A Techno-Economic Analysis of Battery Energy Storage Systems in Combination with Micro CHP Systems for Single-Family Houses

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Abstract— **In this paper, the performance of battery storage systems in combination with micro combined heat and power (CHP) systems are systematically investigated by computer simulations for the supply of single-family houses in various settings. As input parameters for the analysis, energy demand-time series for electricity, heating and domestic hot water are considered for selected building types. The focus of the analysis is on the functional relationship between self-sufficiency (autarky) and self-consumption fraction on the one hand and factors such as system configuration (e.g. battery storage capacity), power and heat demand on the other hand. The results of the analysis shows that battery sizing only significantly affects autarky and self-consumption fraction up to a capacity of 2 kWh. The results of the economic evaluation shows also, that highest NPVs are reached for small batteries with capacities up to 2 kWh. Also, the operation of batteries in combination with CHP systems differs from the operation of batteries in combination with PV systems and results in higher full cycle numbers and different battery utilization patterns with a strong seasonal influence.**

I. Introduction

With the expansion of renewable energy technologies (RETs) and combined heat and power (CHP) systems, there is a trend towards decentralized heat and power supply solutions. The use of battery storage, in combination with photovoltaic (PV) systems, to increase self-consumption has become state-of-the-art in residential buildings. In Germany in 2017, almost every second $< 30\,$kWp PV system in the segment was equipped with a battery. The combination of battery storage with micro CHP systems is currently not as widespread though. Due to the sharp drop in prices for battery storage systems, however, these are becoming increasingly interesting for this application. Some manufacturers for (residential) stationary battery energy storage systems promote the use of batteries in combination with micro CHPs. However, at present there seems to be no statistics available pertaining to the market penetration of batteries in combination with CHP systems.

A. Literature review

As mentioned above, the use of battery storage in conjunction with photovoltaic (PV) systems to increase self-consumption has become state-of-the-art in residential buildings. Therefore, numerous studies have been conducted into the application of grid-connected PV battery energy storage systems (BESS) in the residential sector [1, 2]. Most of these focus on techno-economic aspects, addressing the development and application of optimization approaches and related profitability analyses of PV BESS [3, 4]. Publications with a more technical focus cover a broad range of research questions and topics. For example, different aspects regarding the sizing of residential PV battery systems are described in the literature [1, 5, 6]. The influence of individual consumer behavior and preferences on self-consumption is analyzed, while other sources also focus on aspects of grid independence [7-9]. The market development of PV battery systems and related feed-in tariffs are investigated in Bayod et al. [2].

However, the combination of battery storage with micro CHP systems in the residential context has not been intensively explored in the literature. Nevertheless, there are publications that analyze the combination of battery storage with micro CHP systems. For example, the energy management for a micro-CHP system, in combination with an electrical storage system in a residential application, is examined by Weber et al. and Chen et al. [10, 11]. Studies such as [12-14] focus on techno-economic features for this purpose. A simulation of an integrated approach, combining a PV system, Stirling engine CHP and battery storage, is presented by Balcombe et al. [15]. An optimization of an entirely self-sufficient building equipped with a reversible fuel cell, in combination with a PV system and battery and hydrogen storage system, is analyzed by Kotzur et al. [16].

Thus far, techno-economic characteristics with regard to battery sizing and operation in the context of combined use with a micro CHP system in a residential environment have not yet been investigated in detail. This is one of the key features presented in this work, especially given different CHP technologies (SOFC and PEM-FC) and application cases.

B. Research objective

Within the scope of this contribution, the design of battery storage systems in combination with micro CHP systems for the supply of single-family houses is systematically investigated. As input parameters for the analysis, energy demand time series for electricity, heating and domestic hot water are considered for selected archetype buildings. Using a simulation model, the operation of combined battery micro CHP systems is analyzed. The dependency of the degree of self-sufficiency (autarky) and self-consumption fraction from the system configuration (e.g., battery storage capacity) and the electricity and heat requirements of the buildings is the focus of the analysis. An economic evaluation of battery-supported micro CHP system applications in selected single-family houses complements the findings of the study. The focus is explicitly placed on the impact of batteries and on the techno-economic system performance of battery-supported micro CHP systems, which will be presented and discussed in this manuscript. The analysis considers the state-of-the-art technology parameters of commercially available systems, and therefore has high practical relevance.

II. METHODOLOGY AND BASIS DATA

In chapter A, the general modeling approach is described. Chapter B contains the description of the used load profiles. The definition of the application cases is presented in chapter C. Further, in chapter D, the technical parameters of the system components are determined. Finally, in chapter E the methodology of the economic evaluation is examined. This includes an analysis of the economic framework.

