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OPTIMIZATION OF MICRO-CHP SYSTEMS IN RESIDENTIAL BUILDINGS FROM AN ECONOMIC AND ENERGETIC POINT OF VIEW

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ABSTRACT

This paper investigates the optimal configuration of micro combustion engines (kW_{el} or kW_{th}), the associated volume of thermal heat storage and the thermal capacity of an additional boiler (kW_{th}) for heat supply in residential buildings with 30 units, which have been built in Vienna (Austria) during different construction periods (before 1919 to 2011). The target function for the configuration is defined, on the one hand, as the minimization of heat generation costs represented by investment, operational and maintenance costs. On the other hand, a minimization of the embedded energy, represented by the energy for manufacturing and operation of the micro-CHP plants (including the thermal energy storages), is performed. A power performance ratio is derived by the proportion between the thermal power of micro-CHP plants and the maximum heating load, which also describes the difference between the various performances.

1 INTRODUCTION

The combined supply of buildings with heat and electricity from CHP-technologies is becoming more important in terms of the efficient use of fossil and also renewable energy sources. The evaluation of the market potential and the successful market penetration of micro-CHP plants (1 kW_{el} – 50 kW_{el}) (see EC 2004, [1]) is linked to the optimum generation capacities of micro-CHP plants (including thermal storage and additional boiler capacity) for each consumer group (residential buildings, selected business and industry).

The core objective of this paper is to identify the optimal design of a dual system which consists of a micro-CHP plant, a thermal energy storage and a boiler for covering the heat demand of the analysed building (consumer[1]).To meet this objective we apply two different optimization approaches, an optimization from an economical perspective (under consideration of technical constrains) and an energy efficiency perspective. The purpose of the economic optimization is the minimization of heat generation costs for buildings from different construction periods. The energy efficiency perspective refers to embedded energy and aims to find the minimum of the total needed energy for a dual system (micro-CHP & thermal energy storage). In both cases the covering of the heat demand by a boiler is defined as the reference system. Kim et al. [2] investigated the optimum generation capacity of CHP-Systems (1-500 kW_{el}) in apartment buildings by modelling the transient behaviour of the distributed system. They used hourly residential load profiles based on Korean statistical reports. Lund et al. [3] analysed the optimal design of CHP-Systems in the range of 1-7 MW_{el} and storages in the range of 0-3000 m^3, based on a comparison of annual saving compared to a district heat demand of about 24,000 MWh/year (reference system: natural gas boiler). They took fixed load profiles. The optimization is conducted by variation of electricity tariff models.

Figure 1 illustrates the schematic of economic and energy optimization of micro-CHP plants within dual systems. The variable on which the optimum depends is the electric power of the CHP- systems. The heat demand of the building directly affects the optimization results.

This paper is organized as follows: the next section, methodology, provides an overview of the defined dual system and the used data for the operation simulation. The mathematical descriptions of the target functions close the chapter. The needed data base like demand profiles (heat and power) and the development of the heat demand of the consumer as a function of the construction period are presented in chapter 3. The forth section describes the results due to achieving of the defined target functions. The conclusions and recommendations are drawn in the last section of this paper.

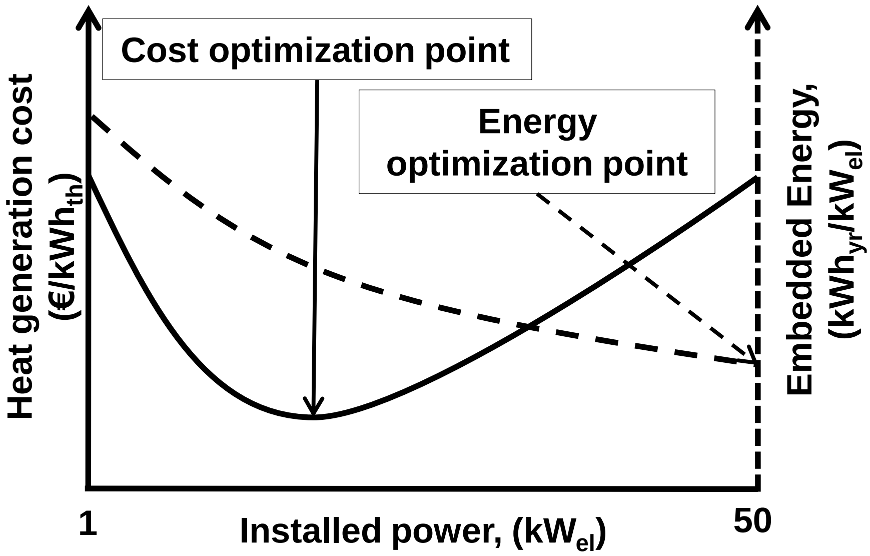

Figure 1: *Illustration of the economic (cost) and energy optimization point of a micro-CHP plant*

[1] The consumer is selected as a residential building with 30 units, which has been built during different construction periods (before 1919 to 2011) in Vienna, Austria.

2 METHODOLOGY

The determination of an optimal configuration for a micro-CHP plant is based on a heat-led control [4] simulation which has been developed in a Matlab (MATrix LABoratory) program. Annual heat (hourly resolution) and power (15 minutes resolution) demand profiles for the supplied unit (residential building with 30 units) and the technical constrains for the operation of a CHP unit and a thermal (hot water) energy storage build up the main data base for the simulation of heat based operation. The following parameters are considered for the optimization of dual systems:

1. energy-supply curve for electricity,
2. heat from a CHP unit,
3. the heat-supply curve from a boiler,
4. the coverage ratio of the energy demand of the building,
5. surplus power from CHP unit as well as
6. the full load operating hours.

