Keywords:

μ-CHP, SOFC, Building energy storage, Thermal distribution network, Primary energy savings.

1. Introduction

The high costs of delivered electricity can be partially attributed to a strong dependence on centralized energy systems, which operate mostly on fossil fuels and require huge investments for establishing transmission and distribution grids that can penetrate remote regions. Further, fossil fuel combustion may result in increased emission of greenhouse gases (GHG) and noxious pollutants, which are directly related to global warming and health hazards [1]. The use of efficient, sustainable and eco-friendly power generating technologies, operating on clean and/or alternative fuels, can help in mitigating the above concerns. Micro-co-generation (μ-CHP) systems, producing both heat and electricity, provide potential reductions in carbon emissions and costs through efficient fuel use and by offsetting the use of centrally-generated electricity from the grid. The life cycle energy saving and environmental benefits of a μ-CHP case have been quantified in a previous work of the authors [2]. Major benefits of Distributed Generation (DG) systems are savings in losses over the long transmission and distribution lines, reduced installation cost, local voltage regulation, and ability to add a small unit instead of a larger one during peak load conditions. The advantages of the DG concept are depicted in Fig. 1.

Despite the advantages provided by cogeneration, its global share reaches only 9% [3]. Difficulties regarding the connectivity of (remote) CHP systems to the electricity grid, lack of information about cost savings and other benefits steaming for the technology itself (e.g. reduced emissions), have restricted the broad market penetration. However, forecasts predict a substantial increase in their share in the global energy scenario [3-5].

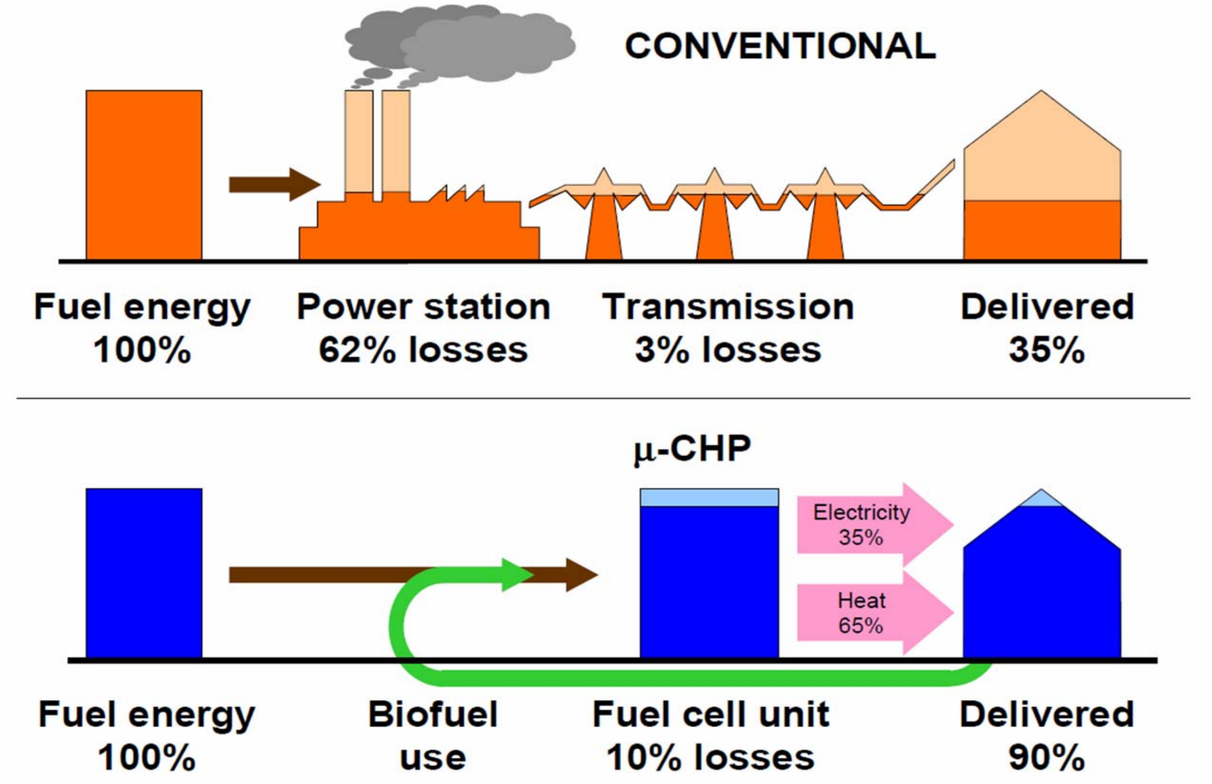

Figure 1. Scheme of the advantages of the distributed generation [6].

Large scale CHP applications are prominent in Denmark [7] where more than 80% of district heating is co-generated, leading to around 30% fuel savings. Further, district heating systems in Poland cover about 70% of the entire heating needs in cities [8]. Besides large systems, indications also suggest economically viable and energy efficient solutions at a smaller, local scale. Simulation studies [9] have shown that heat trading could be a functional way to develop DG systems targeting the size of communities with a few buildings. A potential advantage to be utilized is the connection through a district heating network of buildings with consumption profiles different in shape and/or timing.