A. Modeling approach

The building energy system was modeled with the commercially-available software, "Polysun", version 10.2 [17]. In this program, each component of the energy system is described in detail. The input is made through a graphical user interface in which the components can be individually selected and parameterized. Each component is based on a database that contains the predefined components. The control is carried out either by means of task-related controllers, such as flow controllers, or by means of a freely-programmable controller in which states and conditions of occurrence can be defined in a formula-based manner. To simplify the modeling process, templates for typical systems can be adapted. Various variants in one project file allow for a direct comparison between two or more building energy systems. Figure 1 shows the workflow of the simulation model adapted to the considered application cases of this study.
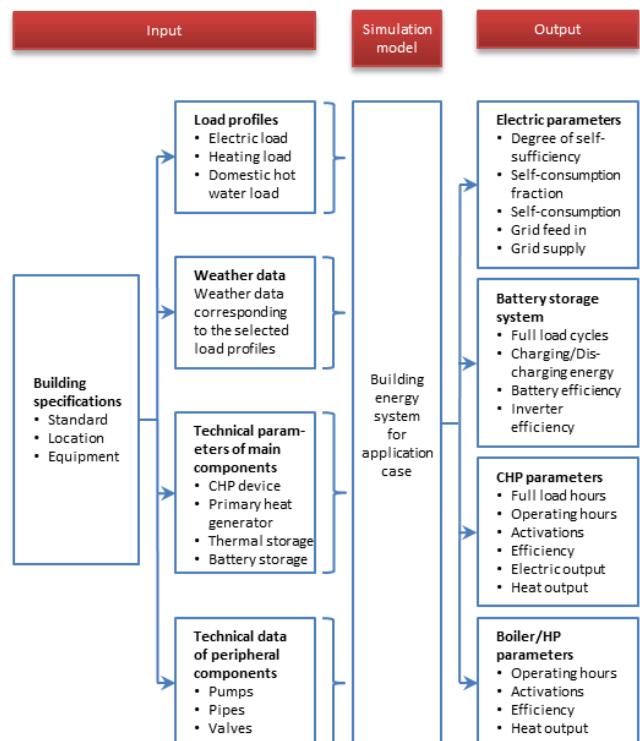

Fig. 1. Implemented simulation workflow

To model a building's energy system, information about the building standard, location and equipment is needed. The building standard and location are defined by the time series data, for the household's energy demand for heating, domestic hot water and electricity. The components are chosen by the criteria explained in chapter D. This includes the CHP system, boiler, heat pump (HP), thermal storage and battery storage system. The battery storage system consists of two components: the battery and battery inverter. For the

peripheral components (see Figure 1), standard components from the Polysun component library are used. The pumps are sufficiently dimensioned to achieve the required volume flow of the heating system. After all the components have been defined, a time step can be specified. Only variable time steps are allowed in this, which means that only a maximum time step can be defined. In this paper, 60 seconds is chosen as the time step.

The main output values are specified in Figure 1. The focus of this analysis is on the electric parameters, in particular the degree of self-sufficiency and self-consumption fraction. The degree of self-sufficiency is defined by the ratio of own consumption to total electrical consumption. For own consumption, the electrical consumption and sum of own-produced electricity and battery discharge are compared at each time step. The minimum of both values results in own consumption of the time step. The self-consumption fraction is defined as the ratio of own consumption to own-produced electricity. The system is characterized by many other parameters that must be taken into account during the evaluation of the techno-economic system's performance (see chapter III).

B. Load profiles

The VDI guideline 4655 [18] provides reference load profiles for electricity, heating and domestic hot water demand for single- and multi-family houses. The reference load profiles are based on the measured load profiles of existing houses. The resolution of the profiles is 1 minute for single-family houses and 15 minutes for multi-family houses. To reduce complexity, the measured load profiles have been aggregated to 10 typical days. To account for the influence of different building sites on the energy demand of single- and multi-family houses, Germany is divided into 15 climatic zones according to a classification of the German Meteorological Service (DWD). Based on the region-specific, typical day distribution for an average climate year (test reference year: TRY [19]), the reference load profiles can be derived for 15 climate zones in Germany. For further details regarding the reference load profile methodology, the basic data and assumptions, see the VDI [18].

In the context of the present work, the load profiles for single-family houses for the climate zone "Lower Rhenish Bight, Westphalian Bight and Emsland" (climate zone no. 5) are considered. Figure 2 shows the resulting electricity load profile normalized to an electricity consumption of 1,000 kWh per year.

