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Abstract

Distributed cogeneration units are flexible and suited to providing balancing power, thereby contributing to the integration of renewable electricity. Against this background, we analysed the technical potential and ecological impact of CHP systems on the German minutes reserve market for 2010, 2020 and 2030. Typical CHP plants (from 1 to 2,800 kW_{el}) were evaluated in relation to typical buildings or supply cases in different sectors. The minutes reserve potential was determined by an optimisation model with a temporal resolution of 15 minutes. The results were scaled up to national level using a scenario analysis for the future development of CHP. Additionally, the extent to which three different flexibility measures (double plant size / fourfold storage volume / emergency cooler) increase the potential provision of balancing power was examined. Key findings demonstrate that distributed CHP could contribute significantly to the provision of minutes reserve in future decades. Flexibility options would further enhance the theoretical potential. The grid-orientated operating mode slightly increases CO_2 emissions compared to the heat-orientated mode, but it is still preferable to the separate generation of heat and power. However, the impacts of a flexible mode depend greatly on the application and power-to-heat ratio of the individual CHP system.

Highlights

- Distributed CHP can significantly contribute to the provision of balancing power.
- Flexibilisation options can further enhance the minutes reserve potential.
- Moving from heat to grid-orientated operation considerably affects the CO_2 emissions.
- The CO_2 saving potential of CHP decreases by half compared to separate production.
- The robust development of CHP is crucial to tap the balancing power potentials.

Keywords

distributed cogeneration; combined heat and power (CHP); CO_2 emissions; minutes reserve market; balancing power; grid-orientated operation mode

1 Introduction

In 2014, around 28% of the electricity produced in Germany was generated by renewables [1], mostly by fluctuating sources such as wind and solar power. The German government envisages to increase this share to at least 80% by 2050 [2]. It is anticipated that the further expansion of fluctuating renewable power generators (wind and photovoltaic) will lead to a growing demand for balancing power to compensate for forecast deviations. Simultaneously, large conventional thermal power plants may be crowded out of the market, which will increase the demand for new reserve capacities and/or for flexible loads. The government also plans to increase the share of combined heat and power (CHP) plants in net electricity production to 25% by 2020 [3]. As a result, in order to provide balancing power for the integration of renewable electricity, we expect that there will be a significant and as yet unexploited potential for small distributed CHP units, especially in the building sector, which can be operated more flexibly.

Three different types of balancing power are used to stabilise the grid frequency and power balance: primary, secondary and tertiary or minutes reserve. Deviations from the forecast levels of wind power production mostly affect the required capacity of minutes reserve, while its effects on the secondary reserve are still not clear [4–6]. Different assessments of future minutes reserve capacities for Germany draw varying conclusions, but all indicate the requirements for a significant short-term increase compared to current levels (see Table 1).

Different studies have analysed and demonstrated the technical feasibility of distributed CHP contributing to the (minutes) reserve market [7–9]. Furthermore, distributed CHP plants are already included in the portfolios of some direct marketers in Germany [10–12]. The issues discussed in this context include framework conditions, requirements, benefits and barriers, as well as costs; costs include political costs and those relating to operators and/or the system integration of renewable power generation. However, analyses relating to how CO_2 emissions will be affected by changing the CHP operation from a heat-orientated mode to a power or flexibilisation-orientated mode could not be identified in the literature. Studies of CHP CO_2 emissions instead compare the heat-orientated CHP operation and its related (dynamic) impacts with different technologies for the separate generation of heat and power [12–16].

Against this background, we aim to determine the technical potential for distributed CHP plants contributing to the minutes reserve market (taking flexibilisation strategies into account) and to assess the resulting impacts on CO_2 emissions for the years 2010, 2020 and 2030 in Germany. We expect to discover a significant reserve potential as well as a notable impact on CO_2 emissions, demonstrating the fact that there will be a trade-off between a more system-compatible and a climate-friendly operating mode of CHP.

In this paper we describe the scope and methodology for the potential and impact analyses in section 2. This comprises the selection and specification of building and CHP types and the descriptions of the flexibilisation cases, the optimisation model and the allocation method used. The findings for the minutes reserve potential and resulting CO_2 impact analyses are then given in section 3. Section 4 outlines the implication of the results, draws conclusions and presents the outlook for the technology.

2 Scope and methodology

2.1 Scope and limits of the analyses

Drawing on the case of Germany the paper explores 17 different kinds of heat supply cases and corresponding CHP units (see ch. 2.2) for the target years 2010, 2020 and 2030 in an hourly resolution for the yearly simulations. The analyses aim at quantifying the technical potential of distributed CHP at the minutes reserve market.

We chose the German minutes reserve (or tertiary) market due to the following reasons: In comparison to the primary and secondary market, it offers the best and easiest access conditions for all considered CHP systems. It has the shortest bidding (daily basis) and supply period (four hours), which lowers the risk of forecast errors and therefore the demand for additional reserve. Also, shorter supply periods raise the bidding potential in times of low heat demand. In addition, the technical preconditions, e.g. for ramps and response time, are much less restrictive than for the other reserve market types.

The participation of distributed CHP in the day ahead market is not examined in this paper, since it is less correlated with the fluctuations and forecast errors of renewable electricity. There is also a correlation between the intraday spot market and the minutes reserve market which could not be examined here, since the German intraday market emerged only after the start of the study underlying this paper. In regard to the minutes reserve market, market data from the year 2010 are used here, since those were the latest data at the beginning of the analyses. Nonetheless, these 2010 data are representative also for the following years, since the market volume has remained on a nearly constant level.

2.2 Selection and design of representative buildings and CHP plants

The study distinguishes between the following fields of application for small CHP units:

1) residential buildings

2) non-residential buildings
3) district heating networks
4) industry

For each area concrete buildings or supply cases were chosen and load curves of their heat demand were calculated. On this basis, suitable CHP systems (including peak load boilers and thermal storage) were selected. These systems were designed to supply the thermal base load (which is typically about 30% of the peak load) in each case in a heat-orientated operating mode.

Ten types of residential buildings of different sizes and energy efficiency standards and five non-residential buildings with high CHP potential were selected to represent the building sector. In terms of district heating networks and industrial applications, this study only examined one example of each. The system sizes considered range from 1 to 50 kW_{el} (residential buildings), 18 to 1,200 kW_{el} (non-residential buildings), 2,800 kW_{el} (district heating network) and 50 kW_{el} (industry). For simplification it is assumed that the electrical and thermal efficiencies of the CHP units will remain constant until 2030.

For the residential sector, a total of seven different CHP units were designed to meet the heat demand for the representative ten building types, which are suitable for co-generation application (see Table 2). The buildings' specific useful heating demand per square meter/year ranges from 129 to 214 kWh for existing buildings over 50 kWh (EnEV 2007)[1] to 15 kWh (Passive House).

In order to scale up the results for the single buildings to the future quantitative structure for the years 2020 and 2030, the CHP "Scenario A" development path, according to the study [17] was used. Future changes in floor area and energy performance standards for buildings as a consequence of energy-saving measures are factored in using our own modelling. The reduction in specific heat energy demand shifts potential CHP applications towards bigger buildings with a sufficient heat demand (cf. residential buildings types 8 to 10 in Table 2).

[1] EnEV = German Energy Saving Ordinance

2.3 Modelling of the technical balancing power potential for 2010, 2020 and 2030

In order to determine the technical potential of distributed CHP systems for providing minutes reserve, an optimisation and simulation model was developed. This model consists of sub models for each type of building and its assigned CHP plant, and each of these sub models consists of the following three modules.