The aim of the present work is to establish the framework for the realization of an optimized de-centralized μ-CHP network that is based both on electrical and thermal integration, at a district level. The development and optimization of the proposed small scale district heating network based on fuel cell (particularly SOFC) systems will enable cogeneration to be profitably set up on a scale much smaller than classical district heating and will give significant push in the commercialization of such technologies. The present work is performed within the frame of the FP7 EU-NMP FC-DISTRICT project on “New μ-CHP network technologies for energy efficient and sustainable districts” [6].

2. SOFC μ-CHP and building integration

The EU CHP directive defines micro-co-generation as “a co-generation unit with a maximum capacity below 50 kWel”. However, a restriction to a maximum of 15 kWel is more suited to small family houses and business buildings [10, 11]. Several power generating technologies (such as internal combustion engines (ICE), micro-turbines, the Stirling engine and fuel cells) can form the basis of a μ-CHP system [11]. The present study focuses on fuel cells due to their expected higher overall efficiencies [11].

There are at least four fuel cell types that have been extensively considered [12] for domestic applications; SOFC (Solid Oxide Fuel Cell), PEMFC (Polymer Electrolyte Membrane Fuel Cell), MCFC (Molten Carbonate Fuel Cell), and PAFC (Phosphoric Acid Fuel Cell). Details for each of the above technologies can be found in [13]. Prototype systems for commercial and industrial applications (~10 kWel) were based on PAFC, MCFC or SOFC types. However, not much economic benefit has appeared yet from the use of such large scale systems. On the other hand, the market of small stationary fuel cell power under 10 kWel seems to be a developing one, with the PEM and the solid SOFC currently being the most promising types for residential CHP [9]. Although more than 70% of the installed systems are PEM based, their operation temperature is too low to deliver the desired domestic hot water temperature. On the other hand, SOFCs work at high temperatures (up to 1300 K) and provide thermal energy for both space heating/cooling and domestic hot water needs. Note that, a cooling extension of domestic μ-CHP systems may be desirable depending on climatic conditions [14]. In this case, combination of cogeneration technologies to various thermally fed systems, such as absorption or engine-driven chillers, can allow for setting up a trigeneration or Combined Cooling Heating and Power (CCHP) system [15].

Furthermore, SOFC systems, due to their high operating temperature, could be operated with various fuel types (such as natural gas) incorporating internal fuel reforming [13]. Overall, SOFC systems are less sensitive to fuel composition variations than low temperature systems. Fuel flexibility provides an opportunity of utilising bio-fuels, which could indirectly improve the carbon saving ratio of SOFC systems contributing towards a zero CO_2 emissions operation.

The estimation of the energy cost savings of a μ-CHP system is highly dependent on the specific case parameters. Generally, the overall economic performance of a μ-CHP is dependent on the annual thermal demand of the dwelling and the power-to-heat ratio (PHR) of the μ-CHP system. Figure 2 presents the Equivalent Annual Cost (EAC) savings versus baseline case (use of country grid electricity and typical natural gas boiler for heat) for three μ-CHP technologies in the UK [5]. The SOFC unit appears to provide higher energy cost savings, especially at lower heat demand cases. In some cases the investment becomes negative (i.e. the grid electricity and boiler option has a weaker case for investment than the μ-CHP option) due to the ability of these systems to operate when thermal demand is low, whilst the high PHR technologies (ICE, Stirling engine) must modulate or switch off.

SOFCs with high PHR could be used more effectively in applications where lower levels of heat are required. Additionally, they feature higher overall efficiencies under partial load operation and thus offer superior electrical efficiencies and higher carbon savings. Figure 3 presents the annual CO_2 savings for various dwelling types in relation to the total μ-CHP efficiency [16]. Note that the total amount of electricity that can be displaced becomes lower as the reduction in space heating demands reduces the engine's potential running time. More in detail, the change in the heating and electricity demand characteristics, namely the reduction in heat demand and increase in electrical power loads alters the PHR (1:5–1:3) of the three examined building types, moving the ratios away from that of the Stirling engine (1:2). Conversely, the PHR now closely matches those of the SOFC and the ICE μ-CHP units (1:3) which results in almost all of the electricity produced by these two units being used internally, displacing grid electricity.

The widespread commercialization of μ-CHP SOFC systems requires the matching of the core energy unit with building construction (e.g. thermal and electrical storage). Energy systems are primarily designed and manufactured as "single components" and are not optimized from the energy and end-user perspective. This does not allow for a holistic optimization of buildings and even less for the optimization of districts. New tendencies in construction go through lightweight buildings (e.g. steel skeleton buildings with dry wall systems) equipped with improved thermal insulation materials and systems. Thermal storage systems, accommodating the 24-hour day and seasonal cycles could be used to compensate energy demand variation. Forecasts on the growth of bioclimatic buildings in Europe suggest a great potential, since the advantages of the Distributed Storage concept could be combined with those of the Energy Distributed Generation concept (addressed via the eco-design Directive, Cogeneration Directive, the Bio fuels Directive, the Energy Services Directive , the Internal Market in Electricity Directive, the District Energy Initiative, etc).

