

# Participating in the control reserve market with PV battery energy storage systems and power-to-heat application

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**Abstract**— One way to enhance the penetration of renewable energies in residential homes is to use renewables in the heating sector. Integrated homes combine PV battery storage systems with heat pumps to use PV-generated energy for heating. During winter, storage systems and especially batteries in an integrated home are not used to their full capacity due to low solar radiation. This potential can be used to enhance the economics of integrated homes by applying a second use scheme. Second use describes the value stacking of home storage operation and participation on reserve markets, as it is the case for this publication. In Germany, markets for primary and secondary control reserve are the most promising for integrated homes. An advantage of integrated homes with power-to-heat coupling in comparison to standalone battery storage system is the additional flexibility to absorb negative control reserve power provided by the heating sector. This allows an extension of the operating limits of a power-to-heat coupled battery. Advantages of integrated homes in comparison to stand-alone battery systems are investigated. Results show that a dual-use operation with participation on the control reserve market can increase profitability of residential storage systems. The economics of the market participation are highly sensitive to numerous factors. Participating on the negative secondary control reserve market can lead to reduced annual cost up to 14.5 % in the investigated scenario. These savings are mainly driven by free-of-charge energy. If a system participates on the primary control reserve market, savings are mainly driven by additional revenues from market remuneration. Annual cost reductions up to 12.5 % are possible. Savings include costs for communication. Costs for market access are not minded.

**Keywords**— *photovoltaics (PV), battery energy storage systems (BESS), power-heat coupling (P2H), thermal storage, integrated homes, control reserve market, heat pump*

## I. INTRODUCTION AND MOTIVATION

The German government aims to reduce the carbon-dioxide emissions by 61–62 % in the electricity sector and by 66–67 % in the building sector until 2030 [1].

One option for the decarbonisation of the residential heating sector is the coupling of the heating sector with the electric power generation from PV systems in residential households. The power generated by photovoltaic (PV) system can be used for space heating and domestic hot water to contribute to the energy transition in private households. Sector coupling of heat and power can be achieved, among others, by using heat pump systems.

Nevertheless, PV generated energy is supply-dependent and only available when the sun is shining. Energy demand on the other hand, is independent of the solar radiation. Storage systems are able to increase the share of locally used PV energy in residential households. Photovoltaic battery energy storage systems (BESS) can increase the self-consumption from residential PV systems and therefore contribute to a decentralized renewable electricity system.

Integrated homes incorporate power-to-heat coupling into photovoltaic battery energy storage systems. The combined system is capable of providing renewable energy to the household demand for heat and electricity. Furthermore, the flexibility of the battery storage is combined with the flexibility of the heating system given by the thermal storage capacity of the building itself and the thermal storage unit of the heating system.

Integrated homes can contribute to the decarbonisation process and support the integration of renewable energies by using renewables in the heating sector. To enhance the share of integrated homes, their economics need to be improved. The economics of integrated homes could be enhanced by the gain of additional revenues. These additional revenues could be generated on control reserve markets. In Germany, the primary and secondary control reserve markets are promising markets for integrated homes because of the favorable requirements regarding the energy-to-power ratio of participating storage units. Beside the enhanced economics, the contribution on the control reserve market, can enhance the system stability and therefore pave the way for further integration of renewable energies [2].

In this publication, participation on the primary control reserve (PCR) and secondary control reserve (SCR) market is investigated. The updated secondary control reserve market is used in this publication, as described in the following. Some countries decided a nuclear power phase-out. In Germany, all nuclear power plants are scheduled to shut down until 2022. After 2020, these power plants are not available for auxiliary services. With a decreasing share of conventional power plants and an increasing share of renewables in the grid, there was a need to adapt the balancing power market rules to the new conditions. This was one reason, the Germany secondary control reserve market was updated to remove burdens for participation of renewable energies and storage units on the market. In July 2018, the latest revision of the German secondary control reserve market became effective. The regulatory update of

the market leads to an increased auction frequency and shortened tendered time slices.