In this work, two different heat supply systems are compared. In the first system (reference) the heat demand will be covered by a boiler. The second system will be supplied through a dual system, which consists of a micro-CHP plant, a boiler and a thermal energy storage. The electricity demand of the supplied object will be covered primarily by power production from the micro-CHP plant and the remaining demand is purchased from the power grid (see figure 2).

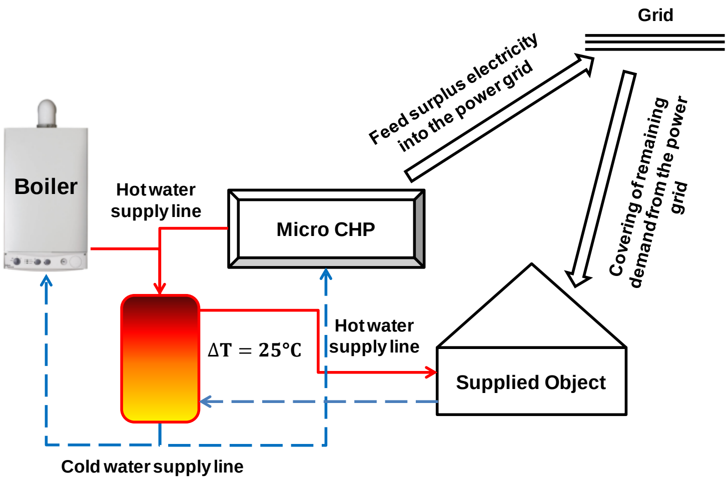

Figure 2: *Scheme of the dual heat system*

In the reference system the heat demand of the building is supplied by a boiler (without additional thermal energy storage), which provides the required heat ($\eta_{Boiler} = 0.95$). In contrast, the dual heat system includes a micro-CHP unit with thermal energy storage and an additional boiler. The heat supply priority of the consumer is defined as follows:

- Heat from the thermal energy storage,
- Operation of the micro-CHP and
- Additional supply through the additional (back-up) boiler.

The micro-CHP plant takes over the thermal charging of the thermal energy storage. This interaction between storage and micro-CHP plant leads to an increase of the micro CHPs' operational hours per year [h/yr] (operation of the micro-CHP and the thermal storage at partial load (see figure 3)) and also raises the coverage rate of the micro-CHP in the heat supply of the object. The optimized storage volume reduces the number of activation and deactivation times of the CHP per annum. Hence, the optimal selection of the storage volume can directly have a positive effect on the micro-CHP plant`s lifetime and its economic performance [5].

The heat flow temperature of a micro-CHP unit must be high (65-95 °C) to ensure a sufficient thermal transfer due to appropriate temperature differences. The return temperature is between 20 and 40 °C.

The difference between flow and return temperature amounts to 25°C which is a medium difference value.

The heat supply of the building through a dual heat system has been simulated after the selection of the micro-CHP plant and the definition of the properties of the thermal energy storage. The simulation of the operation will be done for each configuration of the micro-CHP unit (variation of installed electrical power and thermal power respectively) including the variation of storage volumes. The outcomes of the simulation are the following parameters: thermal and electrical coverage rate of micro-CHP and boiler, power production surplus, full load operation hours of the micro-CHP and the boiler, annual heat and power generation characteristics of the micro-CHP and heat generation characteristic of the boiler.

The mentioned parameters form the data basis for the dimensioning of the dual system from an economic and energetic point of view in respect of the building heat supply. Figure 3 shows the splitting of demand covering between a micro-CHP with connected thermal energy storage and a boiler. As described before, heating from a boiler has the lowest priority for supplying the consumer. So, it will only be triggered in times of low outdoor temperatures.

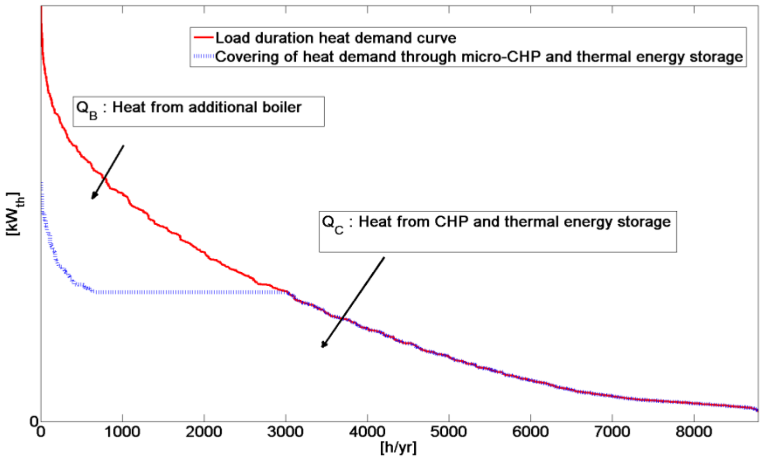

Figure 3: *How heat demand is covered by a micro-CHP plant and a boiler of a dual heat system*

2.1 Optimal design of dual system

2.1.1 Economic performance

For the economic optimization of a dual system we minimise the total system costs (see Eq. 1). The calculation of the heat generation costs is influenced by the following factors:

- Investment costs for the micro-CHP and the thermal energy storage [6],
- Micro-CHP plant start-up costs [6],
- Maintenance expenses for the micro-CHP plant [6],
- Investment costs and running expenses for the boiler.