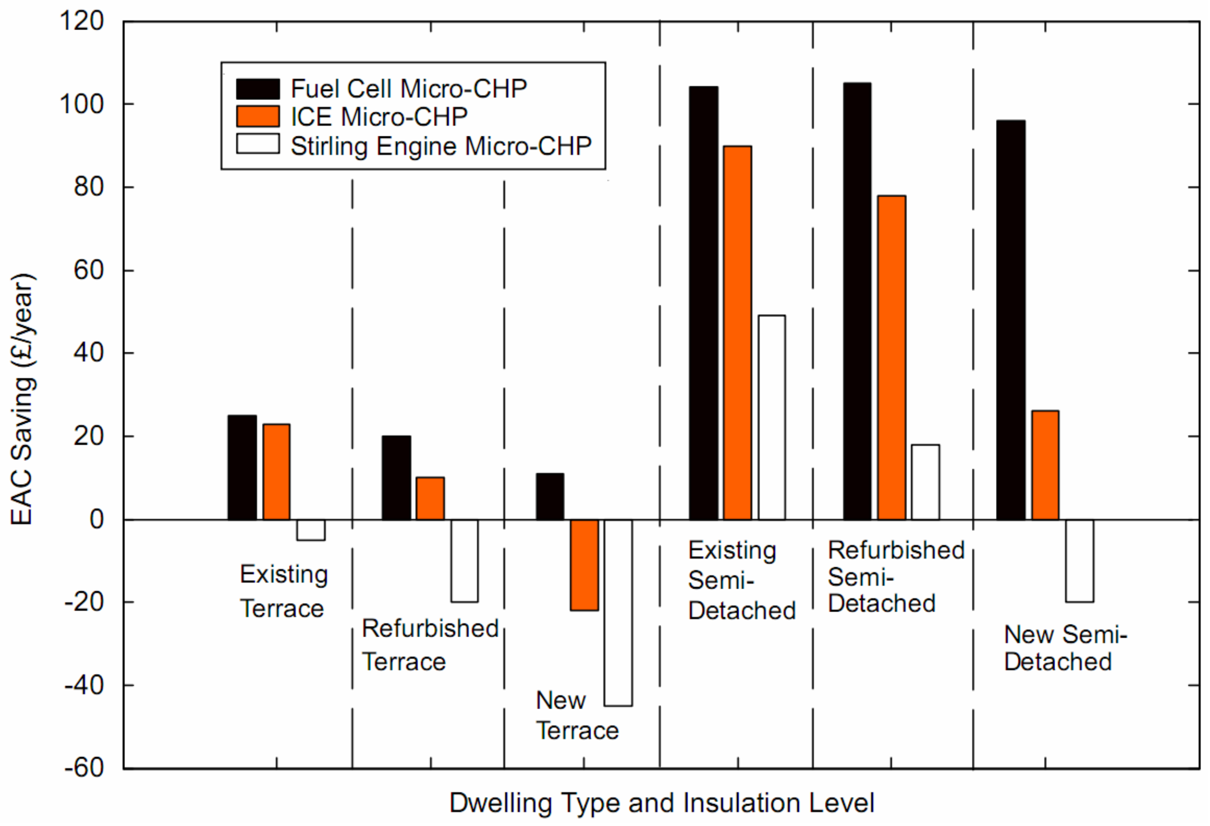

Figure 2: Equivalent annual cost (EAC) savings versus baseline (grid/boiler) for three μ-CHP technologies for terrace and semi-detached dwellings [5].