The German secondary control reserve market is divided in a positive and negative control reserve. In the negative control reserve market, the energy has to be taken from the grid if necessary. In this case energy is transferred to the integrated home that has low costs. Therefore, households with PV battery energy storage systems can gain additional energy from market participation and benefit from energy at very low cost or revenues from market participation.

Additional revenues on the secondary control reserve market can be generated especially in winter months, when the BESS is only used few days a month for home storage operation. The additional revenues from market participation increase the economics of integrated homes and can support the market penetration.

Integrated homes participating in the control reserve are sparsely discussed in literature. Melo et al. [3] investigated PCR provided by hybrid battery storage and power-to-heat system. He points out the advantages of hybrid systems and concludes that the economics can be improved for systems with a capacity-power ratio lower than one. Nevertheless, the studied system is not economically feasible under current market conditions. In the study a stationary BESS in MW size is investigated.

Domestic battery systems with power-to-heat coupling participating on the PCR market are investigated in [4]. The publication concluded that savings up to 31% in comparison to a BESS without P2H and PCR are possible. This publication does not use an aging model for BESS. Furthermore, different PCR offering strategies are not investigated. Publication [5] investigated the provision of BESS with power-to-heat coupling on MW scale. PV home storages participating on the PCR market are investigated in [6]. The authors conclude that a PV-BESS that combines enhancement of PV self-consumption with the provision of frequency restoration reserves leads to profitable investments. A power-to-heat coupling is not investigated in this publication. BESS participating in the SCR market are addressed in [7]. This publication investigates the possibilities in the updated SCR market.

## II. MODELLING

### A. Model overview

The participation on the control reserve market is evaluated based on a heat and power-coupling model of an integrated home. This integrated home consists of a PV BESS and a heat system to provide heating power and domestic hot water (DHW). A heat pump couples the electric PV BESS system with the heat system. The following figure gives an overview of the model components.

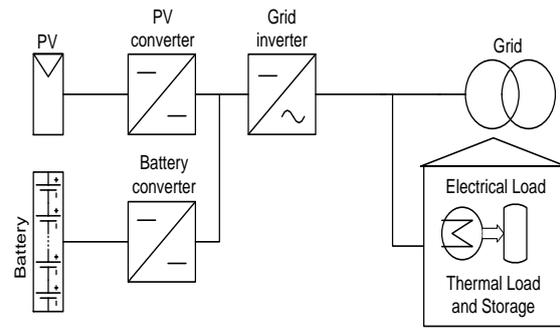


Fig. 1. Model of the grid-connected DC-coupled PV BESS [8]

The electrical model, containing the battery model, is based on the model presented in [8]. This battery model represents a DC-coupled PV BESS with a lithium-ion battery. The model of the lithium-ion battery is parametrized with the results of aging tests of a 2.15 Ah 18650 cylindrical lithium-nickel-manganese-cobalt-oxide (NMC) battery cell from LG-Chem (LG ICR18650MF1). A separate calendar and cyclic aging model is used based on [9, 10]. Input data for the load [11] and PV radiation of the electrical model are based on real data measurement.

A heat pump couples the thermal model and the electrical model. This heat pump model is based on a Vitocal 200-S heat pump from Viessmann [12]. This heat pump supplies a heat system with buffer storage and a DHW (domestic hot water) storage. The DHW storage is in parallel to the buffer storage [13]. Both storage units have been modelled according to commercially available systems [14, 15]. Figure 2 illustrates the investigated heating system.

### B. Component sizes of the integrated home

The sizes of the integrated home are based on typical sizes for commercially available components and the component sizes used for parametrization. Both storage systems have a volume of 300 l as recommended for a four person household [16]. The simulated BESS has a storage capacity of 10 kWh, according to typical sizes of commercially available systems with the highest market penetration [17]. The PV system has a rated power of 10 kWp. This model is parametrized with measurement data of a Vitocal 200-S split heat pump from Viessmann [18] with a thermal heating power of 10 kW<sub>th</sub>. Table I and table II depict the component sizes of the non-optimized integrated home. The presented sizes are typical component sizes for residential households. Except of the inverter size that is oversized to offer control reserve. The annual electrical load of the integrated is 4700 kWh<sub>el</sub> and the thermal load is 12500 kWh<sub>th</sub>.