The **first module** uses an optimisation algorithm to calculate the maximum amount of minutes reserve which can be provided. In order to provide balancing power and concurrently cover the building's heat demand, the model can use distributed CHP to generate heat and power, thermal storage to uncouple heat and electricity supply, and peak load boiler to produce heat without producing power. The algorithm uses a cost function, which weights the operation of the different components versus the provision of balancing power reserve. These weightings are not designed to reflect real costs, but to simulate actual plant operation. The maximisation of balancing power reserve is given a positive weight ("revenues"). Direct heat supply is weighted neutrally, heat storage has a small negative weight and using the peak load boiler has a larger negative weight ("costs"). The boundary conditions of the optimisation ensure that the buildings' heat demand is met (which is always possible due to the peak load boiler) and that the system does not produce more heat than can be consumed by heat demand and storage losses. The offers for balancing power reserve are modelled pursuant to the current market conditions, as follows.

Each weekday, the offers for the next day must be placed (on Fridays for the next three days). An offer consists of constant balancing power for time slices of four hours. The balancing power offered can be positive (i.e. the electricity production can be increased if called upon to compensate for grid deficits) or negative (meaning it can be reduced to compensate for excess situations). In this first module, there is no difference between positive or negative balancing power: both require the ability to run the CHP system for the whole of the offered time (if negative balancing power is offered but not called upon, or positive balancing power is called upon constantly) as well as not to run them (vice versa). De facto, much less balancing power is called upon than provided, but since this implies back-up capacities, it is not taken into account here.

Therefore, the **second module**'s task is to decide whether positive or negative balancing power is offered. Each pool of CHP plants decides which kind of balancing power to offer. The module therefore uses a randomised indicator, designed to reflect the proportions of positive and negative balancing power in each time slice as occurred in the minutes reserve market in 2010. As a result, the shares among the CHP plants mirror the actual shares in the market.

Finally the **third module** calculates the resulting CHP plant operation and adapts it in case the balancing power is called upon. Again, market data from 2010 are used: in the module, the same amount of the offered balancing power is called upon as in 2010. A randomised indicator also decides whether or not the plant's bid is accepted.

The model can simulate the base case of a "heat-orientated" operating mode and an operating mode designed to provide balancing power, which is referred to in this paper as "grid orientated". In the **heat-orientated mode**, the optimisation task is to meet the heat demand in the most energy-efficient way by using storage to maximise the share of CHP and to minimise the share of energy produced by the peak load boiler. In the **grid-orientated mode**, the primary optimisation target is to provide balancing power. The model optimises the plant and storage operation to provide the highest possible levels of balancing power during as many hours as possible. Efficient heat supply is a secondary optimisation target in this mode.

The characteristics of the minutes reserve market were analysed from historical data from the year 2010. The modelling assumes that those characteristics will not change and will remain identical in the years 2020 and 2030. This allows for the effects of changing the mode of the CHP plant operation to be analysed independently of other factors (the implications of this approach are discussed in ch. 4.1).

2.4 Defining the flexibility options for enhanced CHP operating modes

In addition to the default plant design, different flexibility options have been implemented in the model and their effects on the provision of balancing power have been examined. These are:

Flex 1: Doubling both the plant capacity *and* the storage volume

Flex 2: Quadrupling the storage volume

Flex 3: Employing an emergency cooler

Flex 1 and Flex 2 do not require changes in the model design but merely call for adapted input data, but Flex 3 requires an additional model component. The emergency cooler is represented as a heat sink with high “costs” in the weighting target function (see ch. 2.3).

2.5 Allocation and calculation of CO_2 emissions

By moving from a heat-orientated to a grid-orientated or flexibilised CHP operating strategy, the amount of combined heat and power generation changes. Consequently, the proportions of “heat from CHP” to “heat from peak load boiler”, as well as “power from CHP” to “power from grid supply” alter. Due to the various specific CO_2 emission factors for coupled and separate heat and power generation, these shifts lead to different CO_2 emissions of the CHP systems.

These changes have been analysed by means of the following approach:

1. Calculation of the primary energy saving for selected model cases vs. separate generation and allocation of the specific CO_2 emissions to the coproducts of power and heat.
2. Calculation of the absolute CO_2 emissions per building that is supplied by a CHP system in kg/a and comparison of the different operating modes: “separate generation”, “heat-orientated”, “grid-orientated” and “flexibilised”.

3. Upscaling of the CO_2 emissions in t/a according to the CHP quantity structures in the RES long-term scenarios [17] for the years 2010, 2020 and 2030.

The allocation of the specific emissions to the coproducts of power and heat is described as follows. In order to perform an energetic or ecological assessment of the coupled generation of power and heat, it is necessary to allocate energy and emissions to each of the two coproducts. For this allocation, the “Alternative Generation Method” was used in compliance with the European CHP Directive 2004/8/EC [18]. This method is suitable because cogeneration products are not favoured (unlike the Credit Method) [19,20]. In addition, it has the advantage that reference systems and reference fuels are taken into consideration (unlike, for example, the Efficiency Method, IEA Method or Exergy Method). In comparison to the Credit Method, the Alternative Generation Method eliminates the problem of very low or negative emissions for cogeneration by-products. In addition, by performing the allocation, values for primary energy saving in relation to the reference system of separate generation are achieved as an intermediate result.

The primary energy saving (PES) compared to an uncoupled reference system, can be calculated using the Alternative Generation Method according to the following formula, by means of the thermal and electric efficiencies η_{th} and η_{el} of the CHP plant [18].

Equation 1: $$PES = 1 - \left[\frac{1}{\eta_{th}/\eta_{th,Ref} + \eta_{el}/\eta_{el,Ref}}\right]$$

Using the following formulae, the fuel demand (W_{fuel}) for electricity

Equation 2: $$W_{fuel,el} = W_{fuel} \cdot (1 - PES) \cdot \frac{\eta_{el}}{\eta_{el,Ref}}$$

and the complementary fuel demand for heat energy

Equation 3: $$W_{fuel,th} = W_{fuel} \cdot (1 - PES) \cdot \frac{\eta_{th}}{\eta_{th,Ref}}$$

are calculated. W_{fuel} represents the total fuel demand for the CHP system. The absolute CO_2 emissions for electricity and heat energy are calculated by multiplying fuel demand with the specific fuel emission factors $CO_{2,fuel,spec.}$ (in kg CO_2/kWh_{fuel}). The specific CHP CO_2 emissions in kg CO_2/kWh_{el} or kg CO_2/kWh_{th} are calculated by dividing the absolute values by the produced electricity or heat energy.

In accordance with the guidelines of the EU CHP directive, uniform fuel specific efficiency factors are prescribed across Europe as a reference case for the separate generation of electricity and heat. These are taken from the implementation decision of the European commission [21] and are adapted to regional conditions according to climatic factors. Additionally, electricity reference efficiency is further reduced by a correction factor (≤ 1), which depends on the level of the supply voltage to which the CHP plant is connected, and on the share of electricity fed-in or consumed on site. This method is designed to ensure that distributed CHP plants avoid the creation of network supply losses, particularly when they consume a high proportion of their own self-generated electricity.

In this study, according to the EU CHP directive, a natural gas combined-cycle power plant (tabulated reference efficiencies: 52.5%; climate corrected: 53.2%) is used as a reference for the power generation and a natural gas boiler (tabulated reference efficiency: 90%) is used as a reference for the heat generation. For the CHP systems in the residential buildings an electricity reference efficiency of 47.1% applies after correcting the supply voltage and self-consumption rate. A specific fuel emission factor $CO_{2,fuel,spec.}$ for natural gas of 0.202 kg CO_2/kWh_{fuel} is used.

3 Results

3.1 Technical potential of balancing power

Potential without flexibility options

The results of the simulation show that, annually, an average of about 68% (in residential buildings) and 71% (in non-residential buildings) of the installed CHP capacity can be used for the provision of balancing power. For about one third of the year, during the period of low ambient temperatures, the full plant capacity can be used, whereas in summer the balancing power reserve potential is significantly lower. This is the result of the correlation between the bidding potential and the heat demand, which again is correlated in accordance with the ambient temperature (see Figure 1).