The costs for investment, start-up and maintenance are referring to the installed electrical power of the micro-CHP plants. The total heat generation costs are derived as shown in Eq. 2.

$$\min\left(C_{System}(P_{el})\right): \qquad Target\ function \qquad (1)$$

$$C_{System} = A_{CHP,Storage}/Q_D + C_F - \left(R_{Own} + R_{Surplus}\right)/Q_D + C_B \qquad (2)$$

C_{System} : heat generation costs of the dual system [€/kWh$_{th}$]

$A_{CHP,Storage}$: yearly capital costs for combination of micro − CHP plant and buffer storage [€/yr]

Q_D : object total heat demand [kWh/yr]

C_F : fuel cost for the micro − CHP plant [€/kWh$_{th}$]

R_{Own} : annual savings when the produced electricity cover the own electricity demand [€/yr]

$R_{Surplus}$: annual revenues throuth feeding surplus electricity into the power grid [€/yr]

C_B : heat generation costs for the additional boiler [€/kWh$_{th}$]

The total heat generation costs of the additional boiler consider the investment, running [7] and fuel costs. The yearly capital costs for the combination of a micro-CHP plant and thermal energy storage are calculated by using the CRF (capital recovery factor) method (Eq. 3).

$$A_{CHP,Storage} = \alpha_{CHP} * I_{CHP}(P_{el}) + K_M(P_{el}) + \alpha_{St} * I_{St}(V_{ST}) \quad (3)$$

α_{CHP} : CRF(capital recovery factor) for the micro – CHP [1/yr]
α_{St} : CRF for the buffer storage [1/yr]
K_M : maintenance costs of a micro – CHP plant [€/yr]
I_{CHP} : specific investment and start – up costs of a micro – CHP plant [€/kW$_{el}$]
I_{St} : investment costs of a buffer storage dependent on thermal energy storage volume [€]

Revenues from sale of generated electricity

The annual revenues for a dual system during the operation result from the produced electricity. The revenues can be subdivided into avoided electricity purchases from the power grid R_{Own} (annual saving when the produced electricity covers the own electricity demand) and revenues through feeding surplus electricity into the power grid ($R_{Surplus}$). The covering of the own electricity requirements will be considered in the economical calculation with the electricity price from the energy market including taxes and contribution. The revenues from surplus electricity will be calculated depending on the energy market price (see [8]).

2.1.2 Energy performance

The energy optimization of a dual system is derived from the comparison of the reference and the dual system. The energy input for the reference system is defined by the necessary primary energy for heat production. The used energy for the dual system consists of the embedded energy for the manufacturing of the micro-CHP plant, the thermal energy storage and the used primary energy during the operation (heat and electricity production).

Eq. 4 computes the expenditure of energy for the reference system as a function of the heat demand of the consumer and the boiler efficiency factor ($\eta_B = 0.95$).

$$E_{Ref} = Q_D/\eta_B \quad (4)$$

E_{Ref} : embedded energy for the reference system [kWh/a]
η_B : boiler efficiency

The total energy requirement of the dual system for a year, which ensures heat supply for the consumer at any point of time, is shown in Eq. 5.

$$E_{Prim,CHP} = E_{Prim,CHP,1}(Q_c, Q_B, \eta, E_C, E_{St}, L_C, L_{St}) - \Delta_{Electricity} \quad (5)$$

Q_C : heat from CHP unit
Q_B : heat from additional boiler
η : total CHP efficiency
E_C : energy expenditure for manufacturing of micro – CHP unit [6]
E_{St} : energy expenditure for manufacturing of thermal energy storage [6]
L_C : lifetime of micro – CHP
L_{St} : lifetime of thermal energy storage

The minimization of $E_{Prim,CHP}$ is the target function for the energy based dimensioning of a dual system.

Assessment of produced electricity from the dual System

The produced electricity replaces the normally consumed electricity from the power grid. The assessment of the generated electricity will be done with consideration of the marginal power plants (combined cycle gas turbine for the peak hours, lignite-fired and coal fired power plants for off peak hours) from the central European market.

The primary energy demand for the generation of electricity from micro-CHP plants ($W_{Primary,CHP,Power}$) is calculated as a function of the total efficiency (Eq. 6). The replaced electricity from the power grid ($W_{Primary,Grid}$) is represented in Eq. 7. The 5 % factor considers the grid losses from high to low voltage grid level in connection with the covering of the consumer's electricity demand.

$$W_{Primary,CHP,Power} = \frac{W_{el}}{\eta} \qquad (6)$$

W_{el} : Produced electricity [kWh]

$$W_{Primary,Grid} = (1 + 0{,}05 * S_{Own}) * W_{el} * \left[\frac{S_{CCGT}}{\eta_{CCGT}} + \frac{S_{LFPP}}{\eta_{LFPP}} + \frac{S_{CFPP}}{\eta_{CFPP}}\right] \qquad (7)$$