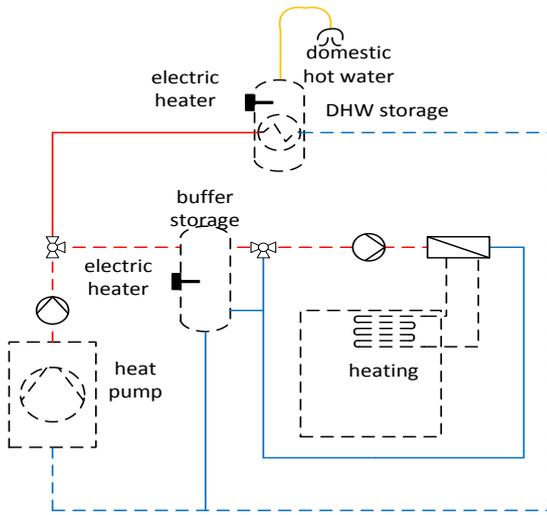


Fig. 2. Overview of the heating system

TABLE I. Component sizes of the electric system

Electric system	size
PV power plant	10 kW
converter sizes	10 kW
inverter	10 kW
Li-ion battery	10 kWh

TABLE II. Component sizes of the heating system

Heating system	size
Heat pump	10 kWth
DHW storage	300 liter
Buffer storage	300 liter

### C. Economic evaluation

To compare the impact of the market participation the annual costs are used. The economic evaluation is based on the annuity [19]. The Annuity incorporate all costs over the system's lifetime including initial investment, cost of operation and maintenance, and cost of capital. This costs cover all investment costs of the electric and heating system. The costs for the electric system include cost for the battery as well as cost for the three converters and the PV system. Costs for the heating system include costs for the heat pump and the two heat storages. Cost for reinvests as well as savings because of residual values are taken into account accordingly. Falling prices of the BESS due to scale effects in case of reinforcements are minded. The variable costs consist of the cost for the grid exchange, concerning the net present value of the electricity costs and savings due to the PV feed-in tariff. The changes of the electricity prices are evaluated by using an electricity price increasing factor. Maintenance costs are considered as fix costs. The following equation depicts the formula to calculate the annuity. Table III provides an overview on the economic input data of the model. This data is used to calculate the annuity.

$$A = \sum_{t=1}^n I_t(r, d_I) + V_t(r, d_V) + F_t(r) \quad (1)$$

A: Annuity

$I_t$ : Net present value of the investments in t

$V_t$ : Net present value of the variable costs in t

$F_t$ : Net present value of the fix costs in t

$E_t$ : Electricity consumption in t

r: Interest rate

d: Discount rate

TABLE III. Input data for annuity calculation

Parameter	Value	Unit	Description
$t_{calc}$	15	A	calculation period for invest assessment
$i_{calc}$	1.3	%/a	interest rate
$c_{bat}$	400	€/kWh	specific battery cost
$i_{bat}$	7	%/a	annual battery cost depression
$i_{c\_bat,kfW}$	13	%	subsidy rate on battery investment cost from KfW funding Q3 and Q4 2017 [27]
$c_{conv}$	173	€/kW	specific converter cost for one converter
$L_{conv}$	20	A	converter lifetime
$c_{PVgen}$	1170	€/kWp	specific converter cost for one converter
$L_{PVgen}$	20	A	converter lifetime
$c_{feed-in}$	0.122	€/kWh	feed-in tariff (Sep. 2017)
$c_{electricity}$	0.292	€/kWh	electricity cost (Sep. 2017)
$i_{electricity}$	1.85	%/a	annual electricity price increase
$i_{maintenance}$	1.5	%/a	annual maintenance cost relative to investment cost
$c_{heat\_pump}$	6795	€	heat pump costs
$c_{buffer}$	449	€	buffer storage costs
$c_{DHW\_storage}$	619	€	DHW storage cost
$c_{pump\_DHW}$	150	€	Costs for the DHW pump
$c_{pump\_heat}$	150	€	Costs for the pump supplying the heat system
$i_{maintenance,heat}$	150	€/a	annual maintenance costs for the heat system