In the building sector, the installed CHP could have provided up to about 7% of the total minutes reserve needed in 2010. Assuming that the balancing power market remains constant from 2010 onwards and a CHP expansion path corresponding to scenario A [17], CHP could provide up to 42% (54%) of the minutes reserve market in the year 2020 (2030) (compare Figure 2).

Potential with flexibility options

The implementation of flexibility options further enhances the possibility of offering minutes reserve. In total, the different flexibility options increase the minutes reserve offered from about 10% (Flex 2 – quadrupling the storage volume) to 45% (Flex 1 – doubling both the plant capacity *and* the storage volume). The employment of an emergency cooler (Flex 3) increases the minutes reserve offered by 30% (see Figure 3).

Each flexibility option results in a different characteristic increase of the minutes reserve potential. The emergency cooler (Flex 3) allows to bid into the market, even if the heat demand is not sufficient for using the corresponding heat. Maximising the storage (Flex 2) allows for a few more hours within the transition period between winter and summer. If the nominal capacity and the storage are doubled, the higher heat demand during the winter period can be met more effectively. However, due to the higher plant capacity, the full load hours reduce with the implementation of this flexibility option (Flex 1). The effects of the flexibility options on the annual duration curve of the minutes reserve offered are shown using the example of a CHP plant in a high-rise building (type 4) in Figure 4.

3.2 CO_2 emissions

CO_2 allocation for different CHP systems

Results of the CO_2 allocation calculations (Figure 5) show that, in comparison to separate generation (even in comparison to a natural gas combined cycle plant plus natural gas boiler), all distributed CHP systems are advantageous in terms of both primary energy use and CO_2 emissions for power and heat. Primary Energy Savings (PES) account for between 15% and 26%, depending on the module. The specific CO_2 emission values for power range between 317g and 364g CO_2/kWh_{el}; for heat they range between 166g and 190g CO_2/kWh_{th}. Larger aggregates demonstrate better results, due to higher electrical efficiency. Despite an equal electrical performance of 1 kW_{el}, the stirling engine (RB 1 and 5) performs poorly compared to the conventional combustion engine (RB 8), due to its low electrical efficiency (only 14.1% in comparison of 26.3%).

In the case of Flex 3 (use of the emergency cooler), the calculation has to take into account adjusted specific CO_2 emission factors for power produced in the combined CHP unit. The modified emission factors arise by setting the thermic efficiency of CHP in the CO_2 allocation calculations to zero. Results for residential building co-generation systems are documented in Table 3. It is evident that when the emergency cooler is used, the specific CO_2 emission values rise by around 90% to 290% (compared to CHP operation) and by around 40% to 230% (compared to power purchased from the grid).

Influence of different operating modes on CO_2 emissions

Based on the specific CO_2 emission values documented in Figure 5 and Table 3 and the model simulation results, annual absolute CO_2 emissions have been calculated for the ten residential building types. The operating modes offering balancing power (grid-orientated and flexible modes) will be contrasted with the one that does not offer balancing power (heat-orientated mode) and with the separate generation of power and heat in the reference system.

Drawing on the example of the three existing residential building types RB 1 to 3, Figure 6 depicts the annual absolute CO_2 emissions produced by the generation of CHP heat, CHP power, heat from the peak load boiler and power from the grid. For the sake of an overall view, this figure does not include the flexibilised variants Flex 1 (double size plant) and Flex 2 (fourfold storage size); it only shows the emergency cooler variant (Flex 3). As this variant produces the highest CO_2 emissions of all the operating modes considered, this ensures that the full range of emissions is represented.

CO_2 emissions increase when switching from the heat-orientated operating mode to the grid-orientated operating mode, and increase further in the flexible mode. The savings in comparison to separate generation decrease or are even negative, such as in RB 1, RB 2 and RB 5 (unembodied), where increased levels of emissions are produced. The increase varies depending on the building type, the CHP load percentage and the power-to-heat ratio of the CHP module. The reason the emissions increase is because the CHP operation decreases (dark red bars), which has to be compensated for by increasing the peak load boiler operation (bright red bars) and by drawing additional electricity supply from the grid (light green bars), with the associated higher specific CO_2 emissions. In the Flex 3 variant, CHP heat is lost due to the use of the emergency cooler.

In the next step, the CO_2 emissions produced by each building have been scaled up for the years 2010, 2020 and 2030 in accordance with the CHP quantity structure of the chosen scenario frame [17] (cf. ch. 2.1). In Figure 7, the aggregated emissions for all the considered residential building types are given for the year 2020.

The scenario shows that, in 2020, the cumulative CO_2 emissions from CHP in residential buildings will be between a minimum of 3.92 Mio t (base case of heat-orientated operating mode) and a maximum of 4.98 Mio t (Flex 3). In comparison to the heat-orientated operation, the emissions will increase by at least 9% (flexibilised with doubled plant size) up to 27% (flexibilised with emergency cooler). Compared to the reference value for separate generation, the CO_2 savings made by the CHP units providing balancing power will reduce from 18% (heat-orientated mode) to 11% in the best possible scenario (Flex 1). In the worst case scenario (Flex 3), there will be an additional 4% of emissions compared to the separate generation of electricity and heat.

Figure 8 shows the additional CO_2 emissions for each residential building type (RB 1 - 10), compared to the heat-orientated reference values, in relation to the achievable benefit (GW·h minutes reserve provided). This presentation method enables the evaluation of the relationship between additional CO_2 emissions and benefits for each of the residential building types.

Overall, all the specific emission values are below 450g CO_2/(kW·h) and, in 26 of the 40 cases, are even below 100g CO_2/(kW·h). In 9 out of 10 cases, a doubling of the plant size (Flex 1) leads to lower specific emissions per minutes reserve provided than the standard grid-orientated variant. Only in RB 1 (113g CO_2/(kW·h)) is the grid-orientated variant marginally (-2.3%) better. The additional CO_2 emissions are particularly low in the cases of RB 3, 4 and 8, with values between 32g and 36g CO_2/(kW·h). Therefore, the Flex 1 variant offers the best relationship between additional emissions and balancing power potential, but it also bears the highest investment costs.

The CO_2 emissions in the Flex 2 variant (quadrupled storage size) are, because of the lower balancing power potential and simultaneous higher storage losses, greater in all cases than the Flex 1 variant and, with the exception of RB 8 (big multi-family passive house), lower than the Flex 3 variant. It would be reasonable to expect some future improvements to this situation if better insulation concepts for storage tanks are successfully introduced to market.

With the exception of RB 8, where the emergency cooler was barely used (309 kWh_{th}/a), the Flex 3 variants are inferior to the grid-orientated variant. It is notable that in the cases of RB 1 (433g CO_2/(kW·h)) and RB 5 (362g CO_2/(kW·h)), the additional emissions are about three times higher than for the other residential buildings. This can be explained by the low power-to-heat ratio (CHP coefficient) of the 1 kW_{el} stirling engine used in RB 1 and RB 5, which leads to excessive heat losses from the emergency cooler (28% or 21%, cf. Table 4).

4 Discussion and conclusions

4.1 Assumptions and boundaries

When considering the results, it is necessary to keep in mind the bases and limitation of this analysis as described in ch. 2.1. This study examines the maximum technical application of distributed and comparatively small CHP systems on the German minutes reserve market. Thus the resulting operation patterns do not necessarily correspond to economic operation. Current economic and political framework in Germany rather incentivises the consumption of electricity onsite than feed-in into the grid, therefore the economic minutes reserve potential is significantly lower at present than the technical potential. Recent trends like increasing electrical heat production ("power-to-heat") will also influence the future operation strategies of CHP.

Though the minutes reserve market has lower access conditions, electricity from CHP can also be offered on the secondary reserve market. This market on the one hand promises higher revenues, but on the other hand dictates more ambitious requirements (see ch. 2.1) and will influence the maintenance costs for cogeneration units more severely. A holistic assessment of the participation on the different suited markets (including the day ahead and intraday market) has to consider the economic frame conditions, which is beyond the scope of this study.

