An evaluation of energy saving potentials for districts served by distributed Stirling m-CHP units

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Abstract

Achieving sustainable development in the energy sector in general and in building energy consumption in particular, requires the reduction of non-renewable primary energy input and greenhouse gas emissions. One possible developmental path is decentralization of the electricity system. The paper presents the results of an energy balance study for an innovative energy management concept for districts. According to this concept, the buildings in a district are interconnected by thermal and electric micro-grids. Heat and power are produced within district limits by a “swarm” of centrally controlled micro-CHP Stirling engines. The balance between district energy production and demand is maintained by power imports/exports to the central grid and appropriate back-up boilers.

The performance of the “micro-CHP” case (gas boilers and Stirling units/back-up gas boilers) is compared to a conventional “Reference” case (individual gas boiler per building). In order to acquire realistic energy (heat) balance data, a detailed energy demand and supply simulation at district level has be performed on an hourly basis. Two district types have been considered: Residential (including Single Family Houses - SFHs) and Financial Center (including office buildings and hotels). Each district features a different heat demand profile: The residential load fluctuates intensively, while the financial district features a smoother heat load profile, with heat demand even in summer months and with a higher total thermal energy demand.

The in-house developed, Matlab based, DEPOSIT software has been utilized in the present work. The importance of heat-led control is shown, especially under fluctuating demand. A clear Primary Energy Consumption (PEC) reduction potential has been identified for all cases examined, ranging from 6% up to 35%.

Nomenclature

- B_i: building width [m]
- D_i=pipe diameter [m] for segment i
- D_{hydr}=hydraulic diameter of the pipe [m]
- f_D= Darcy-Weisbach friction factor [ ]
- g= gravitational acceleration [m/sec2]
- h= head loss [m]
- L = length of the pipe [m]
- L_i: building length [m]
- m=flowrate at maximum flow [kg/sec]
- q : heat loss or gain per unit length of system [W/m]
- Re=Reynolds number
- R_{total} : total thermal resistance of the pipe including a soil layer [(m•K)/W]

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- t_f : fluid temperature [°C]
- TPL= target pressure loss at maximum flowrate [Pa/m]
- t_{si} : soil temperature at timestep (= hour) i [°C] [17]
- v=average velocity of the fuel flow [m/sec]
- ε=pipe roughness height [m)]

1. Introduction

Achieving sustainable development in the energy sector in general and in building energy consumption in particular, requires the reduction of non-renewable primary energy input and greenhouse gas emissions. One possible developmental path is decentralization of the electricity system. Distributed power generation in small, decentralized units is expected to help reducing emissions and saving grid capacity, providing also opportunities for renewable energy [1].

Recent technological advances have led to an increased interest in small CHP units, with the prospects of developing units that can provide electricity and heat for individual buildings (fig. 1). Micro cogeneration (micro CHP or mCHP) is defined as the simultaneous generation of heat, or cooling energy and power in an individual building, based on small energy conversion units below 15 kWel. Whereas the heat produced is used for space and water heating/cooling inside the building, the electricity produced is used within the building or fed into the public grid.

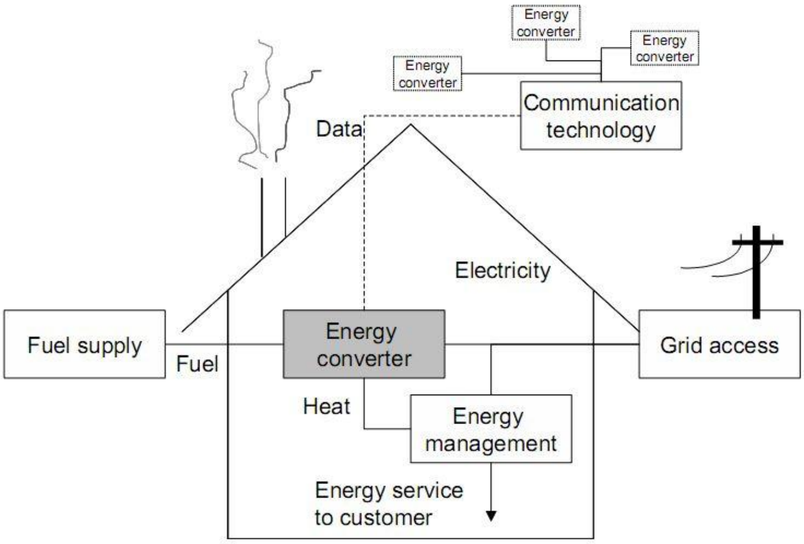

Fig. 1: Main components of a micro cogeneration system [1].

Relevant technical assessment studies focus on the primary energy savings achieved by the operation of small Internal Combustion Engines [2,3] and Solid Oxide Fuel Cells (SOFCs) [4,5]. The corresponding performance of a Stirling engine mCHP system has been examined by Alanne et. al. [6], both in terms of energy and cost savings.

The present work utilizes an in-house developed simulation and tool (DEPOSIT) in order to assess the energetic performance of an innovative energy management concept for districts developed and assessed within the framework of the EU funded FC-District research project (www.fc-district.eu). According to this concept, the buildings in a district are interconnected by thermal and electric micro-grids. Heat and power are produced within district limits by a “swarm” of centrally controlled mCHP Stirling units. The balance between district energy production and demand is maintained by power imports/exports to the central grid and backup boilers. For evaluation purposes, the results are compared to the energetic performance of a conventional case.

The paper is structured in the following sections: (a) Description of the main points of the methodology followed; (b) Definition of the systems examined and presentation of assumptions and assessment scenarios regarding district thermal demand, efficiencies, electric and thermal output, etc.; (c) Results referring to the energy management concept annual performance, the comparison with the conventional reference case and the comparison to alternative operation strategies and (d) Conclusions regarding the energetic performance of the systems examined and the comparisons considered.

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2. District level energy simulation methodology

In order to acquire realistic energy (heat) balance data, a detailed energy demand and supply simulation in district level was performed on an hourly basis. The main features of the simulation approach are presented in fig. 2. The in-house developed, Matlab based, DEPOSIT software has been utilized in the present work. The tool performs an hourly based numerical simulation of the district, the piping, and its heating and power generation units. It calculates the total district heat demand, including piping heat losses and pressure losses (pumping power). Various operating scenarios can be simulated for the CHP units, depending on the overall target: primary energy minimization, cost optimization, maximum CHP operating hours.