### D. Participation on the primary control reserve market

The PCR is tendered on a weekly basis in Germany. The bid power price is paid to the accepted units (first price auction). The PCR is procured as a symmetrical product. Suppliers have to provide an upward and downward regulation related to the power offered. However, for both regulation directions, different technical units can be deployed. The bidding period for PCR is one week. Offers for PCR must guarantee a provision over a weekly period in one time slice. For the PCR market only the provided power capacity is paid [20, 21].

Renewable energy produced by a PV power plant in a domestic household cannot only be used to cover the electric load. This energy can also be used to cover the heating demand of the household if for example a heat pump is installed in the building. The examined household in this section couples the heating sector with the electrical sector to enhance the self-consumption and in some cases the economics of the household [22]. The required power for the heating sector can be taken from the negative PCR. The negative control reserve can be transferred into the heating sector. Therefore, the limitation of the battery can be reduced as depicted in Figure 3. If the BESS is fully charged the negative PCR power can be transferred into the heating sector with the heater rod. The negative PCR has to be used

for heating. It is not allowed to waste the negative PCR power.

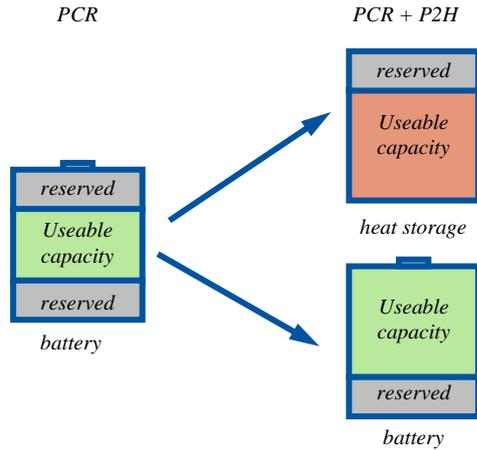


Fig. 3. Allocation of the reserve capacity of a BESS with power to heat coupling participation in the German PCR market in comparison to a standalone BESS. Positive control reserve can be transferred to the heating sector, leading to higher useable capacity.

In winter month the BESS is used less for home storage operation. Therefore, a higher share of PCR can be offered on the market without major limitation of the home storage operation. Therefore, a variable offer of PCR on the market is presented in this section.

To participate on the primary control reserve market the 30-minute criterion has to be fulfilled. The 30-minute criterion ensures that the battery storage system can provided the maximum primary control reserve power for at least 30 minutes. The thermal storages can be used to absorb the negative control reserve power. This is an advantage in comparison to PV battery energy storages systems without power heat coupling, since the battery system is less limited. Due to the 30-minute criteria the maximum PCR power that can be offered with a 10 kWh BESS is 4 kW of PCR. If a power-to-heat coupling is applied, the negative control reserve can be transferred to the heating sector as depicted in Figure 3. In this case, a 10 kWh BESS can provide a maximum of 8 kW of PCR.

The weekly offered PCR is depicted in Figure 4 with respect to the 8 kW limit of the battery size. The determination of the weekly offered requires forecast of the load and the PV feed-in. A persistent forecast for load and PV radiation is used. The variable offer of PCR power leads to an average offer of 5.9 kW/week.

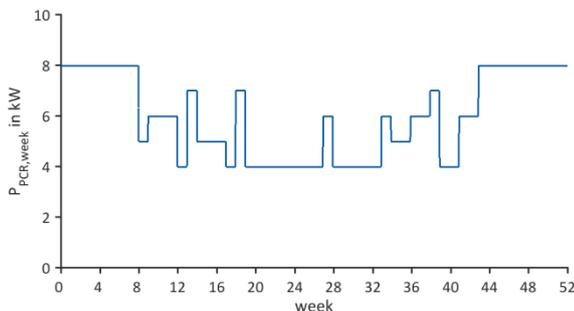


Fig. 4. Resulting variable PCR offer of a PV BESS with power heat coupling and a 10 kWh BESS and a 10 kWp PV system.