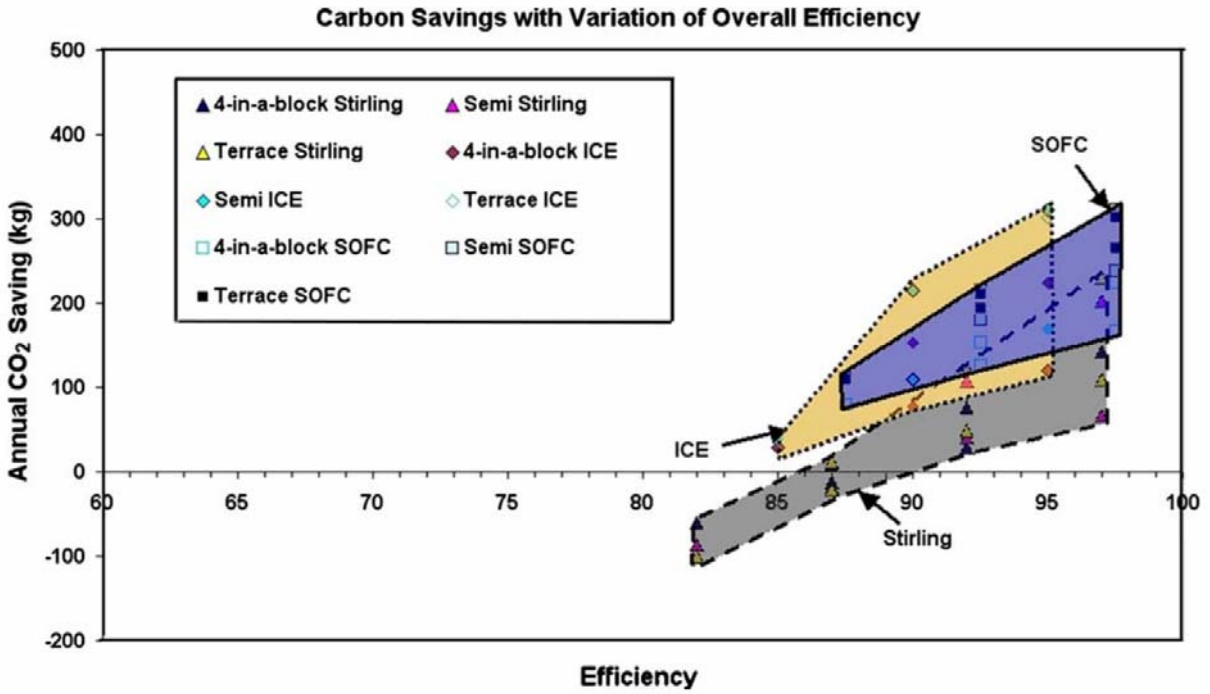

Figure 3. Efficiency vs CO_2 savings for alternative μ-CHP technologies [16].

However, current practices do not address an integrated approach that combines building design with energy production and storage systems, which could adapt their performance to the climatic conditions and energy demand of the building. The combination of μ-CHP energy system operation with active thermal storage (heat and cooling) either centrally or within the building elements is believed to create an impact in the European construction sector. The building will act as an active "heat hub" exchanging heat with neighbouring buildings. The "integrated energy system" will enable circulation of the thermal energy within the building through space and time responding to load variations and taking advantage of this energy that otherwise would be wasted. Such a development comprises thermal storage units together with pumps and controls. These technologies, when integrated with a μ-CHP appliance, face similar system needs-reliability, flexibility, affordability, etc. Developments in energy storage, cooling, controls, and integration methodologies will enhance the performance and operation of μ-CHP appliances enabling the user (or energy manager) to optimally run the power unit. De-coupling of heat and power will offer significant benefits in terms of matching power production either to the electrical demand within the building, or to the grid as a whole. A control strategy is needed to formulate the basic relation between household energy demand on the one hand, and generation of heat and electricity on the other hand. The main distinction is between following demand of heat (heat driven operation) versus following demand of electricity (electricity driven operation). In the former case, there will be either a shortage or an excess of electricity generated compared to the household demand for electricity. The shortage will be automatically met by importing from the grid. In case of excess electricity there are a number of alternatives: feed-in to the grid, store through a coil in the heat buffer, or store in a battery. When, the heat buffer or the battery is full, further excess electricity will be fed into the grid. Eventually, the reduction of total energy demand will reduce end users energy consumption.

3. Unit integration at district level

Appropriate district definition is crucial for the integration of individual units at building level into an overall energy system at district level and should be based on the evaluation of a number of urban and technical characteristics, most prominent of which are each building's and district's cumulative thermal and electrical load profiles. The sizing of the CHP units is then performed on the basis of the total energy amount needed and not on the peak energy demand. Load profile peaks can be smoothed through the use of previously stored energy within the district's boundaries. This kind of integration strategy would take advantage of the complementary nature of load profiles of different buildings in the district.

The electrical integration of fuel cell units has been previously studied [17] and can be generally realized through the establishment of a micro-grid system. The innovation of the proposed concept lies in the development of a district thermal network that would also comprise the in-building thermal storage systems and that it would be able to interact on line with the district electrical grid.

In order to incorporate a residential cogeneration unit in a Virtual Power Plant (VPP) network, advanced control models and operation strategies have been identified [18]: (a) The direct control model, in which the individual units are controlled remotely by the ESCO, who decides how much power a unit provides, dependent on the status of heat buffers, the expected heat demand, and expected electricity prices in the coming hours. (b) The indirect control model, where the individual units are controlled by software agents, which bid on a virtual real time market organised by the VPP co-ordinating ESCO. The biddings are dependant as in the former case.

4. Case study

In order to quantify the expected energy saving potential of the innovative concept, a relevant case study has been performed. The energy demand scenario considered in all calculations was based on domestic hourly heat and power load profiles taken from the literature [19], accounting for typical winter and summer days in the UK. Two energy supply scenarios are studied: (a) a standard case with grid electricity supply and gas boiler (Fig. 4) and (b) the district energy production/distribution concept (Fig. 5). The latter involves an independent and self sufficient district heat network, where all annual heat required within a district (of "n" dwellings) is provided by a "swarm" of μ-CHP SOFC units.