This study does not forecast the development of the demand for balancing power (see ch. 1 and ch. 2.3). This demand is influenced by different factors (e.g. rising fluctuations due to renewable power generation, less controllable conventional generation, capability of renewables to provide balancing power, spatial size of the balancing network, ...), whose interplay is complex and can not be predicted reliably. For this reason, the development of balancing demand towards 2020 and 2030 is not deducted here, but simplifying assumed to be constant. Conducted analyses indicate that the market characteristics of 2010 can be seen as representative for the market hitherto.

The modelling assumes the minutes reserves market to persist in its current form. But given the current challenges in the energy system's design (see for example [24]), it is imaginable that the balancing power markets will be adapted accordingly. Possible modifications could be an enhanced coupling with the intraday market, shorter time slices, shorter announcement terms or smaller minimum bids. Among these, shorter time splices would presumably have the biggest impact on the CHP plants' potential: This would enhance the provision of balancing power in summer, when the limited heat demand restricts the potential.

This study examines an isolated minutes reserve market, the provision of balancing power is influenced only by this market and the buildings' heat demand. Further studies need to examine the interplay with the electricity market: With rising share of renewables, there are times of surplus resulting in low or negative electricity prices. Flexible CHP plants would then be shut down. Due to that, they could offer no negative but solely positive balancing power in these periods. The effects on the balancing power potential needs to be examined in further studies, applying a coupled model which covers both markets.

We calculated the CO_2 emissions in accordance to the EU CHP directive 2004/8/EC (Alternative Generation Method/Finnische Methode) that in our case assumes and prescribes fossil based reference systems for the separate generation of heat and power. However, with future further increasing shares of renewable electricity in Germany, power from CHP in heat-orientated operating mode may drive out renewable instead of fossil electricity in certain periods of time. To explore the quantitative impacts on the CO_2 emissions due to closing down e.g. wind power production as a consequence of CHP heat production is out of the scope of this study and would require detailed simulations of the electricity market in hourly resolution. This is an important issue for the future and should be object of further research.

4.2 Technical potential of balancing power

The simulated results for the maximum pooled bidding potential for CHP on the German minutes reserve market demonstrate a relatively high annual availability of the installed nominal CHP capacity (in the order of about 70%) in the building sector. There are no significant differences between the residential (RB) and non-residential buildings (NRB) considered in terms of availability. While the potential bidding structure is almost the same, distributed CHP plants in non-residential buildings offer much better preconditions for contributing to the minutes reserve market than those in residential buildings. One reason for this is that, as a rule, the average plant size is bigger. Consequently, fewer plants have to pool together for the required minimum offer size of 5 MW_{el} [22]. This results in less effort and lower costs to access the market. The required telecontrol engineering, which has high fixed costs, is an additional drawback for CHP systems in residential buildings. Another reason for non-residential buildings having an advantage over residential buildings is that their total installed capacities were about a factor 7.5 higher in 2010. Although this relationship could change in the future in favour of distributed CHP systems in residential buildings, the potential of which has been largely unexploited to date, it is expected that the installed capacities of CHP plants in non-residential buildings will remain significantly higher [17].

Therefore, if politicians seek to unlock the minutes reserve potential of distributed CHP systems, priority should be given to the non-residential buildings sector or to larger distributed CHP plants. For existing plants this could be achieved, for example, by incentivising the appropriate telecontrol technology, the enlargement of the plants or the heat reservoirs coupled with obligatory marketing of balancing power. New plants of a certain size could obligatorily take part at the balancing power market without incentives. However, there is currently sufficient minutes reserve capacity and a number of competing alternatives, such as gas turbines and demand-side management, which can be achieved relatively quickly. As a result, there is no urgent need for the introduction of supporting instruments and there are already some marketers who are pooling balancing power from distributed CHP systems (mainly biogas) [10,11,13,23].

Nevertheless, the demand for greater minutes reserve capacity and new sources of balancing power in Germany is expected to rise in the order of some 1,000 MW_{el} by 2020 with the further expansion of renewables (see Table 1). This rise in demand would be of a similar capacity to the whole existing technical minutes reserve potential of distributed CHP plants in the building sector (in the order of 2,900 MW_{el} in the year 2010) or could even exceed the most promising additional potential offered by doubled plant size in the Flex 1 variant (in the order of 1,400 MW_{el}). In order to further enhance the potential for CHP to contribute to the minutes reserve, the general expansion of distributed CHP systems will be more important than their flexibilisation (see Figure 3). The assumed CHP development path [17] increases the minutes reserve potential by about 14,000 MW_{el}, while the cost-intensive Flex 1 and Flex 3 options only result in an additional potential of 6,800 and 5,200 MW_{el} respectively, and the less cost-intensive option (Flex 2 - quadrupling the heat reservoir for all plants) only results in an additional 1,500 MW_{el}.

Rough cost estimations for achieving the different Flex options at three different residential building types result in specific costs per additional unit of minutes reserve, amounting to 20-170 €/MW·h for Flex 1, 6-36 €/MW·h for Flex 2 and 26-93 €/MW·h for Flex 3, see [23]. Therefore, quadrupling the heat storage size (Flex 2) seems to be advantageous from a cost point of view. However, this must be considered from a profitability perspective, which is beyond the scope of this study and depends mainly on the development of the market conditions. Further analysis is required.

In terms of the seasonality of the reserve-orientated CHP operating modes, it should be noted that CHP is likely to contribute to the integration of wind power rather than of photovoltaic, due to the significant summer slump of its bidding potential (see Figure 1). Doubling the plant size (Flex 1) leads to a potential offer of almost twice the capacity but this is, however, limited in time to around 2,000 h/a before slowly converging with the non-flexibilised operating mode (see Figure 4). This will be advantageous for compensating for higher wind power deviations, as these are expected to occur mainly during the winter period. Quadrupling the heat storage (Flex 2) helps to increase the total availability by about 1,000 h. This will be particularly advantageous for the transition periods between winter and summer. Last but not least, the use of an emergency cooler (Flex 3) would totally decouple the reserve provision from the heat demand, so that the full power capacity could be offered at any time. However, since this could lead to the uncoupled production of heat and power and therefore decrease the CHP share, this would decrease the ecological advantages of CHP generation.

4.3 Impact on CO_2 emissions

Changing from the heat-orientated operating mode, which is common today, towards a grid-orientated operating mode results in an increase in CO_2 emissions of between 8% and 16% for each of the **ten individual building types**. The savings in comparison to the reference system of separate generation diminish by nearly half, from originally 15% to 25% (heat-orientated operating mode, depending on the building type) to 8% to 13% (grid-orientated operating mode).

The overall picture of the **aggregated CO_2 emissions for all residential buildings in 2020** (see Figure 7) shows that emissions increase significantly while transitioning from the heat-orientated to the grid-orientated operation. The CO_2 saving potential decreases by half from 18% to 9% compared to separate production. Nevertheless, this operating mode still scores significantly higher than the reference value of separate generation, both in terms of primary energy use and CO_2 emissions.

The results show that the **flexibility options** can significantly increase the balancing power potential, but possible additional costs and increased CO_2 emissions must be taken into account. Taking minimum CO_2 emissions as the priority, doubling the plant size (Flex 1) is the optimal variant since a relatively high balancing power potential of approximately 6,000 GW·h, with a moderate increase in CO_2 emissions (about 9%), can be achieved (see Figure 7). Compared to Flex 1, quadrupling the storage tank size (Flex 2) results in less minutes reserve potential (5,400 GW·h), with about 3% higher emissions. Taking the maximum provision of balancing power as the priority, the variant employing the emergency cooler (Flex 3) performs best, producing about 7,000 GW·h, but with over a quarter more CO_2 emissions (27%) compared to the heat-orientated mode. The grid-orientated variant requires lower capital investment as besides telecontrol technology no new equipment is required – the other variants require a larger module, a larger storage tank or an emergency cooler. However the minutes reserve potential in the grid-orientated operating mode is the lowest, at about 4,800 GW·h.