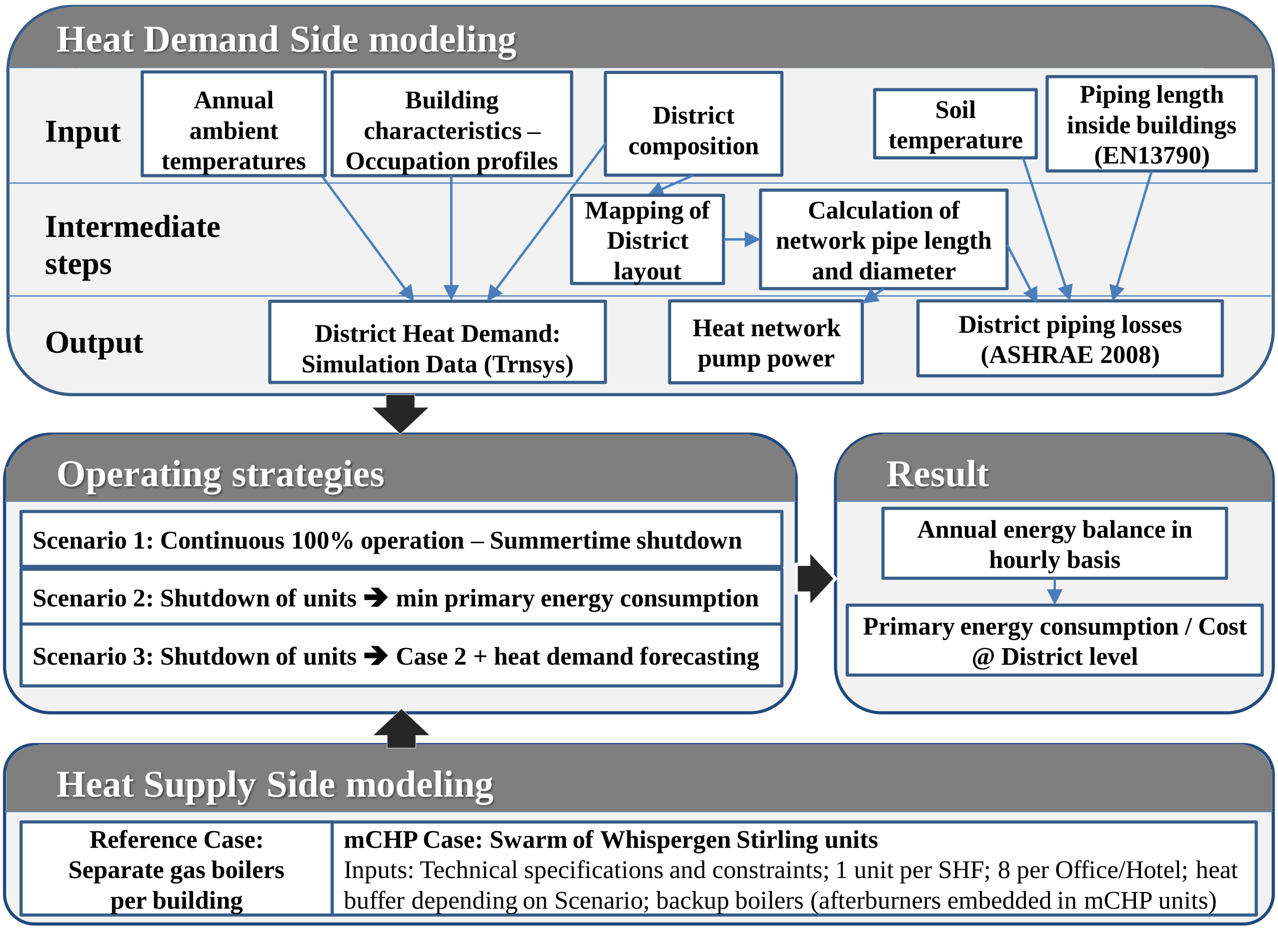

Fig. 2: Overall scheme of the simulation methodology

2.1 Heat Demand Side modelling

The modelling provides the heat required to cover the space heating needs of the buildings in 0.25 km2 of the district considered, plus piping losses. Calculations are performed in an hourly basis for one year. The hourly district heat demand is provided by the component-based, transient thermal and electrical energy simulation platform (Trnsys v. 17.01) [8], which requires as input specific data regarding district composition, building characteristics and climatic data (fig. 3). The simulated Reference Case does not consider network piping losses and is associated only with internal pipes, since there is no pipe network interconnecting the district buildings. On the other hand, the mCHP interconnected district case takes into account both internal and external pipe losses. The data input requirements for the hourly calculation of piping losses include the corresponding pipe length and diameter (internal and external – if needed), assumptions regarding thermal conductivity and soil temperature. A necessary assumption is that the water in the district heat network is kept at 80°C (max) throughout the year. During long shut down times (summer) the network cools down and is reheated at the start of the heating season.

The number of buildings of each type in each of the two districts examined is entered. The algorithm places the buildings automatically in building blocks and determines the number of loops and the buildings served by each loop. The network is divided into main sections and to street loops. The main sections deliver hot water to the secondary (street) loops. Each street loop is connected with buildings and their cogeneration units at both sides of the street, ie the half block on its right and the half block on its left (fig. 3).

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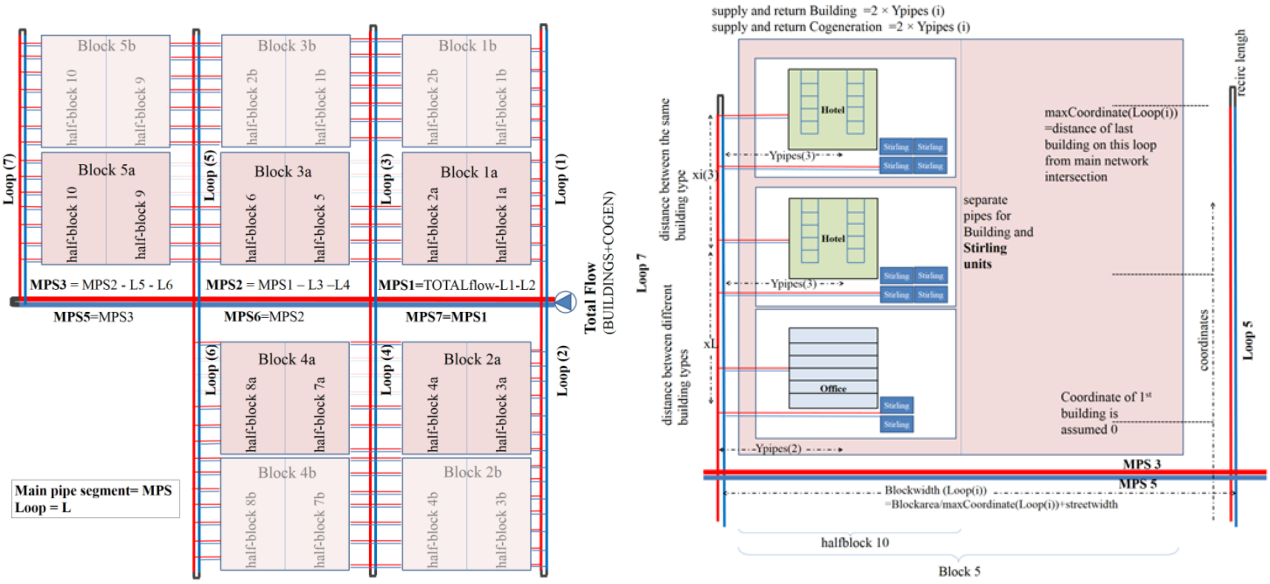

Fig. 3: Mapping of district layout (left: general layout; right: example of financial district - building block detail)

The length of each street loop depends on the distance between each building type and between different building types as entered by the user. The floor to space ratio is used for determining the site area of each building type. The floor to space ratio is assumed to be higher in the financial sector. The created water network consists of main pipe segments , that deliver hot water to the street loops which deliver water to each building and its cogeneration units (via separate pipes).The building blocks are assumed to be 90m x 70m. The algorithm dimensions the piping network based on the maximum target pressure loss set by the user for the peak heat demand [7]: $D_i = \sqrt[5]{\dfrac{8 \cdot f_{D,i} \cdot \dot{m}_{i,\max}}{\dfrac{P_i}{L_i} \cdot \rho \cdot \pi^2}} = \sqrt[5]{\dfrac{8 \cdot f_{D,i} \cdot \dot{m}_{i,\max}}{TPL \cdot \rho \cdot \pi^2}}$

The pipe characteristics are used for calculating the pressure drop amongst the various routes at each timestep. Pump consumption is calculated to include pump electricity primary energy consumption in the comparison. Local losses are assumed to increase linear pressure losses by 10%. Detailed calculation of local losses of a fictitious network would be very challenging.

Head loss can be calculated with the Darcy-Weisbach equation: $h_f = f_D \cdot \dfrac{L}{D_{hydr}} \cdot \dfrac{v^2}{2g}$ (1)

Swamee Jain equation is used to directly solve the Colebrook equation to find the friction factor for turbulent flow:

$$f_D = \frac{0.25}{(\log_{10}(\frac{\varepsilon}{3.7 \cdot D} + \frac{5.74}{\mathrm{Re}^{0.9}}))^2} \tag{2}$$

Tables 1 and 2 contain the main data inputs and assumptions needed for the calculation of the hourly district heat demand provided by Trnsys v17.01 simulations. The required ambient temperatures for the Munich are acquired through the Trnsys databases.

Internal piping losses are provided by EN13790 [9], after calculating the pipe length:

$$L_V = 2 \times L_i + 0.01625 \times L_i \times B_i \tag{3}$$

External piping losses are calculated according to ASHRAE 2008 Handbook [10] $q = \dfrac{t_f - t_{si}}{R_{total}}$ (4)

with the soil temperature t_{si} calculated by the Kasuda correlation [11]:

Table 1: Description of considered buildings

Building Description

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SFH (Single Family House)	Two-storey house without basement. North-South orientation (east-west main axis). Floor area of each level: 70 m². Total living area: 144 m². The Area-to-Volume ratio: 0,66. Occupancy profile: four-member family
Office building	Floor area: 1900m². Divided into 4 main thermal zones: a) Offices b) Conference rooms c) Corridors / auxiliary rooms d) Cafeteria / restaurant Occupancy profiles, internal loads (equipment and lighting) defined according to the Greek Regulation of Energy Efficiency in Buildings [12].
Hotel	Floor area: 3800m². Divided into 5 main thermal zones: a) Public spaces such as corridors, lobby , reception b) Conference rooms c) Restaurant d) Kitchen e) Guest rooms Occupancy profiles, internal loads (equipment and lighting) defined according to the Greek Regulation of Energy Efficiency in Buildings [12].