$0 < S_{Own} < 1$: *Fraction of own usage referred to the total generation*
$0 < S_{CCGT} < 1$: *Share of electricity from combined cycle gas turbine* (PEAK)
$0 < S_{LFPP} < 1$: *Share of* electricity from lignite – fired power plant (OFF PEAK)
$0 < S_{CFPP} < 1$: *Covering part of electricity from hard – coal fired power plant* (OFF PEAK)

The difference between Eq. 6 and 7 results in the contingent of saved primary energy input which is generated from the micro-CHP unit (Eq. 8).

$$\Delta_{Electricity} = W_{Primary,GRID} - W_{Primary,CHP,Power} \qquad (8)$$

3 DATA USED

3.1 Heat and power profiles of residential buildings

For the calculation of the heat load a smoothing function (Sigmoid function) [9] is used. The function describes a representative daily residential heat demand depending on the daily average outdoor temperature. The consumption behaviour of consumers including different constraints (such as age of a building, building type, quality of heat supply or thermal environment) is characterised by the coefficients A, B, C and D (see Eq. 9)

$$\mathrm{h}(\vartheta_A) = \frac{\mathrm{A}}{1 + \left(\frac{\mathrm{B}}{\vartheta_A - \vartheta_{A0}}\right)^{\mathrm{C}}} + \mathrm{D} \qquad (9)$$

The characteristics and meaning of the used variables in Eq. 9 are shown in figure 4. The function implements the beginning of the heat period (transition from constant summer share which describes the temperature-independent hot water consumption to the beginning of the heating period starting at approximately 15 °C) as well as the flexibility in temperature-dependent heat consumption.

In the next step, the representative daily household demand is computed by using the hourly percentage factors. Thereby, the representative daily household demand can be broken down into hourly demand values [9].

Figure 5 illustrates the shares of the daily heat demand depending on measured outdoor temperatures (2008 values) for old buildings (construction period before 1919) in Vienna, Austria. The local extreme values in the morning and evening hours are due to the use of hot water. The multiplication of the data in figure 5 with the average daily heat demand (1,391.7 kWh_{th}/day) and normalized heat demand results in the heat load profile (see figure 6).

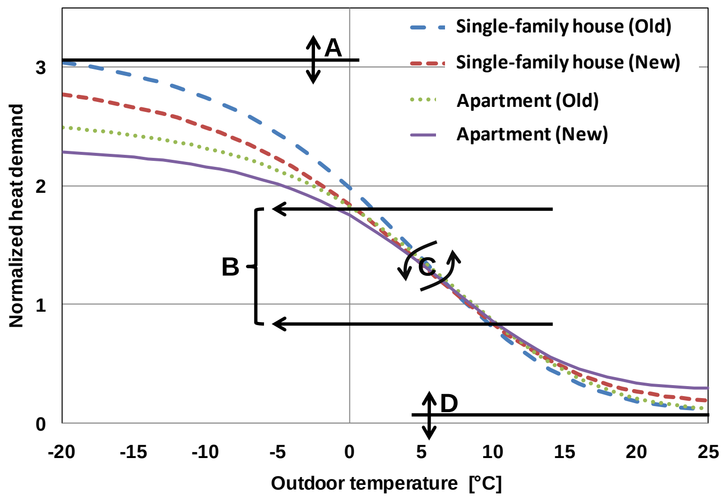

Figure 4: *Selected smoothing function for residential area (supply of space heat and hot water demand)*

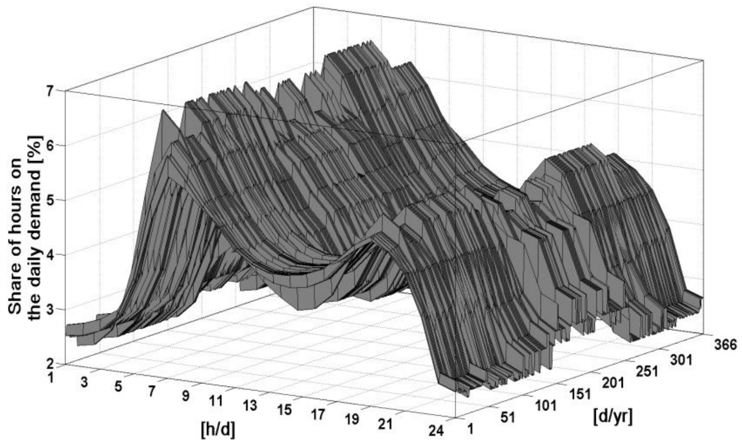

Figure 5: *Share of hours on the daily heat demand for measured outdoor temperatures (year 2008) from Vienna (construction period before 1919)*

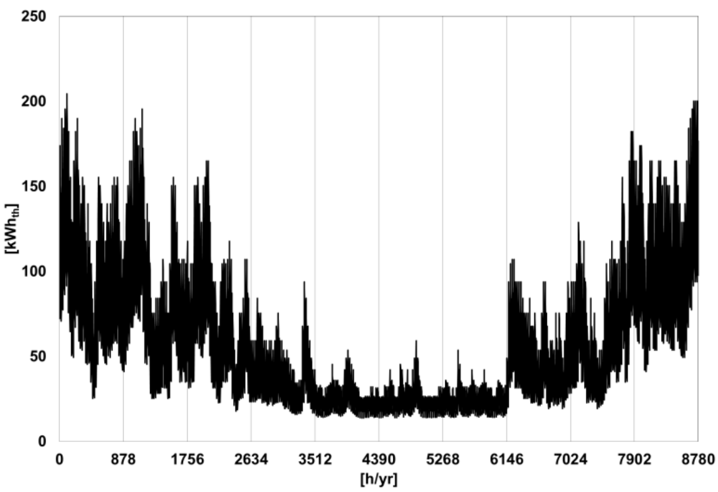

Figure 6: *Heat load profile for a residential building with 30 units based on the outdoor temperature from the year 2008 with 366 days (construction period before 1919)*