As enlarging conventional heat storage tanks (Flex 1 and 2) requires more space and causes more heat losses, politicians should consider the implementation of a "Technology or Innovation Bonus" for technical solutions that reduce storage losses by improved insulation (e.g. vacuum insulation) and that enable the space-saving increase of storage capacity through PCM / latent heat technology. The successful move towards these innovative developments would be a positive measure, as other future-orientated low-carbon technologies, such as heat pumps or solar thermal systems, could also benefit from it.

The findings relating to Flex 3 do not support the use of emergency coolers - to tackle the problem of the heat load slump in summer - from an economic, ecological or technological perspective. This is certainly the case for small CHP plants with lower electrical efficiency, which are dominant in the residential sector. In bigger plants, e.g. in non-residential buildings or for industrial applications, the use of an emergency cooler - strictly coupled to its use in the balancing power market - might be acceptable, if new capacities for balancing power can be avoided by implementing this measure. However, direct funding should not be granted without further analysis of the economy and the energy market. In general, plants with high CHP coefficients (≥ 1 to 2, also for smaller units) are a crucial driver for the development of this flexibility option. In this respect, fuel cells - with their high electrical efficiency potential - could play an important role in the future if they are able to combine an intermittent operation with a suitable lifespan.

Despite the promising technical potential of distributed CHP systems for the minutes reserve market, politicians should not over-prioritise the framework in this respect. Primary incentives for the robust development of CHP in general should be implemented, as this is directly linked to an increase of the technical balancing power potential. Nevertheless, new installations should be equipped with adequate ICT technology (ideally with open or common standards) in order that they are ready to participate in the balancing power market.

Fundamentally, the future role that decentralised systems such as distributed CHP plants should play in terms of providing balancing power must be clarified. The question of which balancing power structures (centralised, decentralised or hybrid) best suit the transformational process of energy supply towards renewable energies remains unresolved. In addition, the comparative size of the CO_2 emissions that are generated by the current conventional energy sources in the balancing power market must be analysed.

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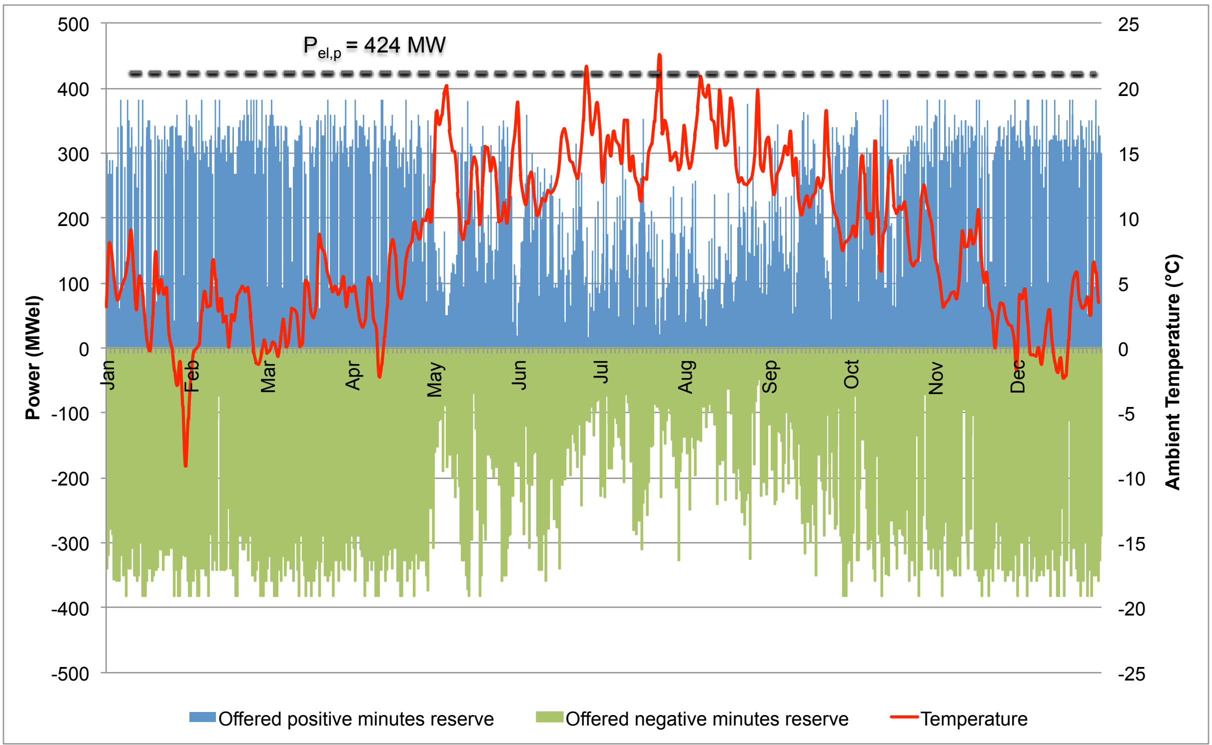
[2] The unit GW·h indicates the reserve power [in GW_{el}] provided for a certain number of hours. It does not represent the actual usage of the reserve power nor the energy provided during these times.

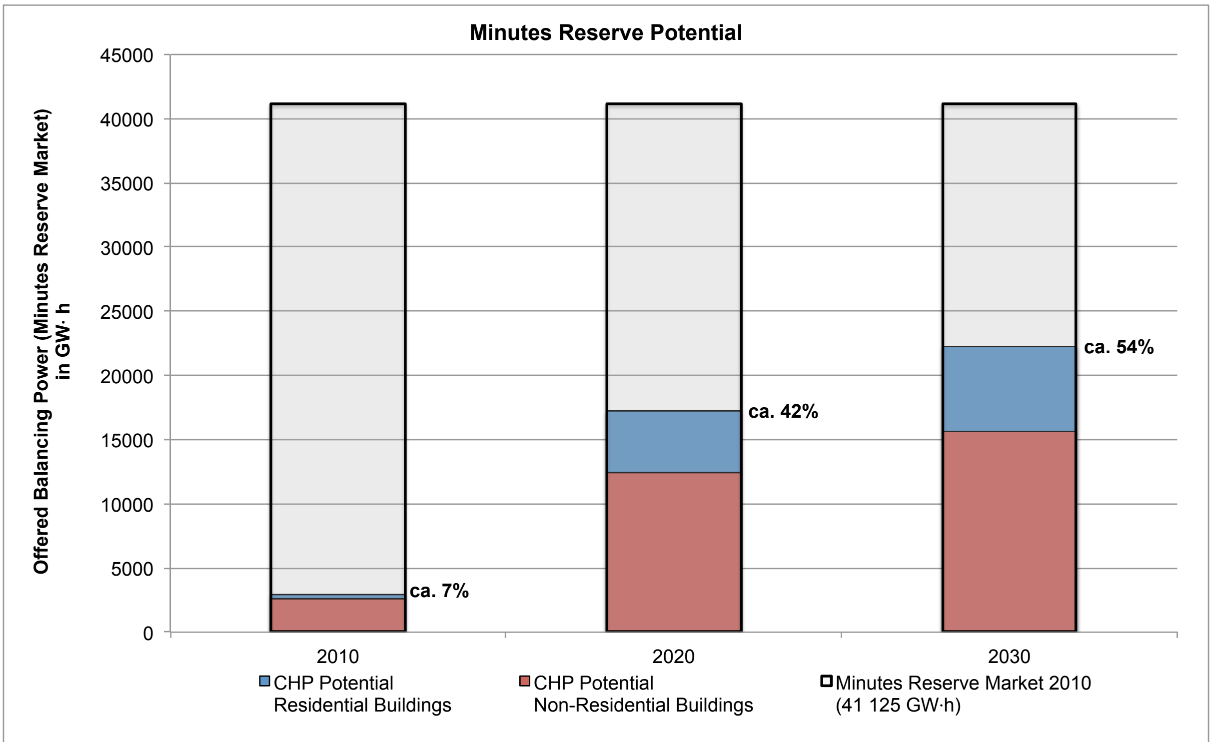
Year	Positive MR	Negative MR	Source
2010	2 308 MW	2 358 MW	[22]
2012	1 908 MW	2 325 MW	
2020	4 200 MW	3 300 MW	[7]
	5 000 - 7 100 MW	5 700 - 7 800 MW	[25]