Table 2: Composition of considered districts (district area: 0.25km^2)

City	Munich, Germany		
District Type		Residential	Financial Center
Number of SFHs (Single Family Houses)	High insulated	100	0
	Low insulated	400	0
Number of Offices	High insulated	0	60
	Low insulated	0	15
Number of Hotels	High insulated	0	24
	Low insulated	0	11
Districts created by the algorithm	District dimensions	700m x 365m	705m x 360m
	Street Loops	20	20
	Block area	6300 m²	6300 m²
	Number of blocks	35	36
	Total Area	255500 m²	253800 m²
Distance between Buildings of the same type in the same loop (X_i)	SFH	14m	
	Offices		43m
	Hotels		90m
Distance between Buildings of a different type in the same loop (X_L)		60m	60m
Distance between street loop pipe and buildings heat exchanger/basement		16m	22m

2.2 Heat Supply Side modelling

In this methodological stage, the systems that provide the required heat to the district are modelled. Separate gas boilers, installed in each building of the district, are considered as the Reference Case for fulfilling the district heat

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needs. The modelling of the mCHP case requires the simulation of: (a) the number of Whispergen units to be installed; (b) basic technical constrains (such as max-min heat output, how fast they respond to load variations (ramp rate – kWh/min, partial load behaviour)) and (c) the Power-to-Heat Ratio (PHR). The simulated district served by mCHPs also includes heat storage tanks; required input data includes tank geometry, heat conductivity and the temperature outside the tank. Due to the constraints relating to available indoor space, the installed number of units had to be limited. Overall, due to these restrictions, the total heat output of the all the mCHP units is not enough to cover the entire district demand, thus a number of backup boilers is required and installed.

Table 4 presents the main assumptions needed for modelling heat supply to the district for both examined cases. Reference boilers are assumed to have 75% average yearly efficiency, while backup boilers have 80% average efficiency. (efficiency includes oversizing and ramping losses). The eHe units have 11.4% electric and 88% thermal efficiency (accounting for Lower Heating Value). The technical constrains of the Stirling mCHP unit include maximum / minimum thermal output (7.4 and 0 kW, respectively, with no modulation) and the time from hot start to maximum thermal and electrical output is 16-19min . The mCHP units are operating at an on-off basis with not heat modulation. Units are not allowed to be shut down more than 10 times per 24h. Storage losses are calculated by adapting the equation of the piping losses (Eq. 4).

Table 2: Main assumptions for heat supply modelling

Case	Reference		mCHP		
District Type	Residential	Financial Center	Residential	Financial Center	
Number of Gas boilers/Stirling units	1 Gas boiler per SFH able to cover peak demand	1 Gas boiler per Office/Hotel able to cover peak demand	1 eHe Stirling unit per SFH (=500 units in 0.25km^2 of district). No of backup boilers determined by the heat required to cover the peak demand.	8 eHe Stirling units per Office/Hotel (=880 units in 0.25km^2 of district). No of backup boilers determined by the heat required to cover the peak demand.	
Storage size	-		Depending on operating scenario 0-250l per eHe unit	Scenario 2 and 3	1x1000l per ehe Unit
				Scenario 1 , (Scenario 3 with 16 units per building)	2x1000l per ehe unit

2.3 Operating strategies

In the Reference Case, the gas boilers are simply assumed to have the ability to modulate instantly to any demand. In the mCHP case, the coupling between district heat demand and supply is performed through alternative operating strategies of the mCHP units. The present work considers three types of mCHP “swarm” operation (fig. 2):

(a) Scenario 1: Stable (at full output with a shutdown summer period).

In this scenario all Stirling units are operated at full power. In this scenario the stirling micro CHP units operate continuously at 7.4kw thermal and 1 kw (0.97) electric output. Excess heat is stored in the buffer tanks. If the thermal demand exceeds the thermal output, the storage tank is checked if heat is available. The remaining demand after the buffer tank contribution is covered by backup boilers in the district. The eHe units’ auxiliary burner could serve for this purpose. Units shut down only in the summer period and there is a possibility of a different shut down period for each of the 3 possible unit groups, so that we can adapt more to the actual level of thermal demand.

(b) Scenario 2: Intermittent mCHP operation (allowing individual control of the Stirling units with shutdowns according to achieving the minimum primary energy during each timestep).

In this scenario more cogeneration units can be used since they can be shut down if demand is too low. Units can be divided into 3 main groups. The first two groups can be switched on and off simultaneously with no option of individual control. The third group can individually control its units. Units can be shut down with a 10% resolution. If the demand is very low, resolution increases up to 1% of the units to follow the demand. In the current simulations are units are assigned to group 3.

The strategy in this scenario can be described as heat and primary energy following. Then the algorithm determines how many units shall operate at this timestep to avoid overproduction of heat. If demand is very high , all units will operate. At this combination of units in different statuses (starting, shutting down , or operating etc) the efficiencies are determined, the electric output and the thermal output is calculated and the primary energy is deducted according to the primary energy factor for electricity and natural gas (at this timestep or yearly average (depending on state policy)). The algorithm decides if it is environmentally benefitable to operate the units as chosen , or if it would rather shut them

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off and use buffer energy or backup boilers. It must be noted that,if the primary energy factors are constant, the algorithm will always chose as its first priority, the cogeneration units , due to the high primary energy factor of produced electricity. The remaining uncovered demand (if any) is covered first by the buffer tank and then by the backup boilers.

(c) Scenario 3: Intermittent mCHP operation with demand forecasting

The main disadvantage of scenarios 1 and 2 and all similar 'static' scenarios is that they operate according to the present timestep and chose the optimum operation in order to minimize a cost or a primary energy function. However if a period of time is seen as a whole the operations performed may not be ideal, because if for example excess heat was produced at a timestep with low demand , that excess heat would be used at the next timestep with very high demand , unable to be covered by m chp units. Thus , in 3rd scenario we implement forecasting. Heat demand for the following 6 timesteps is foreseen . Primary energy factor is also foreseen for the 7th timestep ahead. (if the primary energy factor is taken as constant , the result is constant). Matlab neural network toolbox is used for the forecasting, with parameters such as historical data (previous values), weather forecast data etc. Hovewer till this is ongoing work the results presented here are shown by simply using the future values of heatdemand and primary energy factor since they are available, and because the forevasting model is not yet verified.

The third scenario is very similar with the second scenario with the only difference (till the forecasting model is initiated) that depending on user control, storage contribution is supplied to the net before or after the m-chp units thermal output. After some hours when the algorithm has enough historical data to train the neural network, the heat demand of the next 6 hours and (if necessary the Primary energy factor of the 7th hour from the current timestep are available) are estimated. Afterwards Case3 uses a decision routine according to these nearly future values, which is depicted in Figure 4. The idea of this decision routine, is to cover the demand of the district (of a 7hour span) with the minimum possible primary energy consumption. So if the heat available in the buffer in addition to the minimum* heat that would be produced by the cogeneration units during this timesteps is enough to cover this and the next 6 hours, the units operate according to the second case described above. If the demand is predicted to be higher than the minimum outputs and the storage-heat available, then the primary energy factor evolution of electricity is checked. If it falls then it is environmentally more profitable to have now an overproduction of electricity (which leads to an overproduction of heat), than in the near future with a low electricity primary energy factor. Thus the units operate at a capacity to charge the storage as much as possible during the current timestep. On the other hand if primary energy factor (PEF) of electricity will rise , it is preferable to operate at the current timestep according to the current decision as described in Case2 and in the future the decision will be taken then.