The standard electricity load profile H0 (see figure 7) is comprised of whole households with dominant private consumption. The households with marginal commercial consumption (such as home offices) will be represented also within the H0-profile. The H0-profile does not consider special applications such as using of storage heating and heat pumps. Furthermore, the annual consumption of a H0-profile is normalized to 1,000 kWh/yr. Assuming that the average annual power consumption of the analysed consumer is around 72,660 kWh in the year 2010, the H0-profile must be multiplied by the factor 72.66 [10].

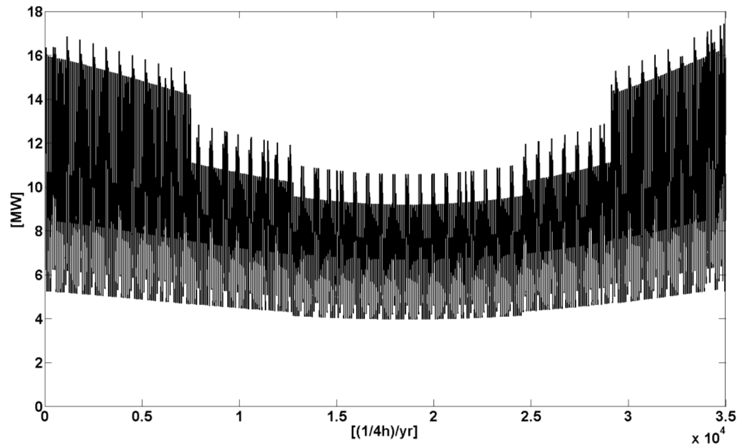

Figure 7: *Power load profile for a residential building with 30 units*

3.2 Dependence of building heat demand from different construction periods

The appraisal of different configuration methods for the micro-CHP plants and the estimation of heat production costs are based on various influencing factors. One of the major influence parameter is the heat demand. Figure 8 shows the heat demand for selected building from different construction periods in Austria. The estimation of the heat demand in the residential area is based on the results of a simulation tool for the calculation of the room heating supply (see [11]). The tool uses a bottom-up strategy for computing the needed energy in the residential area. It is calibrated with the disaggregated building and energy demand data from micro-census and Austrian energy balance data. The interval from 2002 to 2006 builds up the data basis for the estimation [12].

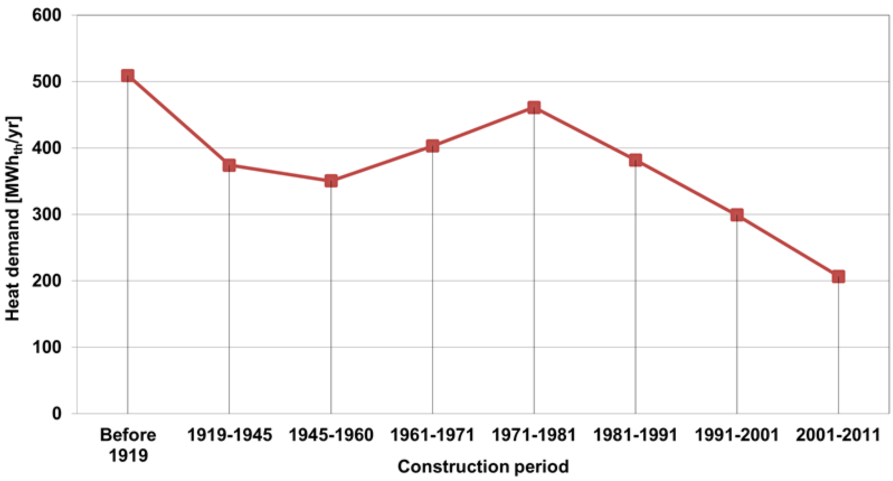

Figure 8: *Heat demand in residential building with 30 units as a function of construction period*

4 RESULTS

4.1 Economic vs. Energy efficiency optimization

Figure 9 shows the economic and energy performance of a micro-CHP unit for the analysed building. The heat demand of building from different construction periods influences the performance of the micro-CHP plants. Therefore, a factor called power performance ratio has been used for a better description of the micro-CHP performance (Eq. 10).

$$Power\ performance\ ratio\ [\%] = \frac{Thermal\ Power\ of\ \ CHP\ plant\ [kW_{th}] * 100}{Maximal\ heating\ load\ of\ the\ analysed\ consumer\ [kW_{th}]} \qquad (10)$$

The average power performance ratio for the studied building as a function of different construction periods is about 17 % in case of economic performance. This leads to an installed electrical power of the micro-CHP between 10 and 12 kW_{el} for the considered construction periods. [5] mentioned regarding to a paper from ministry of economy in Baden-Württenberg (Germany) which described the dimensioning of micro CHPs for residential buildings, a power performance ratio between 15 and 30 %.