#### E. Participation on the secondary control reserve market

In Germany, the provision of positive and negative SCR is tendered separately. For the SCR a capacity price and an energy price are paid. Therefore, the bid of each supplier has to specify a capacity price bid for provided reserves (paying the provision) as well as an energy price bid for deployed reserves (paying a possible activation) [20, 21]. Since July 2018, new market regulations for the German SCR market are in effect. These regulations are defined in [23] and aim to reduce excess barriers for renewable energy generation, demand-side-management-systems and BESS to the SCR market. Therefore, the time slices of the SCR are shortened. Before the new regulations were lunched, two time slices per day were auctioned. In the updated market, six time slices each four hours, are auctioned.

The maximum temperature of the water from the heat pump is 55°C. The maximum allowable temperature of the buffer and DHW storage is 95°C. The heating capacity of water is  $c = 4190 \text{ J}/(\text{kg}\cdot\text{K})$ . The maximum chargeable capacity from SCR in each storage unit can be calculated as following:

$$\left(4190 \frac{\text{J}}{\text{kg}\cdot\text{K}} \cdot 40 \text{ K} \cdot 300 \text{ kg}\right) = 14 \text{ kWh} \quad (2)$$

Each storage unit can absorb at least 14 kWh of SCR. Therefore, in total the heating system can store 28 kWh of additional SCR energy. Minding the 4-hour criterion the maximum SCR power is 7 kW for the non-optimized integrated home as calculated in the following equation.

$$P_{SCR,max} = \frac{14 \text{ kWh} + 14 \text{ kWh}}{4 \text{ h}} = 7 \text{ kW} \quad (3)$$

The maximum SCR power (7 kW) for the integrated home can only be offered, if the temperature in the heating sector is below 55°C at the beginning of the 4-hour time-slice. In some cases, the aforementioned assumption is not fulfilled. In this case, the integrated home with a constant SCR power offered on the market, cannot participate on the SCR market. The algorithm calculated the storage temperature and checks if the integrated home can participate on the SCR based on the storage temperature and the offered SCR power. Additionally an operation strategy to a variable among of SCR power is developed. The participation on the SCR market influences the SoC of the battery and thermal storage. In order to fulfil the prequalification requirement, the absorption of the offered SCR power for the following 4 hours has to be guaranteed. This is why, the SoC of the storages determine the maximum SCR that can be offered on the market. The variable SCR offering strategy calculates the maximum SCR power that can be offered. Therefore, the available remaining storage capacity, in dependency of the actual SoC, is calculated. The remaining storage capacity is divided by 4 hours to determine the maximum SCR power that can be offered. Equation (4) depicts this correlation. The offered SCR power is rounded down to the next integer.

$$P_{SCR \text{ var}} = \frac{Cap_{bat} \cdot (1 - SoC_{bat}) + Cap_{heat} \cdot (1 - SoC_{heat})}{4 \text{ h}} \quad (4)$$

With the developed strategy, more SCR power can be offered on the market that leads to an enhanced economics. The time delay between bidding and provision of SCR is neglected. Additionally it is assumed that the pool, in which

the integrated home is operated, is flexible enough to capitalize the offered SCR power. The offered SCR power, is depicted in Figure 5. The offered SCR power ranges can from 1 kW to 9 kW. If the 10 kWh battery storage as well as the 28 kWh heat storage are empty, the integrated home can offer a maximum SCR power of 9 kW.

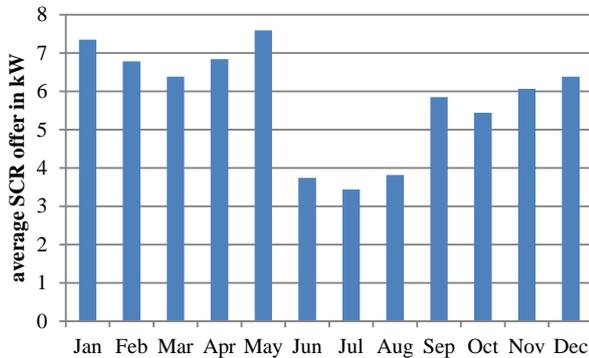


Fig. 5. Resulting variable SCR offer of a PV BESS with power heat coupling, a 10 kWh BESS, a 28 kW heat storage and a 10 kWp PV system.