** minimum output refers mainly to units which cannot be shut down often (eg. SOFC units)*

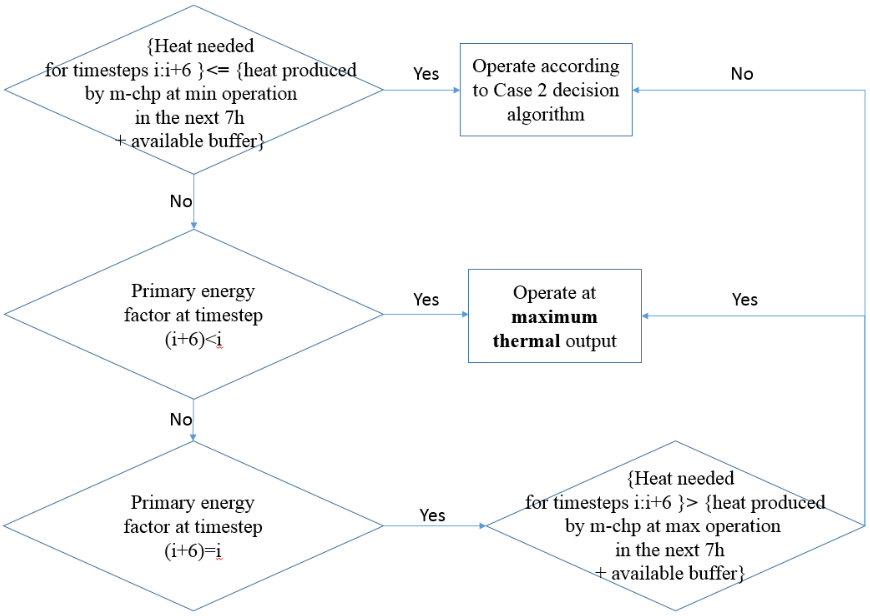

Fig. 4: Decision routine of forecasting methodology

The general priority rule regarding the three potential heat sources is: First utilize the heat stored in tanks and operate the mCHPs at the lowest possible output. At higher demands (or when there is no stored heat) the Stirling units work at higher output and finally, if that is not enough, the backup boilers cover the remaining heat load.

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3. Results - Discussion

The modelling of the operation of the studied concepts is presented in figures 5 and 6, by the respective qualitative Sankey diagrams.

As shown in fig. 6, heat produced by the mCHP "swarm" follows three possible directions: (a) to district demand; (b) to storage (if thermal overproduction occurs) or (c) discarded (if the storage temperature has reached a maximum point (80°C)). Accordingly, the district demand is covered by three heat sources: (a) from the storage tanks (considering the corresponding losses); (b) from the mCHP thermal production and (c) from the backup boilers.

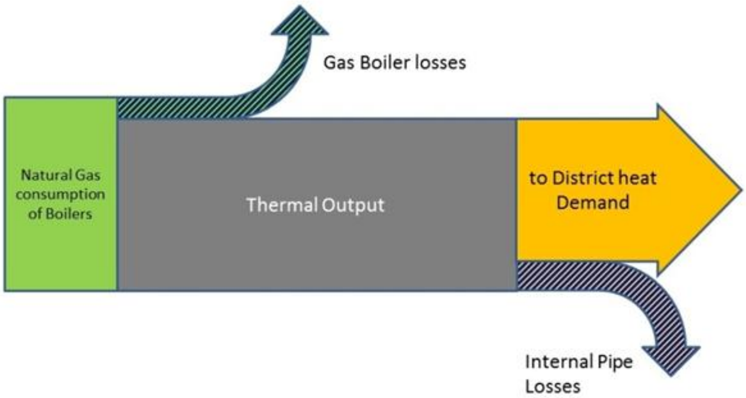

Fig. 5: Qualitative Sankey diagram of Reference Case study (Separate Gas Boilers)

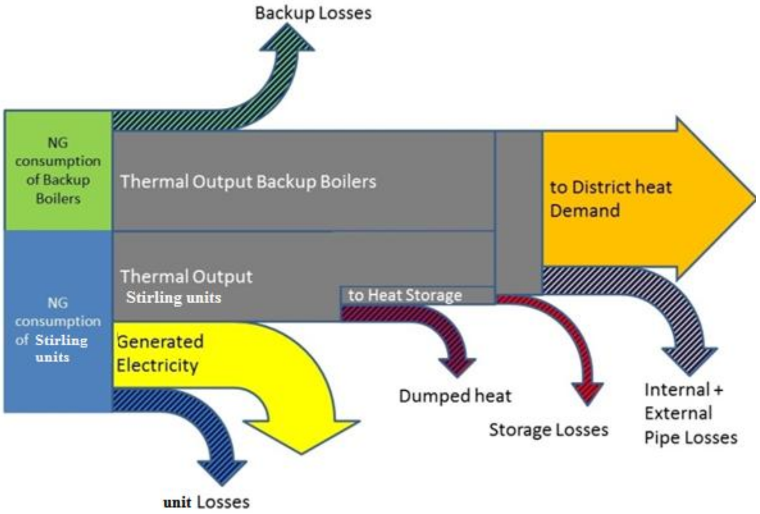

Fig. 6: Qualitative Sankey diagram of mCHP Case study (Stirling units, storage tanks and backup boilers)

3.1 Residential district

The result of the hourly simulation is shown in fig. 7 (a,b and c), for Scenarios 1, 2 and 3, respectively. Data have been sorted according to the level of heat demand. The mCHP operation covers the base loads, while backup boilers deal with the higher thermal demands. The contribution of the storage tanks is accordingly shown.

The Stirling units cover nearly 90% of the annual heat demand in all scenarios, while the heat buffer contribution is significant only under constant full operation, since there is high heat overproduction to be stored.

Figures 8 a, b and c present the annual energy balance for the residential district case. The comparison shows that the mCHP case requires more fuel energy to cover the same demand. Under full scale operation, a significant overconsumption of natural gas is identified (4 times the actual district heat demand), due to the fact that the mCHP units are actually uncontrolled. A side effect of the lack of controlled operation is the large amount of dumped heat. Scenarios 2 and 3 perform more or less the same as the reference case in energetic terms. The forecasting scenario seems slightly less efficient, due to the additional storage losses.

Scenarios 2 and 3 may be equivalent to the reference case as regards total energy consumption; however the electricity produced will enhance their performance in terms of Primary Energy Consumption (PEC). As shown in the relevant figures (9a, b, c), operation scenario 1 proves largely inefficient, requiring more than 80% more primary energy than the standard reference case. The positive effect of displacing grid electricity is decisive towards providing a PEC

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decrease in the order of 23-24%. The forecasting scenario proves less efficient than scenario 2, due to the additional storage losses and the constant primary energy factor for electricity.

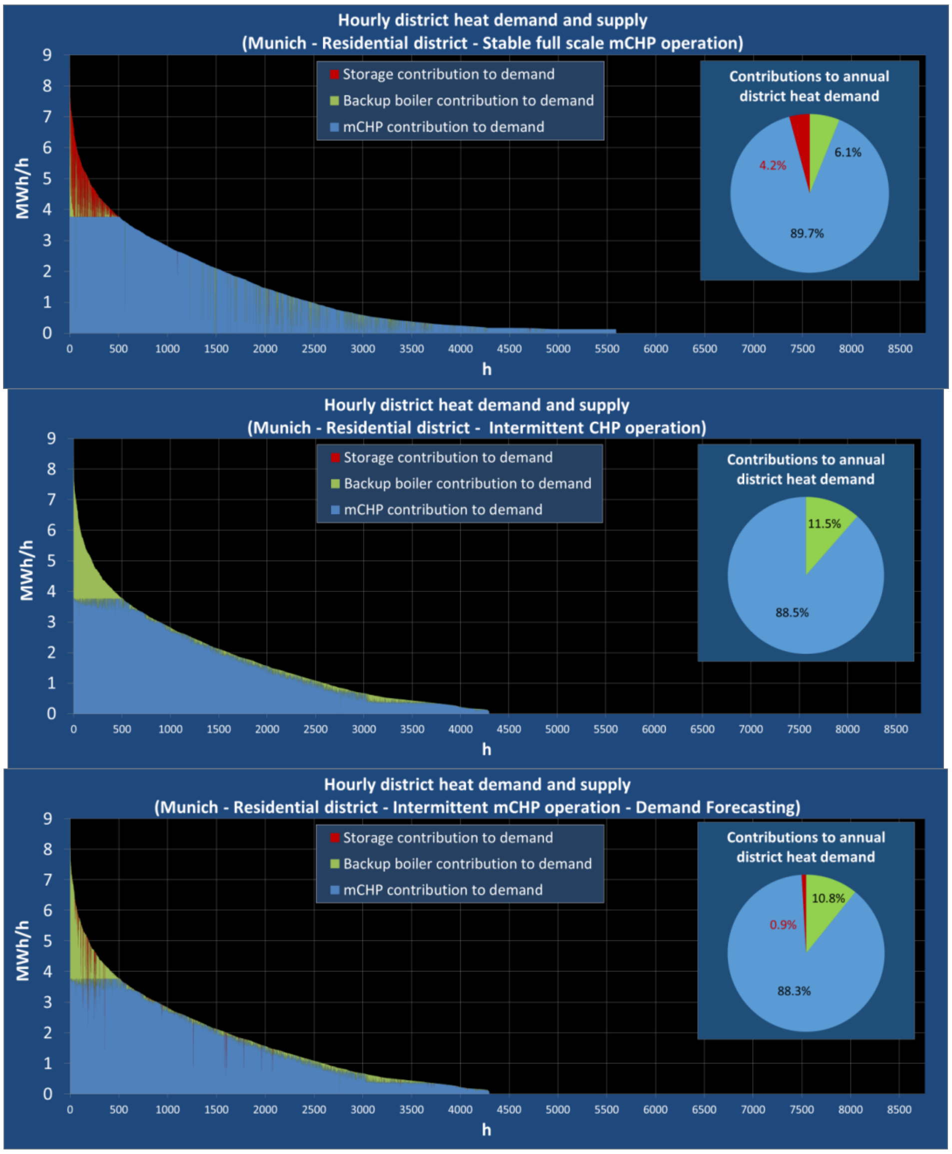

Fig. 7 a, b and c: Hourly residential district heat demand and supply for operation scenarios 1, 2 and 3, respectively.