The energy performance can be described with a mean power performance ratio of about 54 %. The installed electrical power in this case is 50 kW_{el} for each construction period (except the period 2001-2011) which defines a thermal power of about 84 kW_{th}. The mentioned thermal power is lower than the maximal heating load of the mentioned construction periods. Figure 10 shows the needed power of an additional boiler within the dual system due to a complete supply of the consumers heat demand. The characteristics of the depicted curves are similar to the heat development of the different construction periods. The energy performance needs lower installed boiler power because of higher installed micro-CHP power in comparison to the economic performance. The heat demand can be covered without an additional boiler in building of the construction period 2001-2011 in respect to energy performance of the dual system. This means that the annual heat demand can be covered by a micro-CHP unit (49 kW_{el}) and associated thermal energy storage (6.1 m^3) alone for this specific construction period.

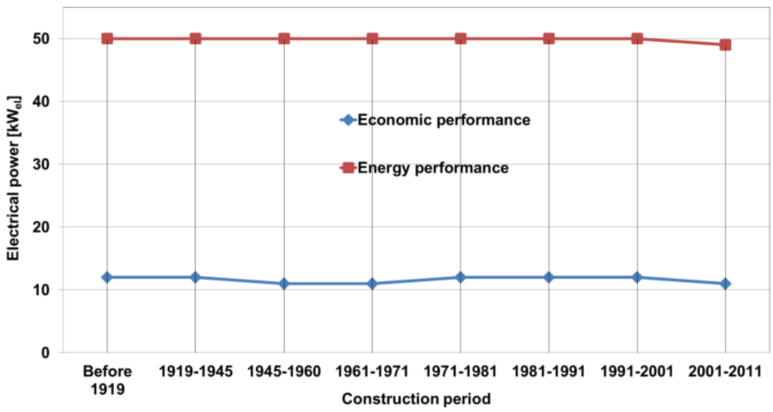

Figure 9: *Economic and energy performance of micro-CHP plants (gas engine) within a dual system for the analysed building (different construction periods)*

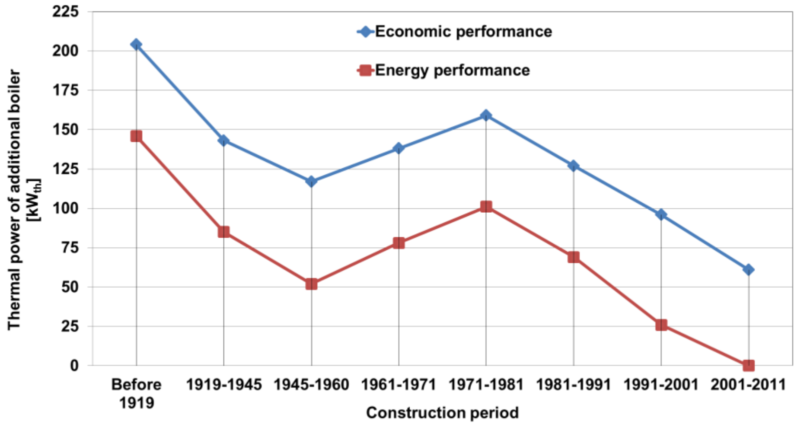

Figure 10: *Thermal power of an installed additional boiler within the dual system for the analysed building (different construction periods) for both performances*

The comparison of further operation parameters of the two performances clearly shows the differences between them. Table ***1*** gives an overview about the covering rates, full load hours and optimal capacity of installed thermal energy storages. The parameters refer to average values which have been derived from the dual system performances for different construction periods. The high electrical covering rate (economic performance) leads to a better economic situation of the dual system (lower heat generation costs). The thermal covering rate in the case of the energy performance is around 95 %. The energy performance is defined by a high electrical and thermal power. Here, the full load hours show the impact of the high thermal power, since they are only half of those of the economical dimensioning. The optimal storage capacities for both dimensioning methods are higher than 5 m^3, which means that the installation of the dual system in a residential building (our selected consumer) presupposes enough floor space for the thermal energy storage.

Table 1: *Average operation parameters for economical and energy-efficiency optimization for all construction periods*

	Electrical covering rate [%]	Thermal covering rate [%]	Full load hours [h/y]	Storage capacity [m^3]
Economic performance	87	53	7,600	5.2
Energy performance	50	95	4,200	6.7

4.2 Comparison of heat generation cost and embedded energy of both performances

Figure 11 presents the heat generation costs, embedded energy and electrical power of micro-CHP plant for both performances in comparison to reference system (heat supply through a boiler). The heat generation costs of the energy performance are about 37 % higher than those of the economic performance with a value of about 6.45 c€/kWh_{th}. The use of the reference system for covering of the heat demand results in the lowest heat generation costs of about 6.39 c€/kWh_{th}. In contrast, the used energy in the energy performance case is about 33 % lower than in the economic performance case with an annual energy use of about 456 MWh. From an energetic point of view, both performances of the dual system show a lower annual energy use of about 15 % (economic performance) and 43 % (energy performance) compared to the reference system with a value of approximately 536 MWh/yr (see Eq. 4). The installed electrical power of the micro-CHP unit in the dual system is 12 and 50 kW_{el} in case of economic and energy performance, respectively (see also figure 9). Figure 12 shows the impact of the volume of the thermal energy storage on the heat generation costs in case of the economic performance (building from the construction period before 1919) with a CHP electric power of 12 kW_{el}.