The calculation of the Annual Primary Energy Demand (APED) for both cases (1) requires the definition of the annual heat and electricity demand of the single dwelling. For the Standard case:

$$APED^{SC}(\text{MWh nat.gas/year}) = n^{D} \cdot (PED^{SC\_w\_el} + PED^{SC\_w\_th} + PED^{SC\_s\_el} + PED^{SC\_s\_th}) \quad (1)$$

Where: n^{D}: number of dwellings, SC: Standard case, w: winter, s: summer, el: electric and th: thermal.

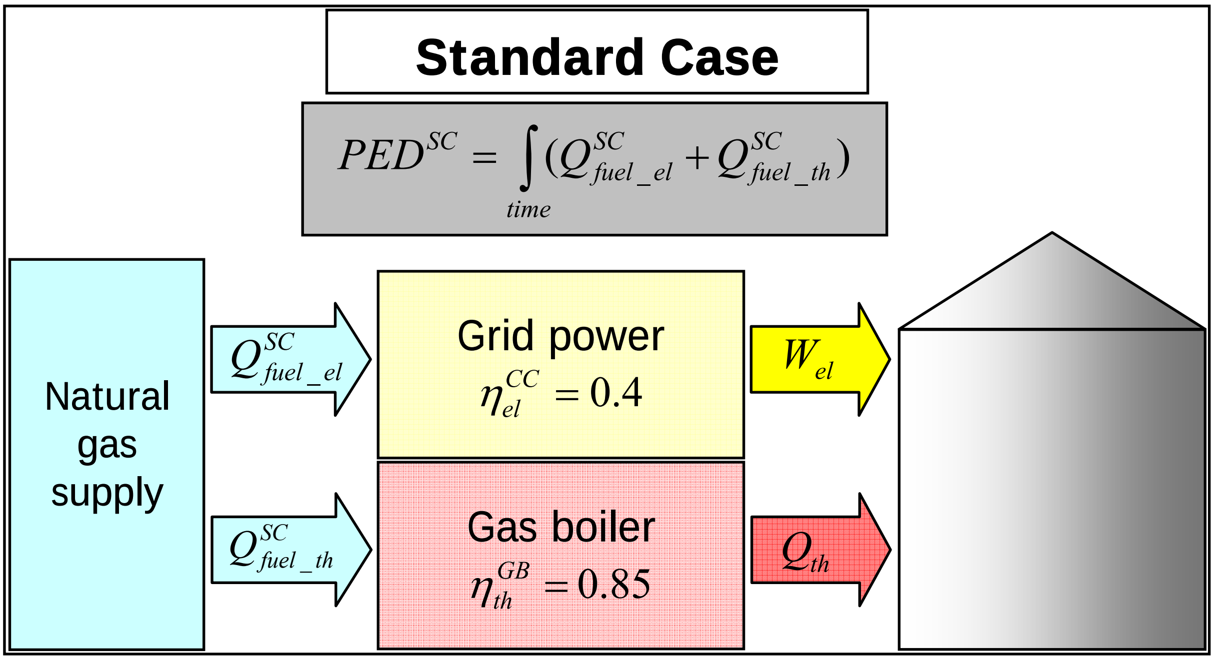

Figure 4. Standard energy supply case (PEDSC: Primary Energy Demand for Standard Case)

According to the assumptions presented in Fig. 4, the standard case PED is derived from (2) and (3) (the summer PED is accordingly calculated):

$$PED^{SC\_w\_el} = \frac{6 \cdot 30 \cdot \sum_{1}^{24} P^{el\_w}}{1000 \cdot \eta^{CC}_{el}}, \qquad (2)$$

$$PED^{SC\_w\_th} = \frac{6 \cdot 30 \cdot \sum_{1}^{24} P^{th\_w}}{1000 \cdot \eta^{GB}_{th}}, \qquad (3)$$

where the electric efficiency refers to combined cycle generation and the thermal to a domestic gas boiler. The corresponding CO_2 emission factors [20] considered are: 0.508 $kgCO_2/kWh_{el}$ and 0.239 $kgCO_2/kWh_{th}$.

Regarding the μ-CHP case, a simple operational strategy has been modelled, assuming a 24h nominal capacity operation of the SOFC units (assuming high and low electric efficiencies, technical data in Table 1), which covers the daily district thermal demand, plus a heat reserve of 15% (network heat losses). The number of units required is calculated considering full coverage of the winter district heat load, plus the heat reserve:

$$n^{CHP\_w} > 1.15 \cdot \frac{n_D \cdot \sum_{1}^{24} P^{th\_w}}{24 \cdot \dot{Q}^{CHP}_{th}}. \qquad (4)$$

The (lower) number of units covering the summer heat load is calculated correspondingly. The surplus of the steady heat output of the SOFC units is stored in a central heat buffer during night and used the next day to cover peak thermal loads. Competitive μ-CHP technologies were also considered [21] (Table 1), following the same operational strategy and covering the same annual heat demand.