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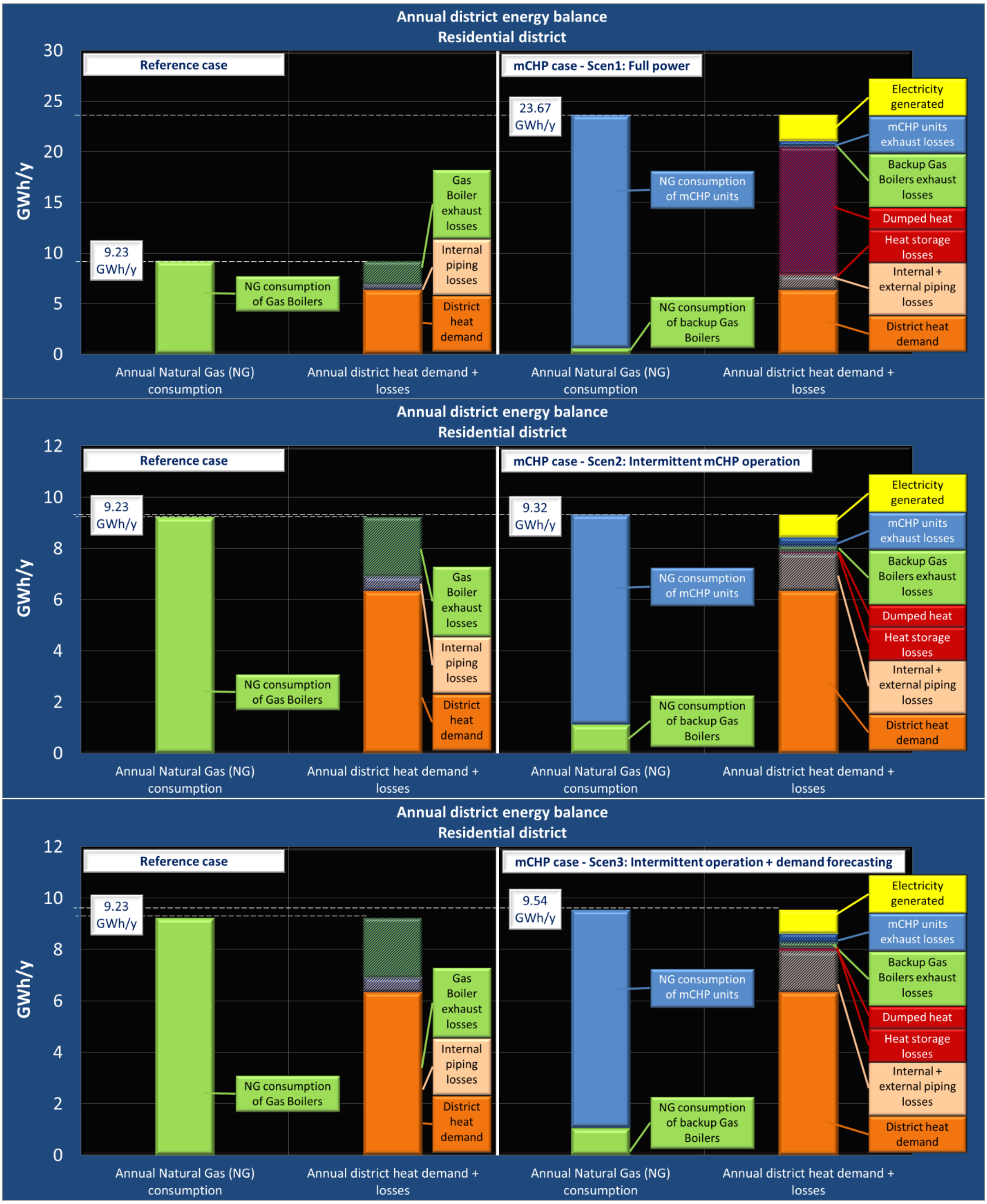

Fig. 8 a, b and c: Annual residential district energy balance for operation scenarios 1, 2 and 3, respectively.

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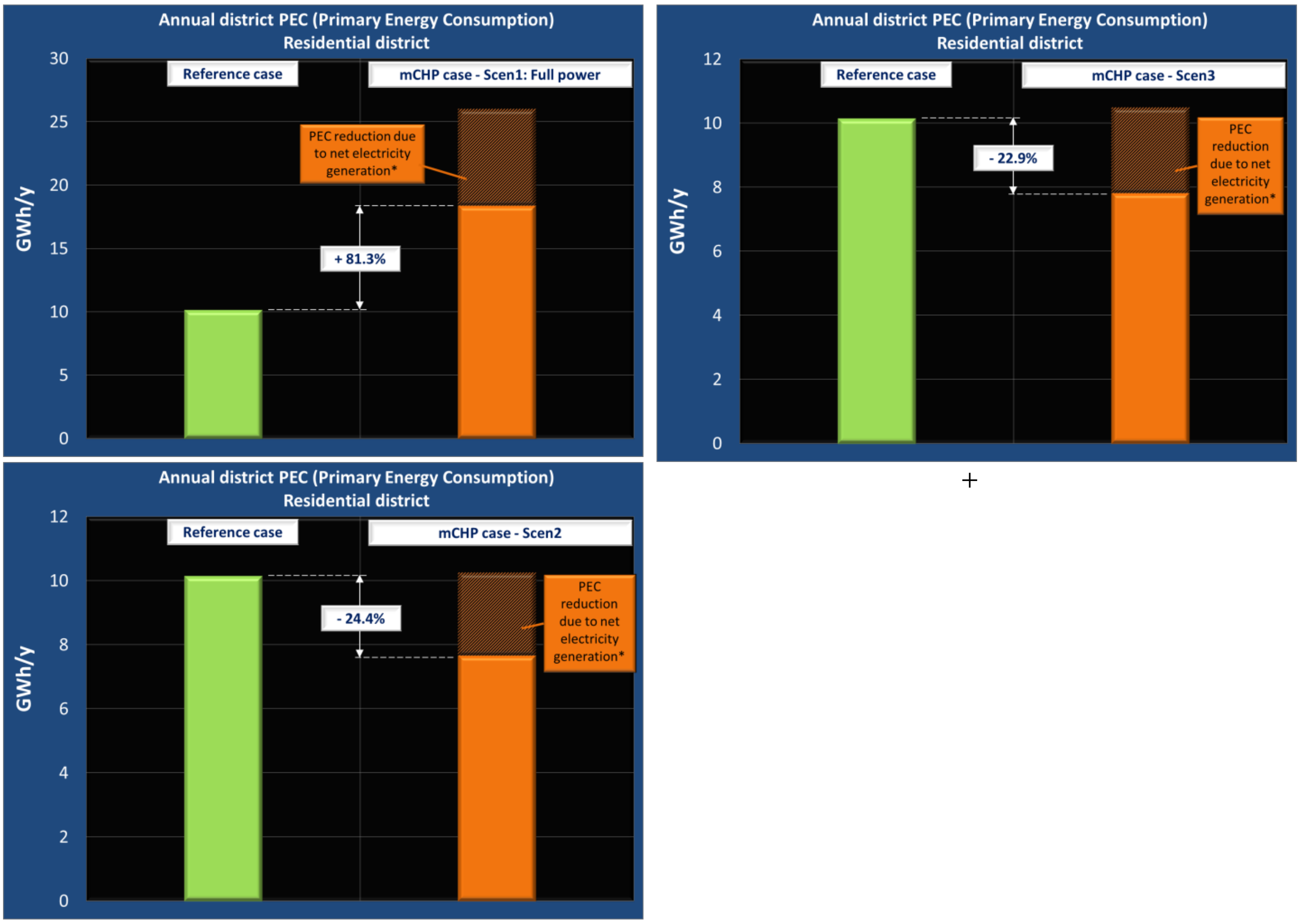

Fig. 9 a, b and c: Annual residential district PEC for operation scenarios 1, 2 and 3, respectively. (*net electricity generation considers mCHP production and pumping station consumption (~1% of production))

3.2 Financial center district

The result of the hourly simulation is shown in fig. 10 (a,b and c), for Scenarios 1, 2 and 3, respectively. Data have been sorted according to the level of heat demand. The mCHP operation covers the base loads, while backup boilers deal with the higher thermal demands. The contribution of the storage tanks is calculated to be less than the residential case, due to few load fluctuations and consequently few opportunities for charging the heat buffer.