### III. RESULTS

#### A. Economic impacted of the participation on the primary control reserve market

This section investigates the economic evaluation for PV BESS participating in the PCR market. The analyses include the costs for reduced self-consumption rate and increased battery aging, due to PCR participation. Costs for market participation and communication are minded. Further savings, due to additional energy gained from the utilization of the degrees of freedom, are taking into account. The depicted results in Figure 6 present the annuity of the integrated home. Participation on the market with 1 kW of PCR leads to higher annual costs in comparison to a household not participating in the market. The reason is the additional costs for deployment. Whereas a provision of 5 kW PCR reduces the costs, due to higher revenues from the market participation. The revenues for control reserve are higher, when the integrated home offer 8 kW of PCR in comparison to an offer of 5 kW. Nevertheless, the overall annuity is higher. The participation on the market leads to an reduced battery capacity for home storage operation. This is why the provision of 8 kW PCR leads to higher annual costs compared to the provision of 5 kW PCR. The lowest annual costs are achieved with a variable PCR provision. This is why, the variable PCR provision leads to the highest economics.

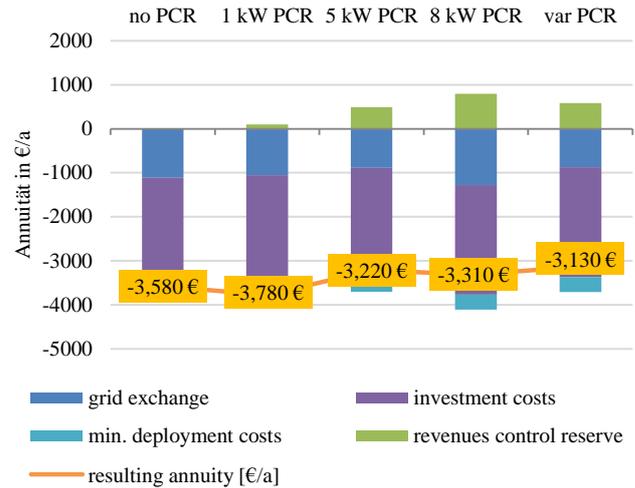


Fig. 6. Annuity in relation to the PCR offers of a PV BESS with power-to-heat coupling and a 10 kWh BESS and a 10 kWp PV system.

#### B. Economic impacted of the participation on the secondary control reserve market

The participation on the negative secondary control reserve market can provide low-cost or free-of-charge energy for the integrated home. The received energy leads to reduced grid consumption as well as an enhanced PV feed-in. Figure 7 depicts the annuity of an integrated home participating in the secondary control reserve (SCR) market in comparison to an integrated home without market participation. The annuity depends on the SCR power offering. The SCR power can be used to reduce grid consumption and increase PV feed-in. These savings overcompensate the additional costs for battery aging. Therefore, the integrated home saves costs when participating in the SCR market. However, in the case the integrated home offers 1 kW of SCR the costs for market deployment exceeds the revenues of market participation. In case of a provision of 5 kW SCR the reduced costs for grid exchange exceed the costs of the deployment. This leads to a higher economic in comparison to an integrated home not participating on the SCR market. In case the integrated home offers 7 kW SCR the annual costs are higher in comparison to an integrated home offering 5 kW SCR. The reason is that the storages of the integrated home have temporarily a high SoC. When the storages have a high SoC the integrated home cannot fulfil the market participation requirement, because it is not able to absorb SCR for the next 4-hours. In this case, the integrated home cannot participate on the SCR market. This is the incentive for the developed variable SCR offering strategy. This strategy is presented in section II E and leads to the lowers annuity and therefore to the highest economics of the integrated home.