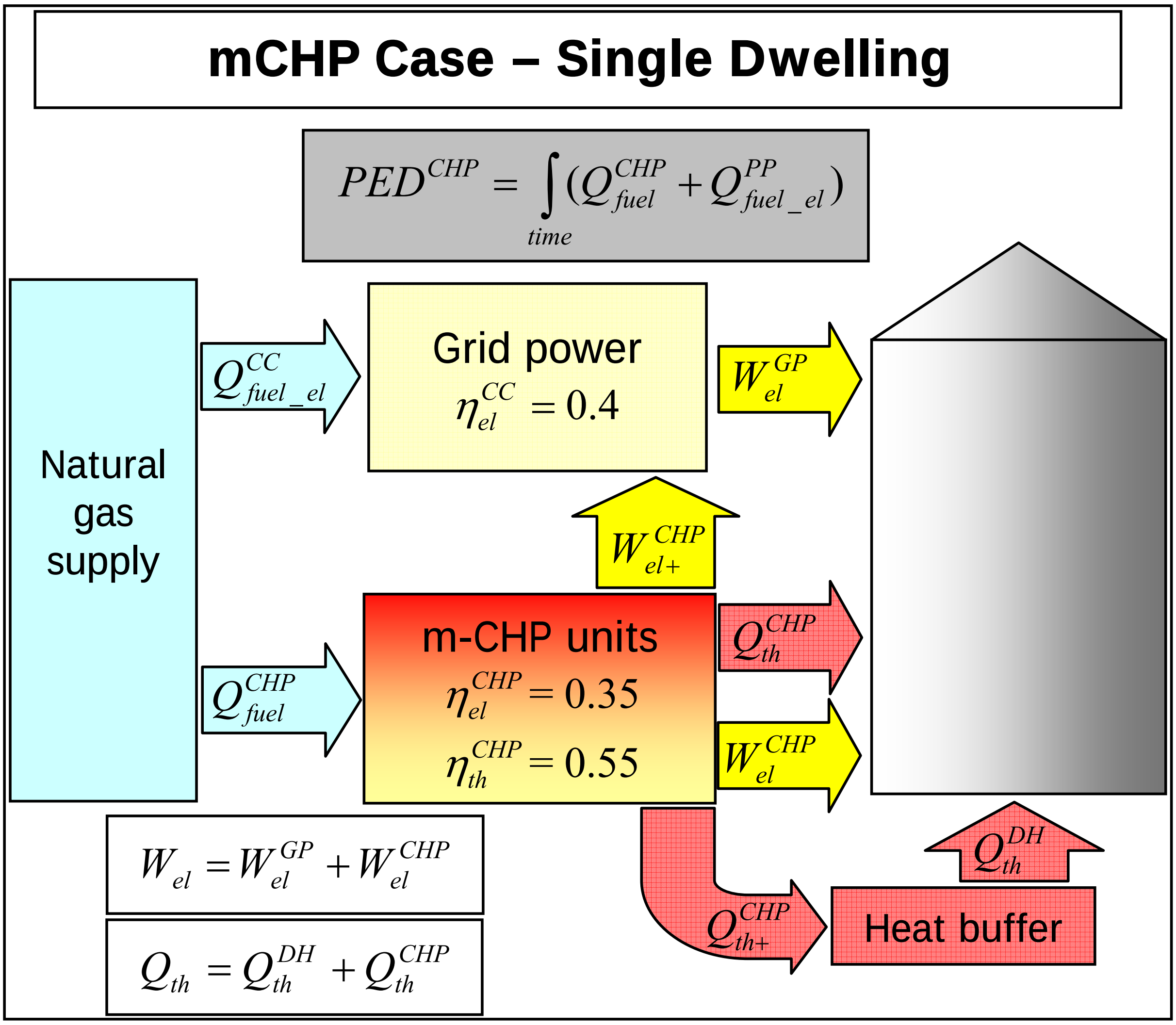

Figure 5. μ-CHP energy supply case (PED^{CHP}: Primary Energy Demand for CHP case).

Table 1. Technical characteristics of examined μ-CHP systems [21]

	μ-CHP System				
	SOFC		Stirling engine	I.C. Engine	Micro-turbine
Manufacturer	(Literature data)		Stirling Systems	Senertec	Capstone
η^{CHP}_{el} (%)	25%	35%	20%	27%	26%
η^{CHP}_{th} (%)	65%	55%	70%	61%	59%
Power to Heat Ratio (PHR)	0.38	0.64	0.29	0.44	0.44
Nominal thermal output $\dot{Q}^{CHP}_{th}$ (kW_{th})	5.2	3.1	4.67	12.4	67.8
Nominal electric output $\dot{W}^{CHP}_{el}$ (kW_{el})	2.0		1.33	5.5	30.0

The annual electricity production from the systems considered is expected to differ, according to the corresponding PHRs. In correspondence to (2) and (3), the primary energy demand of the μ-CHP case is calculated as follows:

$$APED^{CHP}(MWh_{NG}/year) = n_D \cdot (PED^{CHP\_w} + PED^{CHP\_s} - PED^{G\_w} - PED^{G\_s}), \qquad (5)$$

where

$$PED^{CHP\_w} = \frac{6 \cdot 30 \cdot 24 \cdot n^{CHP\_w} \cdot \dot{Q}_{th}^{CHP}}{1000 \cdot \eta_{th}^{CHP}}. \quad (6)$$