The Stirling units cover the majority (nearly 78%) of the annual heat demand in all scenarios, while the heat buffer contribution is notable only under constant full operation, where (limited) heat overproduction occurs.

Figures 11 a, b and c present the annual energy balance for the financial district case. The comparison shows that the mCHP case requires almost the same fuel energy to cover the same demand. Despite the uncontrolled operation, the stability of the heat demand (shown in fig. 10) is responsible for the difference when compared to the residential district. Scenarios 2 and 3 perform better than the reference case, even in energetic terms. The forecasting scenario seems slightly less efficient, due to the additional storage losses.

When considering the PEC savings (figures 12 a, b, c), operation scenario 1 provides a fair reduction (21.7%) compared to the standard reference case. The positive effect of displacing grid electricity is decisive towards providing a higher PEC decrease, which reaches 30% in scenarios 2 and 3.

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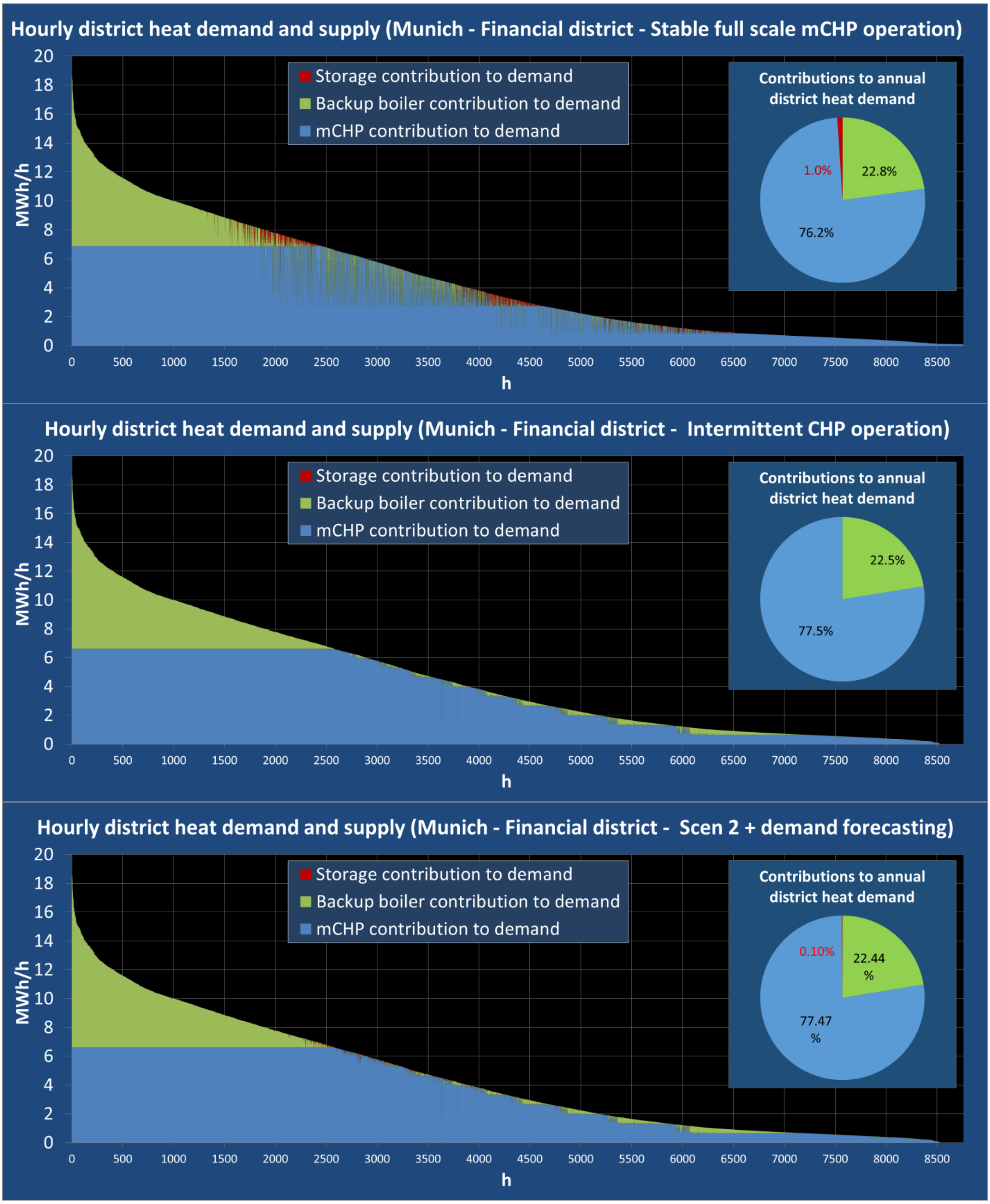

Fig. 10 a, b and c: Hourly financial district heat demand and supply for operation scenarios 1, 2 and 3, respectively.

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Fig. 11 a, b and c: Annual financial district energy balance for operation scenarios 1, 2 and 3, respectively.

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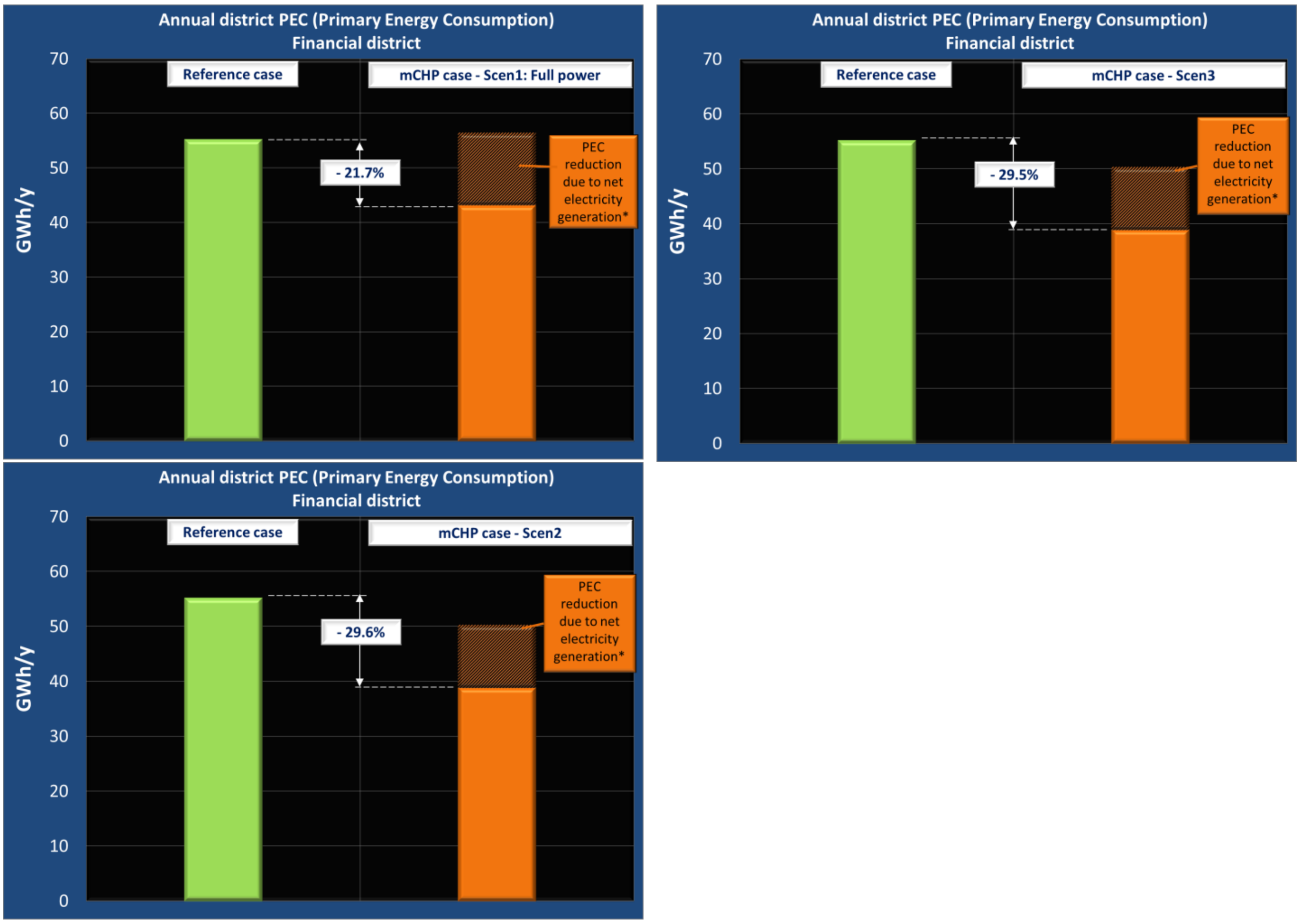