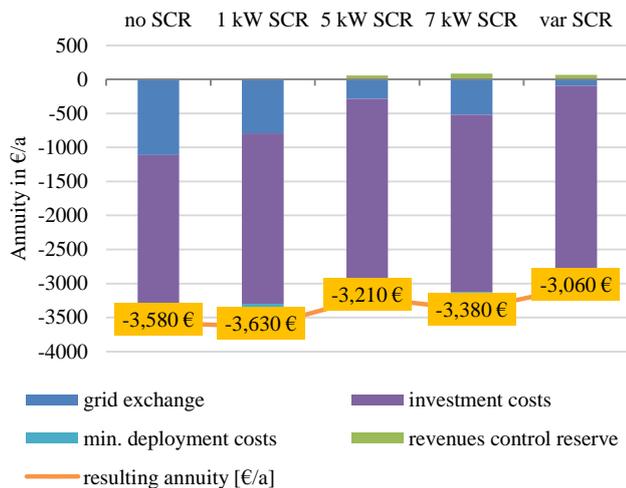


Fig. 7. Annuity of an integrated home (10 kWp PV system, 10 kWh BESS, 10 kW heat pump) participating in the SCR market in comparison to an integrated home without market participation.

#### IV. CONCLUSION AND DISCUSSION

In this section, a comparison of the SCR and the PCR participation of the integrated home is presented. The comparison of the SCR market participation and the PCR market participation leads to the conclusion, that the savings participating in the SCR market are slightly higher compared to the savings of the PCR market participation as depicted in Figure 8. Additionally the PV BESS with combined heat and power is compared to a common concept of the energy and heat supply. Therefore, a comparison to a household with gas heating and electric supply from the grid is presented. Heating power from gas is used as the benchmark for the thermal energy consumption. The costs for the gas heating system are based on [24]. The costs of the house with the gas heating system combine the costs for the electricity and gas consumption as well as the annual costs for the gas heating system.

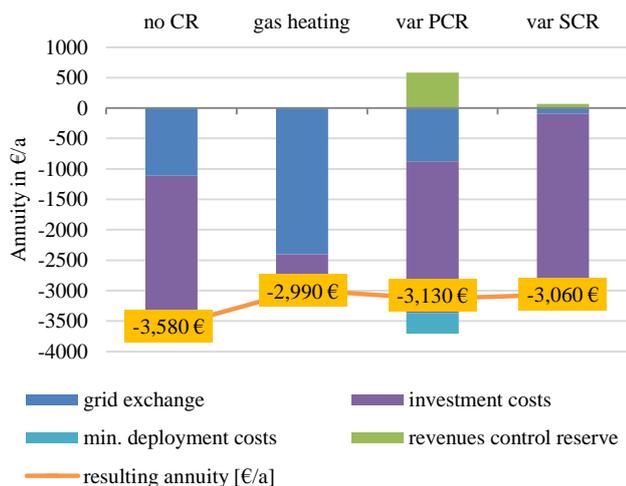


Fig. 8. Annuity of an integrated home (10 kWp PV system, 10 kWh BESS, 10 kW heat pump) participating in the PCR and SCR market in comparison to an integrated home without market participation and a house with gas heating.

The presented analysis leads to the conclusion, that an integrated home participating on the control reserve market has similar annual costs as a household with a fossil heating

concept. Nevertheless, the participation on the control reserve market is challenging. One challenge are the decreasing remuneration of control reserve. Additionally, the costs for market participation and communication are not clear and need to be reduced in future. The pooling of small PV battery energy storage systems for market participation is challenging, since a complex measurement procedure has to be installed. Finally yet importantly, it exist regulatory issues when integrated homes participate on the control reserve market. For example in Germany additional charges (e.g. Renewable Energies Act levy (EEG-Umlage), grid utilization charges (Netznutzungsentgelt), interruptible loads levy (Umlage für abschaltbare Lasten)) occur on heat from primary control reserve power. Additionally a sophisticated measurement concept has to be applied, because if electricity form the grid (Graustrom) is mixed in the storages with electricity form the PV power plant, levy and taxes for the energy from the PV power plant incurred. This is the case if the BESS is bigger than 10 kWh.

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