		Building		**CHP Module**					**Boiler**	**Storage**
		Heat demand	**Heat load**	**Techn. principle**	**Capacity electr.**	**Capacity therm.**	**Power-to-heat ratio**	**Full load hours**	**Capacity therm.**	**Volume**
		kWh/a	**kW_{th}**	**-**	**kW_{el}**	**kW_{th}**	**-**	**h/a**	**kW_{th}**	**Litre**
Existing Build.	**1 SFH**	22 700	14	Stirling	**1.0**	**5.6**	0.18	3 570	20	300
	2 MFH (small)	76 700	44	Otto	**5.5**	**12.5**	0.44	4 470	40	750
	3 MFH (big)	127 000	62	Otto	**5.5**	**12.5**	0.44	5 650	55	1 000
	4 High-rise	883 900	466	Otto	**50.0**	**82.0**	0.61	5 670	440	3 000
EnEV 2007	**5 MFH (small)**	27 400	16	Stirling	**1.0**	**5.6**	0.18	4 050	20	300
	6 MFH (big)	49 300	26	Otto	**3.0**	**8.0**	0.38	4 810	26	500
	7 High-rise	404 400	206	Otto	**34.0**	**66.0**	0.52	4 680	206	3 500
Passive H.	**8 MFH (big)**	23 600	20	Otto	**1.0**	**2.5**	0.40	5 940	20	500
	9 High-rise	193 200	89	Otto	**15.2**	**30.0**	0.51	5 390	90	2 000
	10 Terraced H.	85 100	75	Otto	**5.5**	**12.5**	0.44	5 140	75	1 100

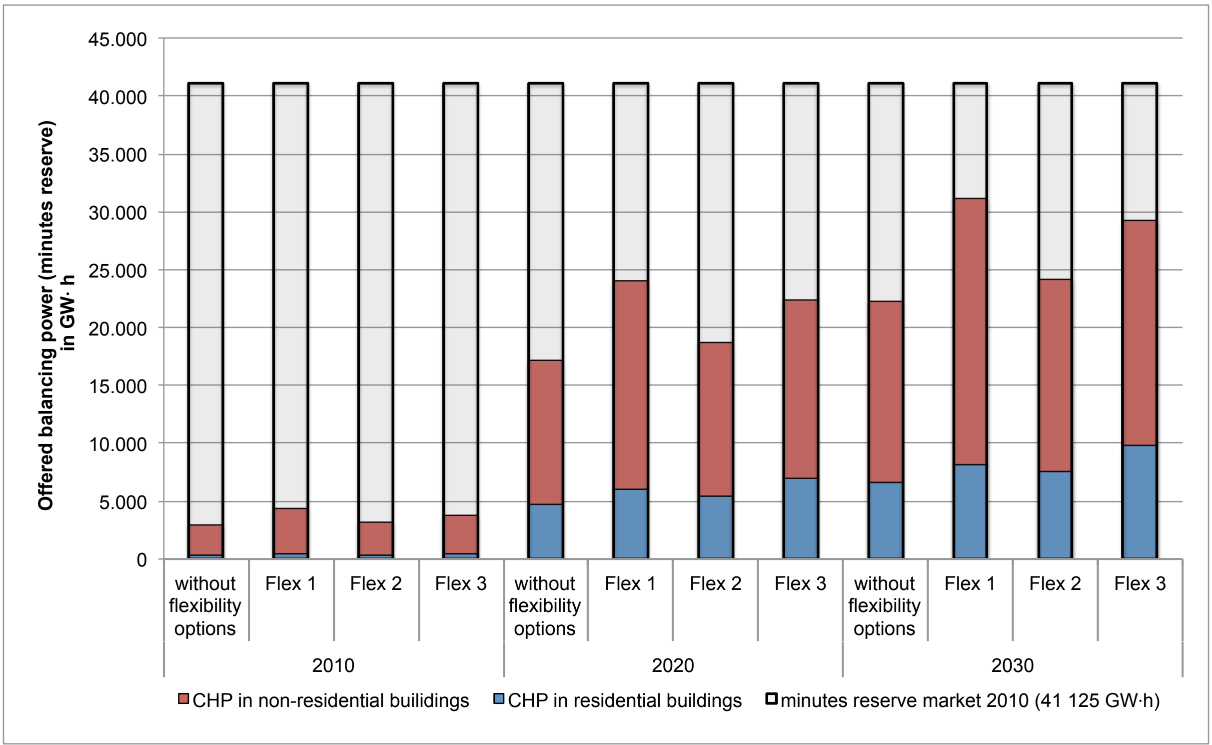
SFH: single-family house MFH: multi-family house Terraced H: terraced housing



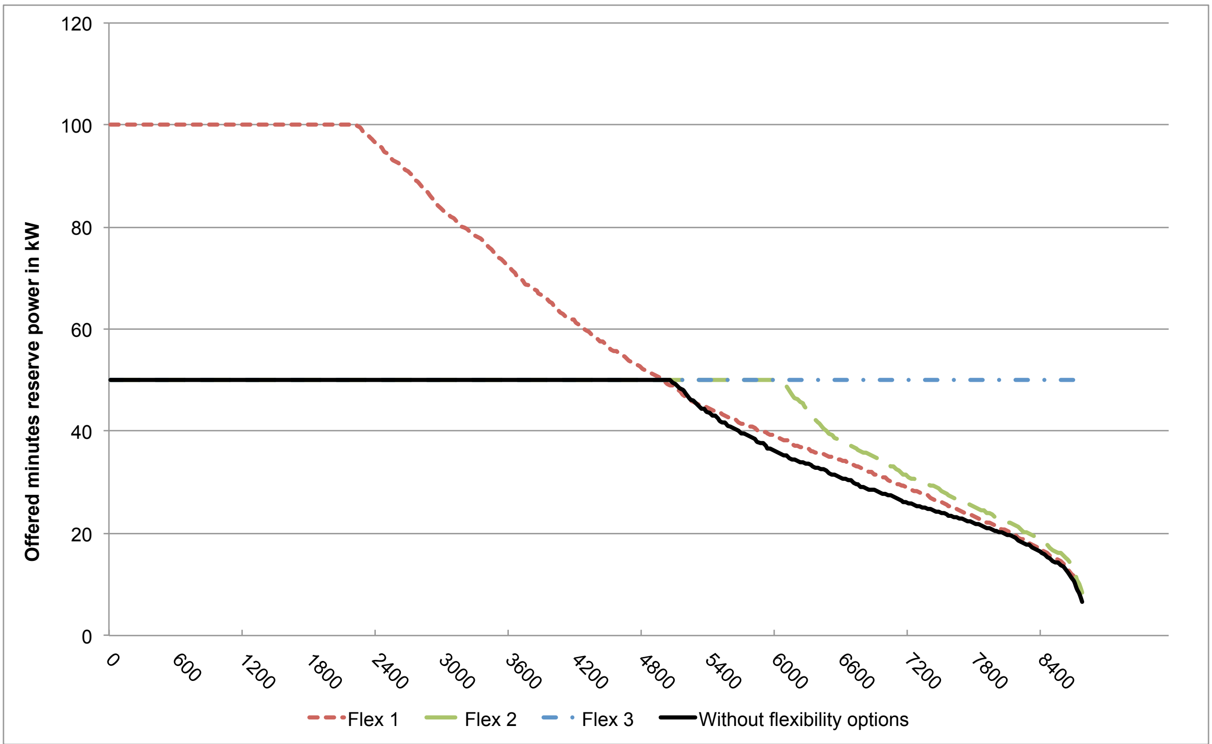
500
400
300
200
100
0
-100
-200
-300
-400
-500
25
20
15
10
5
0
-5
-10
-15
-20
-25
$P_{el,p}$ = 424 MW
Power (MWel)
Ambient Temperature (°C)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Offered positive minutes reserve
Offered negative minutes reserve
Temperature