Figure 13 shows the total specific embedded energy of the dual system as a function of installed CHP power and the capacity of the thermal energy storage for the heat supply of the analysed building (construction period before 1919). The embedded energy considers the used energy during the operation of the dual system and the energy for manufacturing of installed CHP unit and thermal storage. It shows that an increase of the installed micro-CHP power result in a decrease of the specific embedded energy due to the assessment of produced electricity and the lower thermal power of the additional boiler in the dual system. The share of used energy for manufacturing of the micro-CHP unit and thermal energy storage is below 2 % of the total life-cycle energy demand.

Figure 14 shows the impact of the thermal energy storage on the embedded energy of the dual system with a 50 kW_{el} micro-CHP plant. The figure refers to a building from the construction period before 1919. The figures 13 and 14 depict a dual system with a 50 kW_{el} micro-CHP plant (figure 13) and a thermal energy storage with 6.4 m^3 capacity (figure 14) as the optimum in the energy performance case for the building from construction period before 1919.

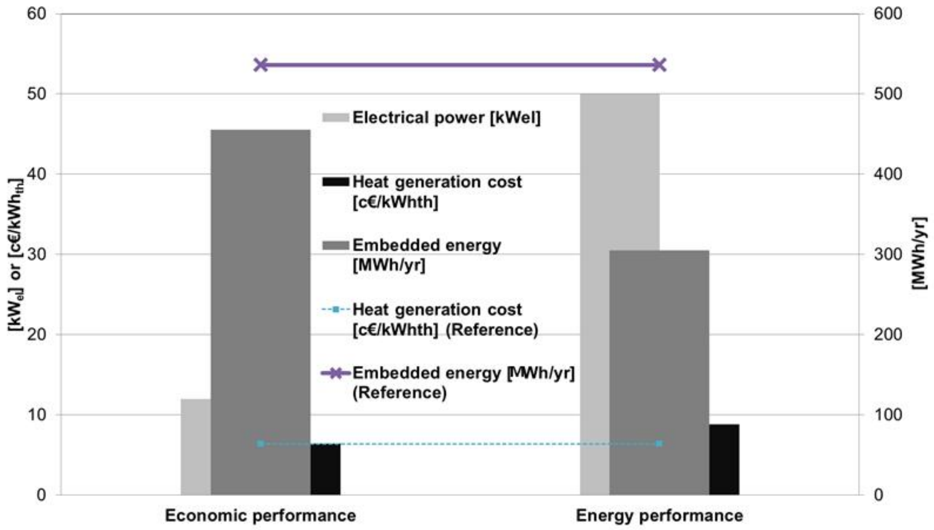

Figure 11: *Heat generation cost and embedded energy for both performances in comparison to the reference system for the analysed consumer (construction period before 1919)*

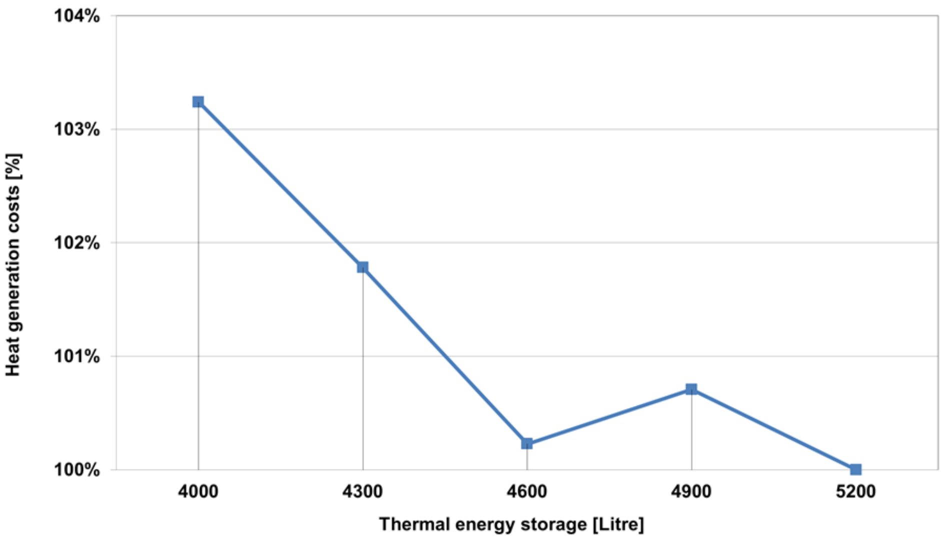

Figure 12: *Heat generation costs as a function of the volume of the used thermal energy storage (electric power of CHP is 12 kWel, construction period of the building is before 1919)*