Fig. 12 a, b and c: Annual financial district PEC for operation scenarios 1, 2 and 3, respectively. (*net electricity generation considers mCHP production and pumping station consumption (~1% of production))

3.3 Sensitivity analysis

The sensitivity analysis performed aims in assessing the effect of different levels of mCHP installation in the two districts examined. As shown in Table 4, the initial relevant assumption referred to 1 unit per SFH and 8 units per Hotel/Office building. In the residential district, the installation of 1 unit per 2 and 4 SFHs has been calculated (results in fig. 13a, b and 14a, b). Correspondingly, the sensitivity analysis of the financial center involves calculations for half (4) and double (16) units per hotel/office building (results in fig 15 a,b and 16a, b). All sensitivity analysis calculations were performed under operational scenario 3 (intermittent operation + demand forecasting).

As regards the residential district, the installation of less mCHP units does not affect the total district energy consumption; however the mCHP contribution is less, as expected. Nevertheless, even when installing 1 unit per 4 SFHs, approximately half of the heat demand is covered by CHP. The lower electricity production is responsible for the corresponding decrease in the PEC savings, falling from 23% to 6%. In any case, the mCHP «swarm» has proven a robust PEC saving potential, which does not require a unit to be installed in every district building. The decision regarding the optimal number of units should be determined by techno-economic criteria.

A similar effect is observed in the financial center case. The PEC saving rises up to 35% when considering the maximum number of installed units and features a linear increase of 5% for every calculation case (4 → 8 → 16 units per building).

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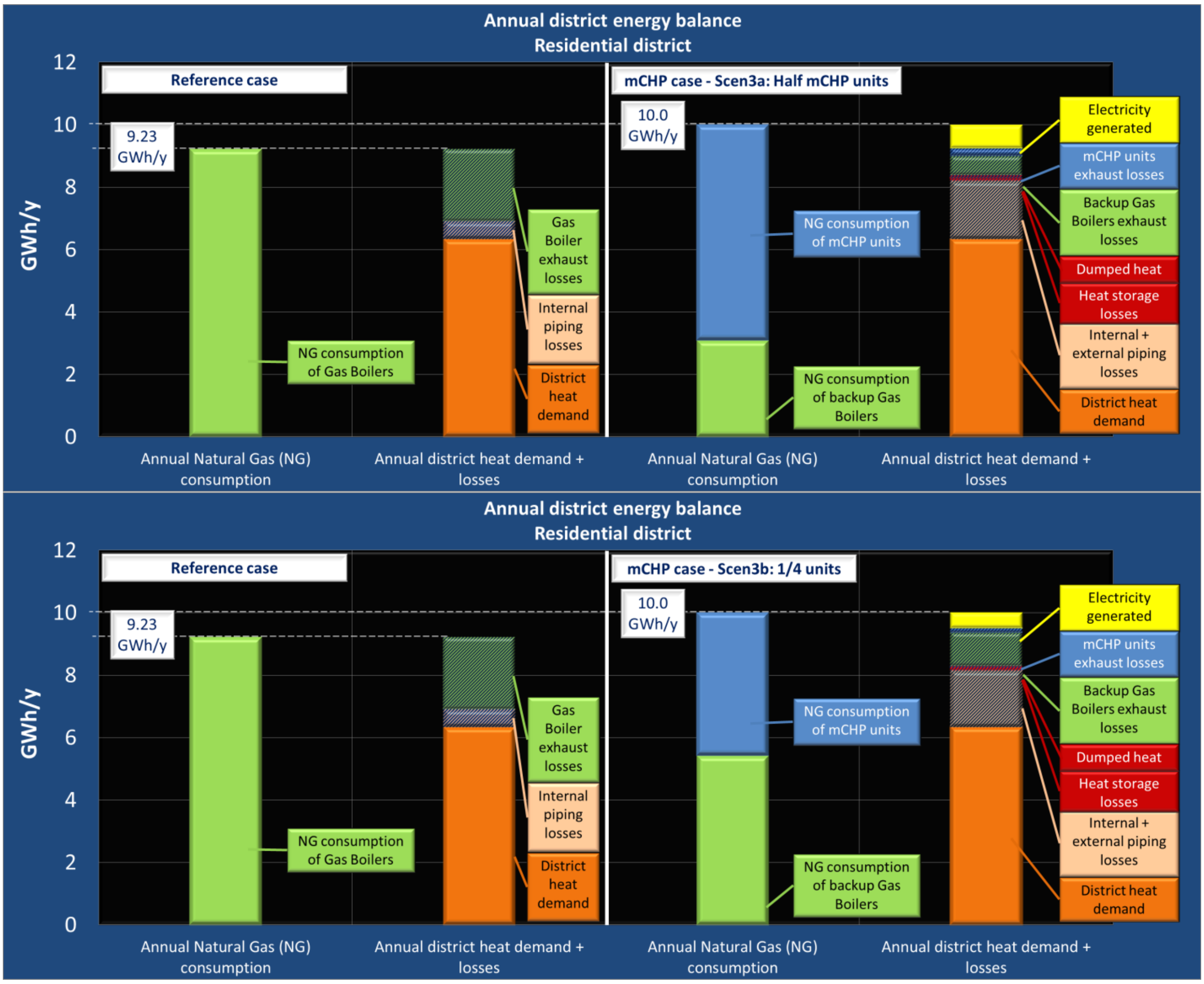

Fig
. 13 (a and b): Annual residential district energy balance for 1 mCHP installation per 2 and 4 SFHs, respectively.

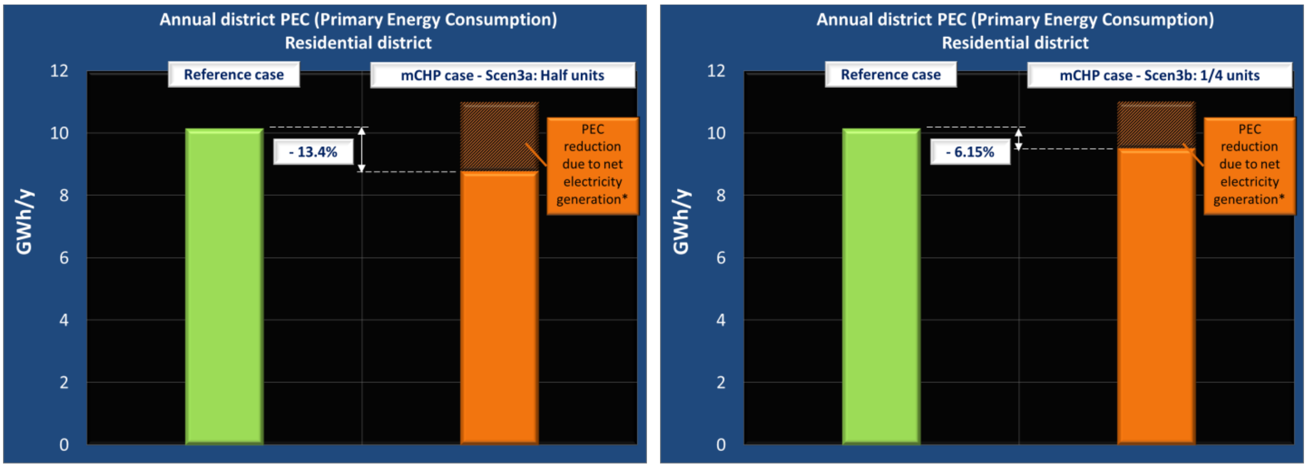

Fig. 14 (a and b): Annual residential district PEC for 1 mCHP installation per 2 and 4 SFHs, respectively. (*net electricity generation considers mCHP production and pumping station consumption (~1% of production))