The amount of primary energy saved (if PED^{G_w} is positive) or consumed (if PED^{G_w} is negative) due to electricity exports or imports is calculated by (7):

$$PED^{G\_w} = \frac{6 \cdot 30 \cdot \left(24 \cdot n^{CHP\_w} \cdot \dot{W}_{el}^{CHP} - \sum_{1}^{24} P^{el\_w} \right)}{1000 \cdot \eta_{el}^{CC}}. \quad (7)$$

The summer season case is accordingly calculated. Regarding the CO_2 emission factors of the μ-CHP systems, a value of 0.208 kgCO_2 per kWh of natural gas consumed [20] is considered.

The results of the APED and the relevant annual CO_2 emissions for a number of 100 dwellings are presented in Table 2 and Figs. 6 and 7. The overview shows the direct correlation of the APED and the CO_2 reduction to the PHR of the systems considered.

Table 2. Primary energy demand and CO_2 emissions reduction for alternative μ-CHP systems

		m-CHP systems					**Standard Case**	
		SOFC		Stirling engine	I.C. engine	Micro-turbine		
		η_{el}^{CHP}						
		25%	35%					
PED^{CHP_w}	MWh_{NG}/ (winter or summer)	4838.4	5697.7	4393.1	5181.2	5460.8	PED^{SC_el}	1606.5
PED^{CHP_s}		345.6	389.6	316.8	351.3	496.4		
PED^{G_w}		2218.5	4248.9	1440.3	2699.1	2758.5	PED^{SC_th}	3409.4
PED^{G_s}		-585.0	-455.4	-642.6	-563.4	-477		
APED	MWh_{NG}/ year	3550.5	2293.8	4012.2	3396.7	3675.7	5015.9	
Annual reduction potential	%	29.2%	54.3%	20.0%	32.3%	26.7%	-	
Annual CO_2 emissions	Tonnes CO_2/year	720.8	465.6	814.5	689.5	746.2	1018.2	
Annual CO_2 emissions reduction		297.4	552.6	203.7	328.7	272.0	-	

Despite the fact that a high PHR is associated to low thermal efficiency (thus higher energy demand due to NG consumption for cogeneration – see line PED^{CHP_w} of Table 2), it also provides higher exports to the grid (line PED^{G_w}), resulting in indirect primary energy reduction due to avoiding central generation (Fig. 6).

A district heat and electricity network heated and powered by SOFCs (Figure 7) can reduce the Annual Primary Energy Demand (APED) more than 50%, by saving 2.72 GWh primary energy every year, otherwise used for grid electricity production (for a district of 100 dwellings).