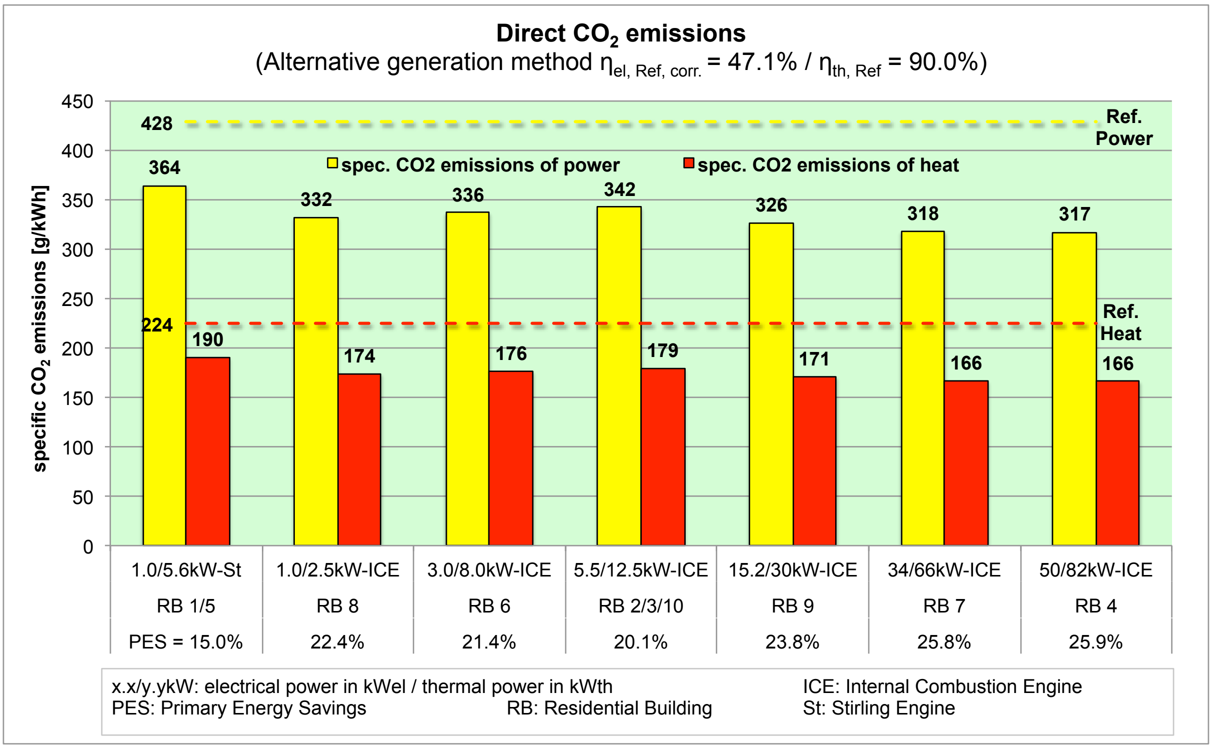
Minutes Reserve Potential
Offered Balancing Power (Minutes Reserve Market) in GW· h
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
ca. 7%
ca. 42%
ca. 54%
2010
2020
2030
CHP Potential Residential Buildings
CHP Potential Non-Residential Buildings
Minutes Reserve Market 2010 (41 125 GW·h)



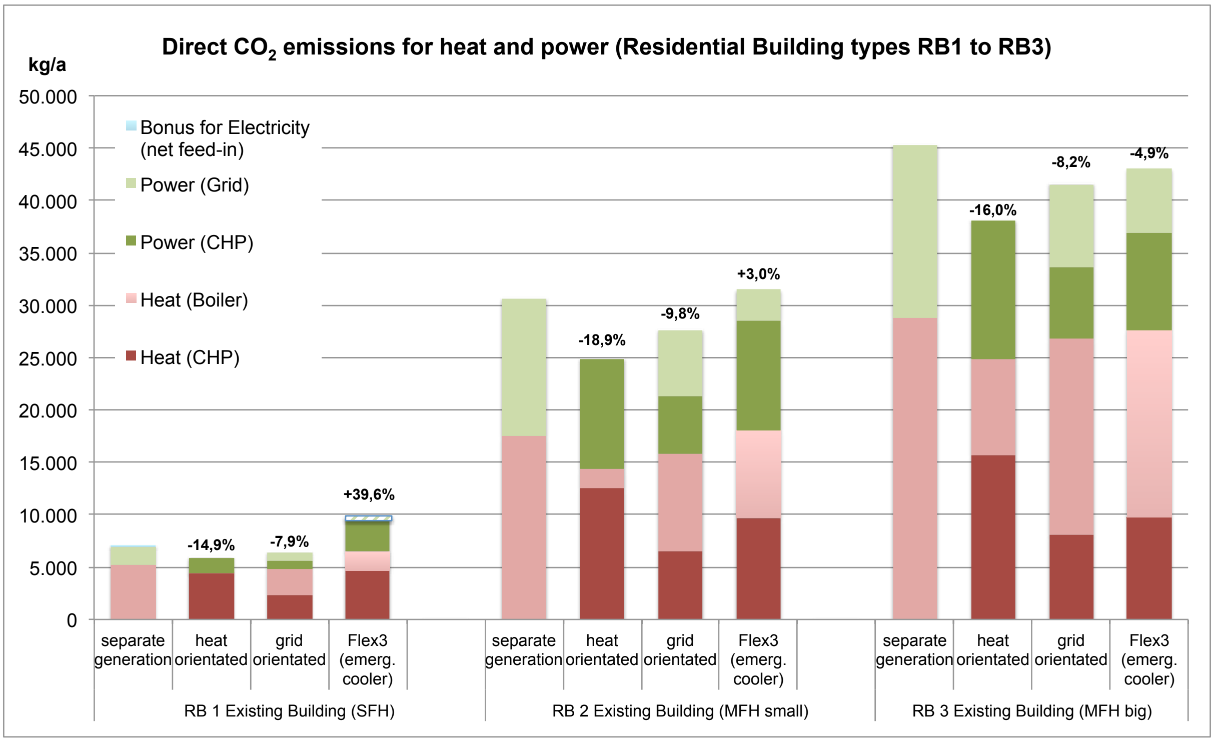
Offered balancing power (minutes reserve) in GW·h
45.000
40.000
35.000
30.000
25.000
20.000
15.000
10.000
5.000
0
without flexibility options
Flex 1
Flex 2
Flex 3
2010
2020
2030
CHP in non-residential builidings
CHP in residential buildings
minutes reserve market 2010 (41 125 GW·h)