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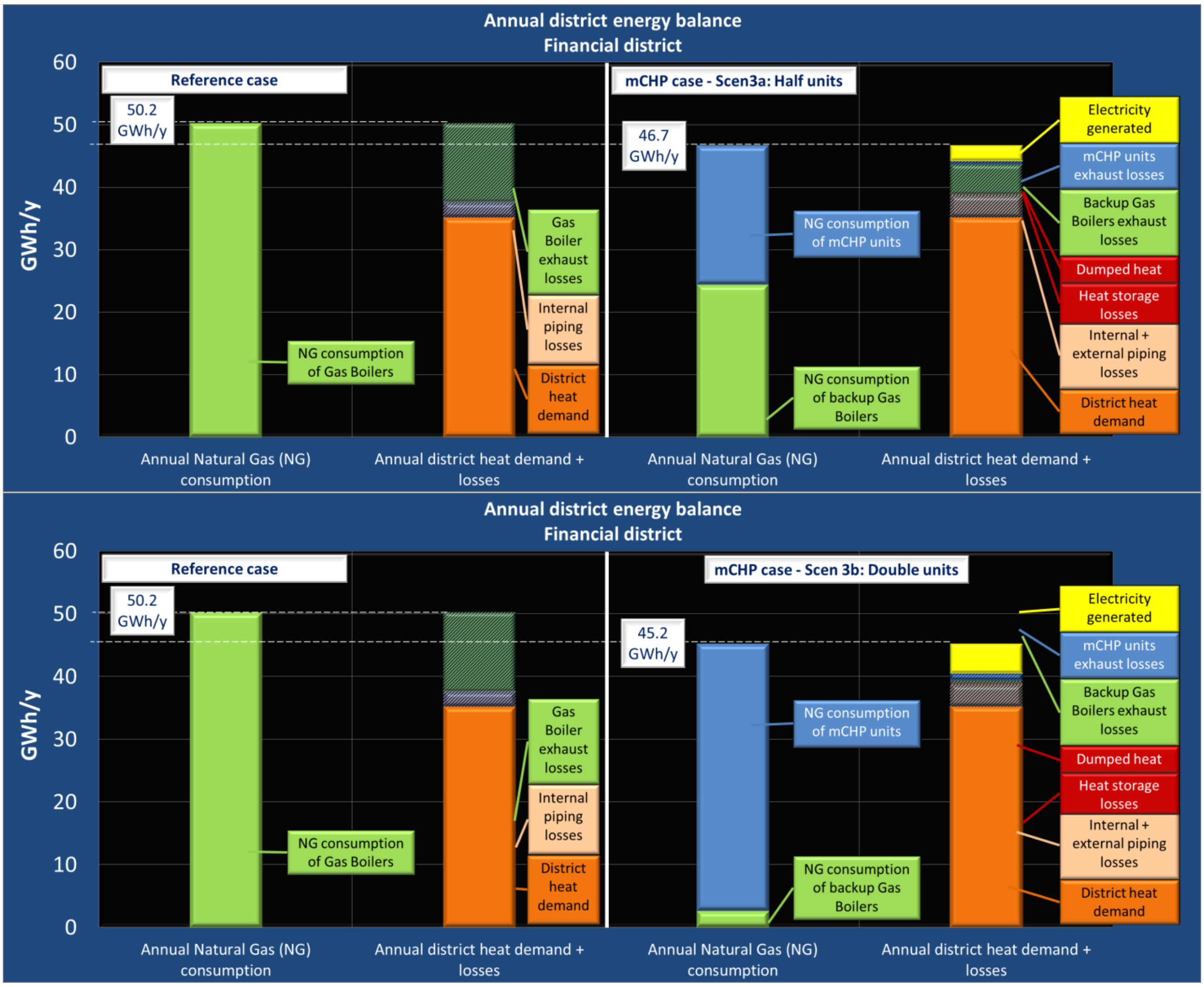

Fig. 15 (a and b): Annual financial district energy balance for 4 and 16 mCHP installations per hotel/office building, respectively.

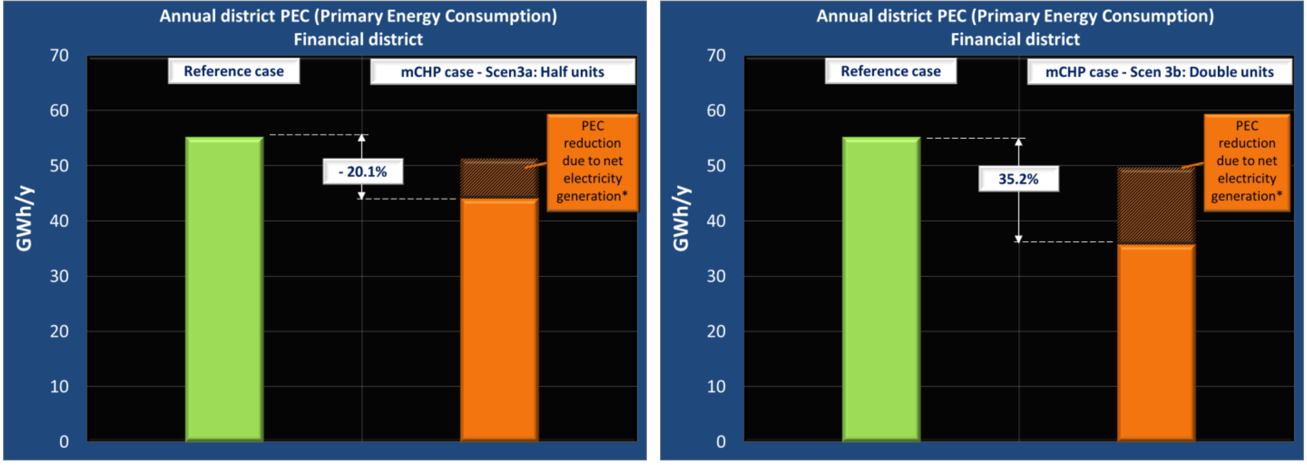

Fig. 16 (a and b): Annual residential district PEC for 4 and 16 mCHP installations per hotel/office building, respectively. (*net electricity generation considers mCHP production and pumping station consumption (~1% of production))

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4. Conclusions

The present work utilizes an in-house developed simulation and tool (DEPOSIT) in order to assess the energetic performance of an innovative energy management concept for districts. Actual building characteristics were assumed, providing input to dedicated heat demand calculation software. Overall, the Primary Energy Consumption saving of the mCHP case is realized through: a) the high total efficiency of the Stirling units and b) avoiding central generation emissions when the m-CHP electricity is exported to the grid. The comparative analysis identified a clear potential towards decreasing the PEC up to 35%, provided that all the electricity produced is utilized. However, the accurate estimation of the PEC factor of the displaced grid electricity is quite difficult, since it is uncertain what kind of generation takes place at the specific time of the m-CHP export to the grid. In other words, one cannot be confident how efficiently the grid-kWh produced at any specific moment was.

4.1 Effect of district type and corresponding control strategy

Two district types were considered: Residential (including Single Family Houses - SFHs) and Financial Center (including office buildings and hotels). The heat demand of the two types has distinctive differences: The residential load fluctuates intensively, while the hotels and offices of the financial center demand a smoother and longer (demand even in the warmer months) heat profile (and more thermal energy per km2). Within this context, mCHP contributes more and the storage is active in the residential district. Possible synergies can be described in a mixed type of district, where the residential district can provide more space needed for the installation of mCHPs and the financial district can contribute towards a smooth demand. A potential system featuring balanced demand/supply and no heat storage is certainly worth examining.

The heat-led control was found to be absolutely necessary under fluctuating demand (residential district). The stable full scale operation is not advisable for the residential district, at least in terms of the assumed volume of heat storage. It provides, however, many more opportunities of charging the heat storage and raising its utilization. Consequently, an optimal operational strategy could perhaps consider full scale operation for some time, regardless of the district demand. A smooth heat profile can be approached with seasonal full scale operation, nevertheless accompanied by a considerable loss of PEC saving.

4.2 Effect of mCHP penetration

The major direct influence in terms of energy balance is the level of mCHP utilization and contribution to the annual balance. In any case, the mCHP «swarm» has proven a clear PEC saving potential, which does not require a unit to be installed in every district building. The decision regarding the optimal number of units should be determined by techno-economic criteria.

A promising future research pathway would be the consideration of district cooling loads, in order to assess the potential implementation in Southern Europe. Additionally, a most interesting enhancement to the work presented would include the incorporation of an optimization methodology, in order to identify optimal cost system configurations (number of mCHP units installed, total volume of storage, optimal operating strategies, etc.).

Acknowledgement

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