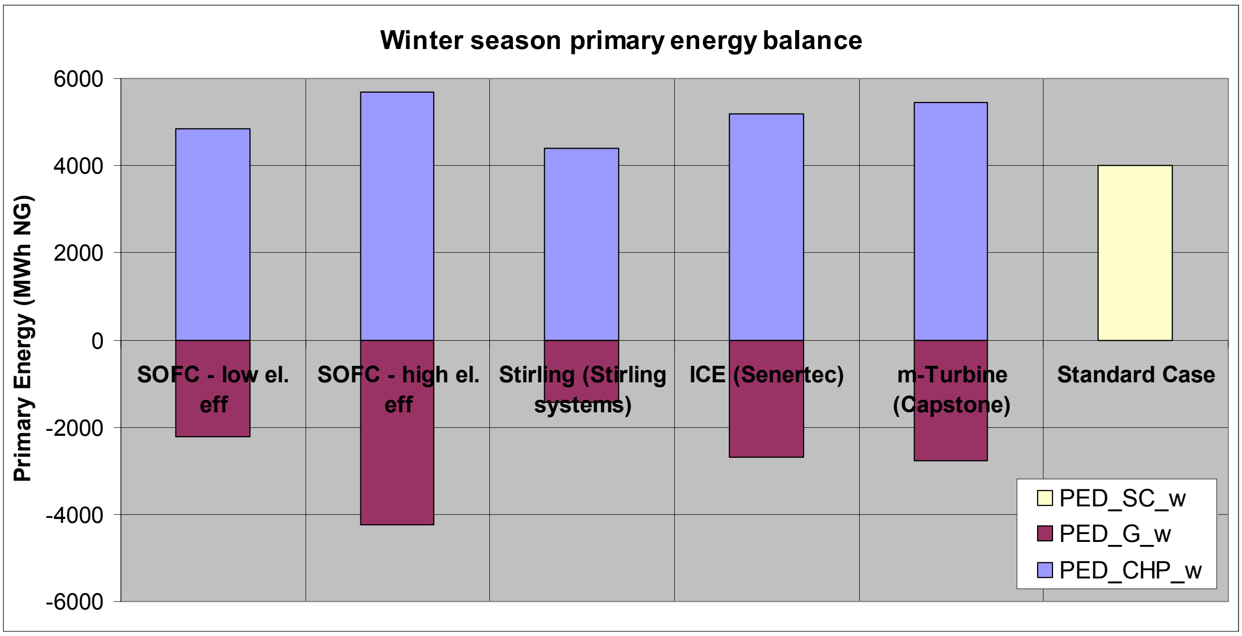

Figure 6. Annual primary energy demand and CO_2 reduction of m-CHP systems

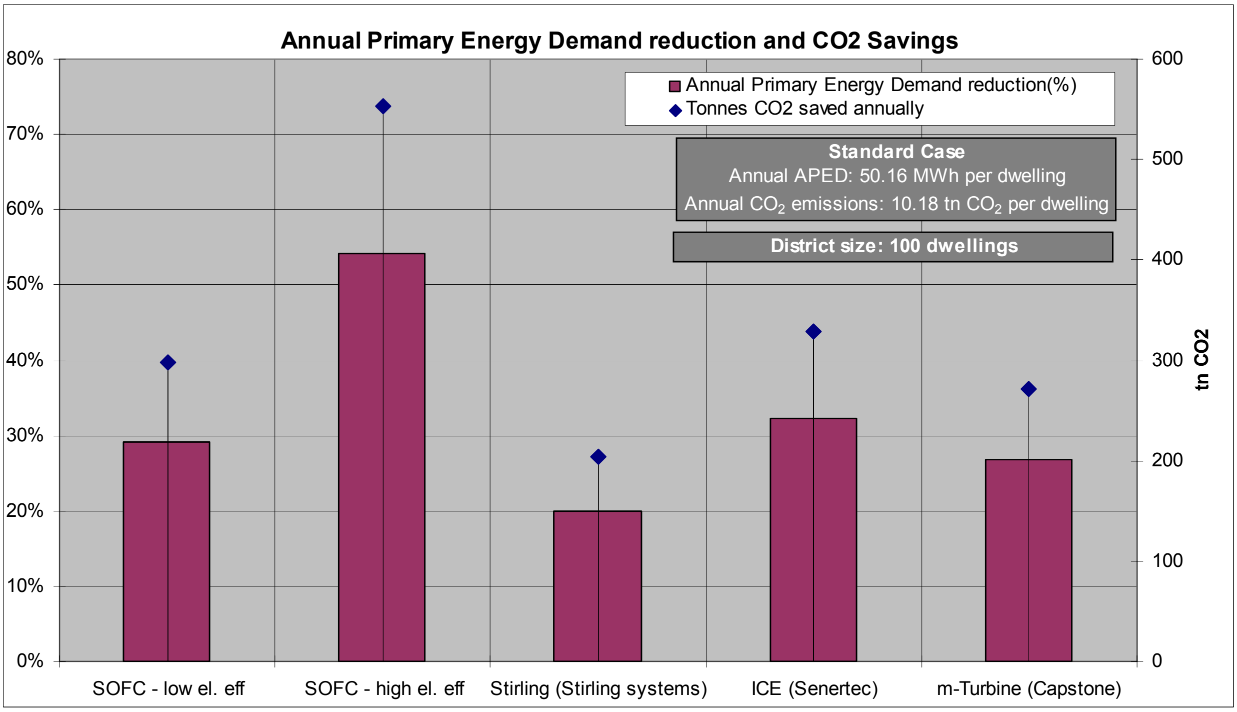

Figure 7. Winter season - primary energy balance. SC vs alternative μ-CHP systems

The prevalent position of the SOFCs is explained by the higher power to heat ratio, which provides from 45% to 120% more electricity for each kWh_{th} produced when compared to the other μ-CHP systems. The potential adoption of the SOFC technology for the innovative concept presented is fully supported, since a remarkably higher energy and carbon saving potential is identified. These findings are also supported by relevant literature results [20], where it is argued that since all μ-CHP technologies have more or less the same overall efficiencies (85-90%), it is the Power to Heat ratio that will primarily determine the level of carbon savings.

5. Conclusions

An innovative energy production and distribution concept for sustainable and energy efficient districts exploiting decentralized co-generation coupled with optimized building and district heat storage and distribution networks has been presented. The concept is based on dynamic heat exchange between the building(s) (fitted with SOFCs, for energy production, collaborating with improved building thermal storage systems), the distribution system (optimized piping and district heating with or without a heat buffer) and the consumer (new business and service models), aiming to achieve energy balance at district level.

A simplified test case for a virtual district of 100 dwellings, based on domestic hourly heat and power load profiles, has been examined. It has been shown that, for the specific case, a district heat and electricity network heated and powered by SOFCs can reduce the Annual Primary Energy Demand more than 50%, by saving 2.72 GWh primary energy every year, otherwise used for grid electricity production. Further reductions could be anticipated at district level when the building typology and construction characteristics, the corresponding heat and load profiles and the local and district level thermal storage characteristics are taken into account.

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