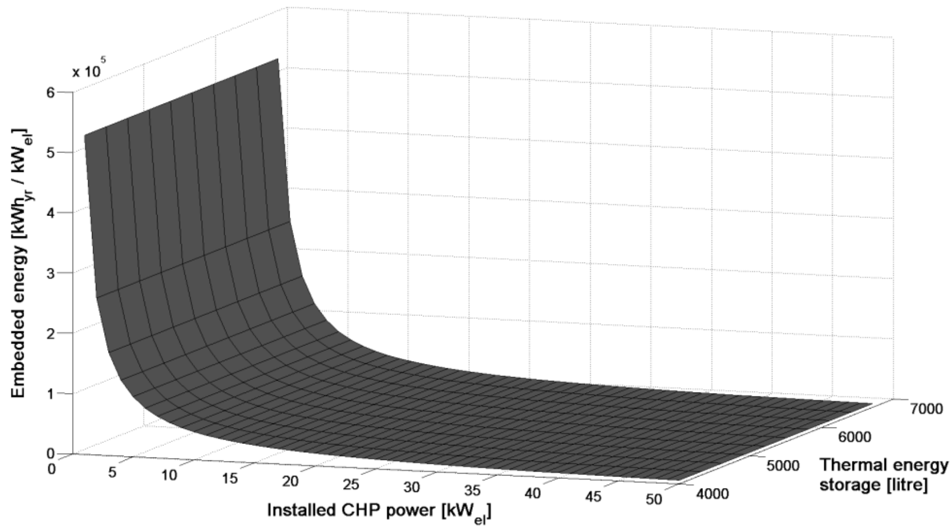

Figure 13: *Total specific embedded energy of the dual system as a function of installed CHP power and capacity of the thermal energy storage (construction period before 1919)*

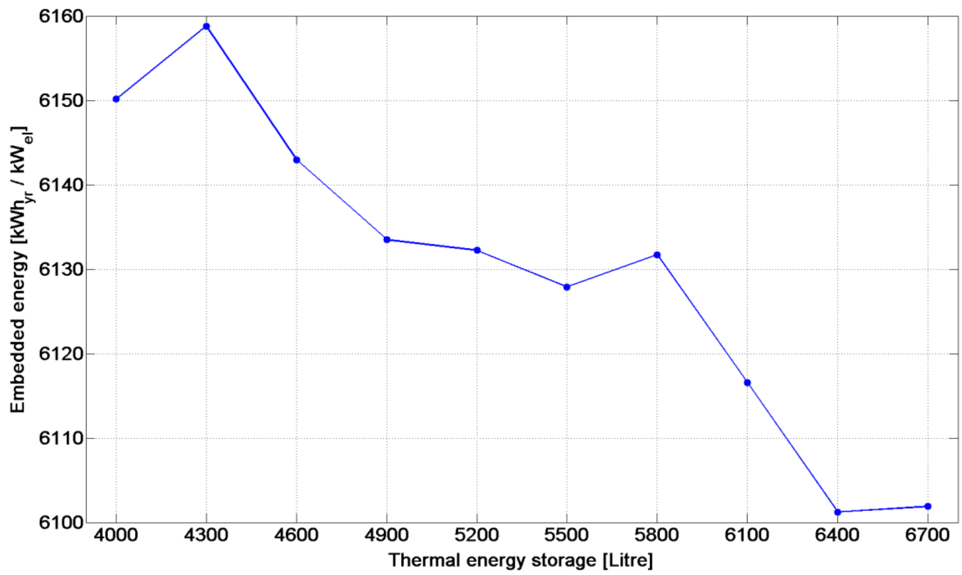

Figure 14: *Impact of thermal energy storage on embedded energy of the dual system with a micro-CHP electric power of 50 kWel (construction period before 1919)*

5 CONCLUSION AND RECOMMENDATION

The optimal economic performance case for heat supply of buildings from different construction periods indicates an average power performance ratio of about 17 % which corresponds with values from the literature [5]. The result is almost the same for all considered construction periods. The installed electric power of the CHP plant lies in a range between 10 and 12 kW_{el} (from 22 to 26 kW_{th}).

In the case of energy performance, a dual system can cover the consumer's heat demand for buildings from the construction period 2001-2011 without an additional boiler. This period depicts a decrease of heat demand of about 59 % in comparison to the construction period before 1919. Generally, the installed CHP power in this case reaches the upper limit of the micro-CHP range.

In both performance cases, thermal energy storages with capacities higher than 5 m^3 and additional thermal power of a boiler, which shows the same characteristic as the heat demand development during the different construction periods, are needed. The needed storage capacity leads to high space requirements in a building.

Therefore, an increase in the thermal density of the storages in comparison to used hot water energy storages is suggested. An important outcome is the low share of used embedded energy (about 2 %) in the life-cycle energy demand for the dual system.

The embedded energy in both performance cases depicts lower levels as the calculated value for the reference system in case of a building from the construction period before 1919. The amount of embedded energy is about 15% and 43 % lower than the used energy in the reference system in case of economic and energy optimal performances, respectively. This fact results in a higher efficiency of the dual system in comparison to the reference systems, independent of the target of the performance.

On the other hand, the economic performance case of the dual system is characterized by high annual full load hours for the micro-CHP plant. The high full load hours can be assured with an optimal heat engineering (e.g. appropriate difference between flow and return temperature) of the dual system. In comparison to the reference case (heat supply by a boiler), the heat generation costs for a consumer from the construction period before 1919 are still higher in the economic performance case.

With respect to the mentioned outcomes, a substitution of the reference system (heat supply through a boiler) with a dual system results in a higher efficiency in the heat supply of buildings in the residential sector. Therefore, an introduction of a subsidizing system can be recommended to overcome the economic disadvantage of the dual system. The subsidizing must apply for dual systems which use the same primary energy source as the reference system or utilise primary energy sources with lower emission factors as the reference system

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