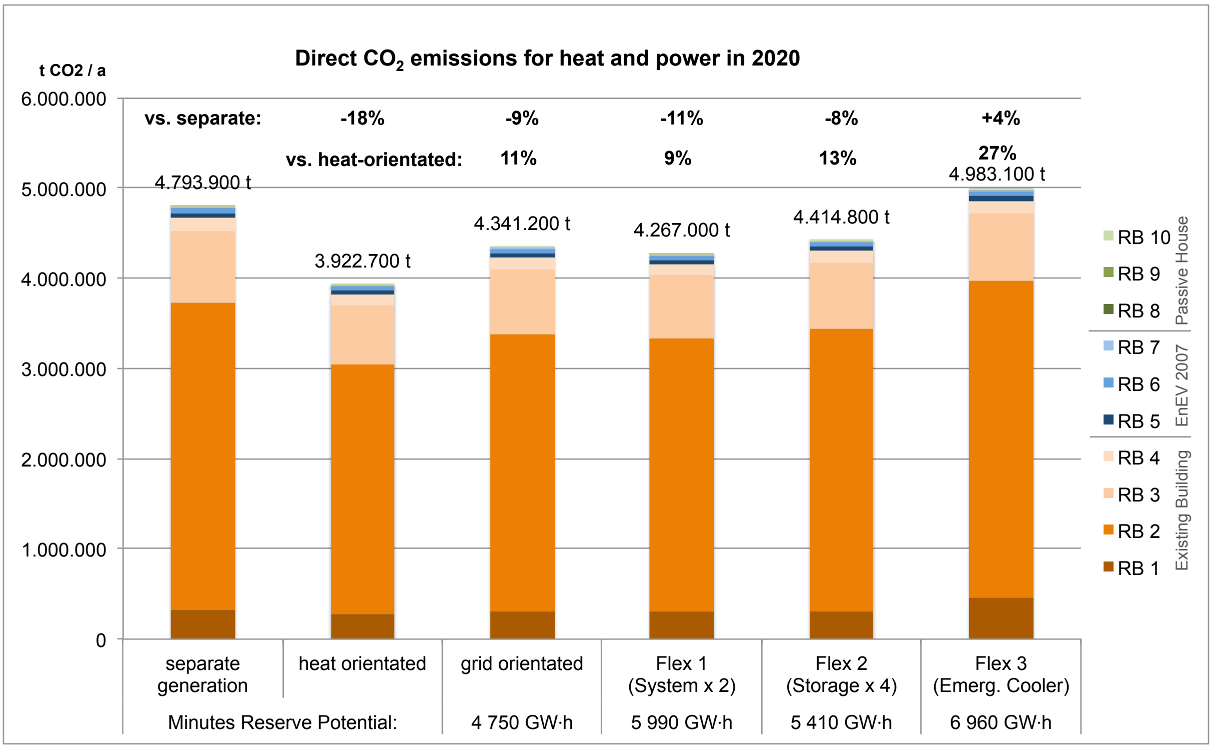
Offered minutes reserve power in kW
120
100
80
60
40
20
0
0
600
1200
1800
2400
3000
3600
4200
4800
5400
6000
6600
7200
7800
8400
Flex 1
Flex 2
Flex 3
Without flexibility options



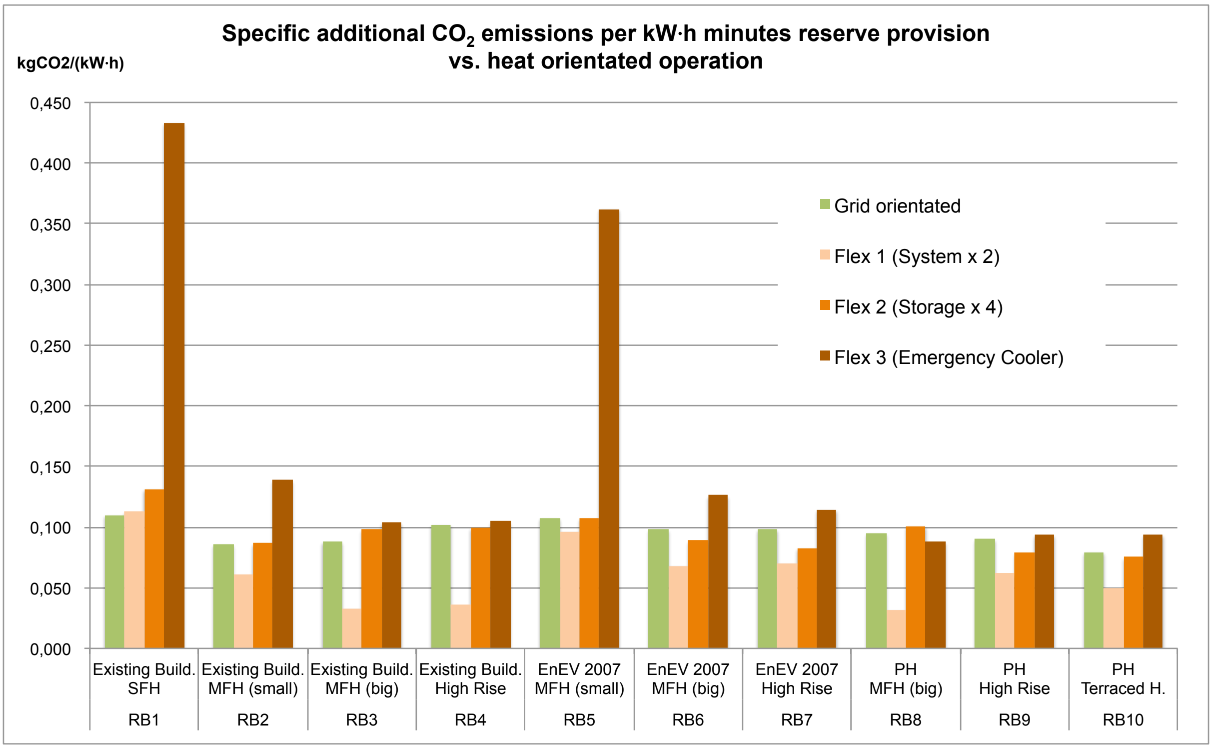
RB type	**RB 1**	**RB 2**	**RB 3**	**RB 4**	**RB 5**	**RB 6**	**RB 7**	**RB 8**	**RB 9**	**RB 10**
spec. CO_2 emissions for power *with* emergency cooler [g CO_2/kWh_{el}]	1.430	747	747	589	1.430	806	640	767	663	747
Additional emissions vs. CHP operation [%]	293	118	118	86	293	140	102	131	103	118
Additional emissions vs. separate generation [%]	234	75	75	38	234	88	50	79	55	75



Direct CO_2 emissions for heat and power (Residential Building types RB1 to RB3)
kg/a
50.000
45.000
40.000
35.000
30.000
25.000
20.000
15.000
10.000
5.000
0
Bonus for Electricity (net feed-in)
Power (Grid)
Power (CHP)
Heat (Boiler)
Heat (CHP)
-14,9%
-7,9%
+39,6%
-18,9%
-9,8%
+3,0%
-16,0%
-8,2%
-4,9%
separate generation
heat orientated
grid orientated
Flex3 (emerg. cooler)
RB 1 Existing Building (SFH)
RB 2 Existing Building (MFH small)
RB 3 Existing Building (MFH big)



Direct CO_2 emissions for heat and power in 2020
t CO2 / a
6.000.000
5.000.000
4.000.000
3.000.000
2.000.000
1.000.000
0
vs. separate:
-18%
-9%
-11%
-8%
+4%
vs. heat-orientated:
11%
9%
13%
27%
4.793.900 t
3.922.700 t
4.341.200 t
4.267.000 t
4.414.800 t
4.983.100 t
RB 10
RB 9
RB 8
Passive House
RB 7
RB 6
RB 5
EnEV 2007
RB 4
RB 3
RB 2
RB 1
Existing Building
separate generation
heat orientated
grid orientated
Flex 1 (System x 2)
Flex 2 (Storage x 4)
Flex 3 (Emerg. Cooler)
Minutes Reserve Potential:
4 750 GW·h
5 990 GW·h
5 410 GW·h
6 960 GW·h



Residential building type	**RB 1**	**RB 2**	**RB 3**	**RB 4**	**RB 5**	**RB 6**	**RB 7**	**RB 8**	**RB 9**	**RB 10**
CHP coefficient (power-to-heat ratio)	0.179	0.440	0.440	0.610	0.179	0.375	0.515	0.400	0.507	0.440
Losses from the emergen-cy cooler	28%	15%	4%	5%	21%	10%	13%	1%	8%	7%