In the following, the characteristics of the resulting reference load profiles for electricity, heating and domestic hot water demand are briefly described. All profiles are available at 1 minute resolution.

According to the VDI [18], the annual electricity demand in single-family houses is assumed to be 2,000 kWh per person for households with less than 3 persons, 1,750 kWh per person for 3 to 6 persons and 1,500 kWh for more than 6 persons. This results, respectively, in a total annual electricity demand of 4,000 kWh for a 2-person household and 7,000 kWh for a 4-person household. The electricity demand is limited to domestic purposes and does not include the electrical energy required for domestic hot water and heating.
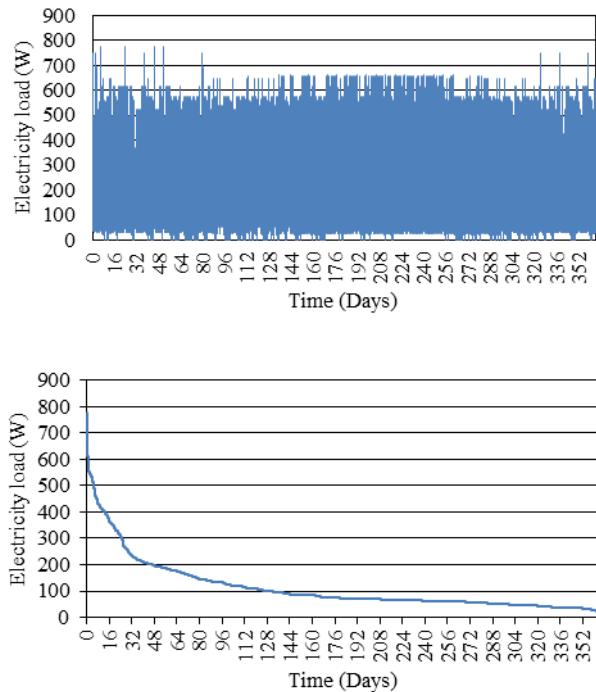
Fig. 2. Annual electricity load profile (above) and sorted annual electricity load profile (below), each normalized to an annual electricity demand of 1,000 kWh (own presentation based on the VDI [18])

To adapt the normalized profile (Figure 2) to different annual electricity demand values, the normalized profile is linearly scaled with a factor. The resulting scaling effect on the peak load and average electricity load is shown in Figure 3. The peak load is scaled from 0.775 kW for an annual electricity consumption of 1,000 kWh (normalized profile) to 3.1 kW for an annual electricity consumption of 4,000 kWh with the factor of 4. In general, it can be stated that a relatively low peak load, especially for households with low electricity consumption, and a relatively high base load, is characteristic for the electricity load profile considered. A comparison of the peak load of the electricity load profile to the peak load of single electrical devices (e.g., an electric stove with > 10 kW for 4 hot plates and an oven) confirms this statement. It therefore seems that load peaks tend to be underrepresented in the considered electricity load profile.
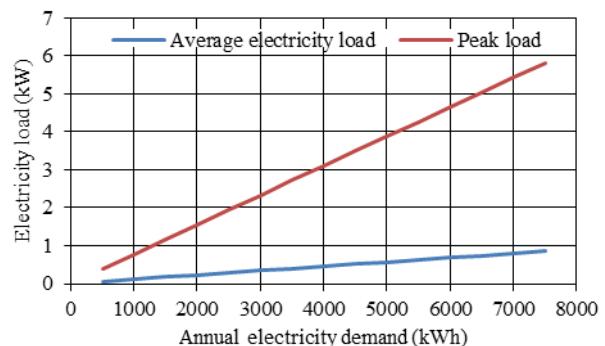
Fig. 3. Scaling of peak load and scaling of average electricity load depending on annual electricity demand

Figure 4 shows the resulting heating and domestic hot water load profile normalized to a heat / domestic hot water demand of 1,000 kWh per year.

The heating and domestic hot water load profiles both show clocked behavior. The peak load of the normalized heating load profile is 1.89 kW and occurs frequently over the year. In general, the heating load profile follows a typical course and the heating period can be clearly allocated to the winter months. Nevertheless, shorter heating demand periods can also be observed in the summer months. The absolute heating load profile is scaled with a factor, in accordance with the annual heating demand of the building. The peak load of the normalized domestic hot water profile is 41.60 kW and occurs frequently across the year. In general, the domestic hot water load profile follows a typical course, with relatively short demand periods and is evenly distributed over the year. According to the VDI [18], the annual hot water demand in single-family houses is 500 kWh per person. The absolute domestic hot water load profile is scaled with a factor that corresponds to the total number of persons.
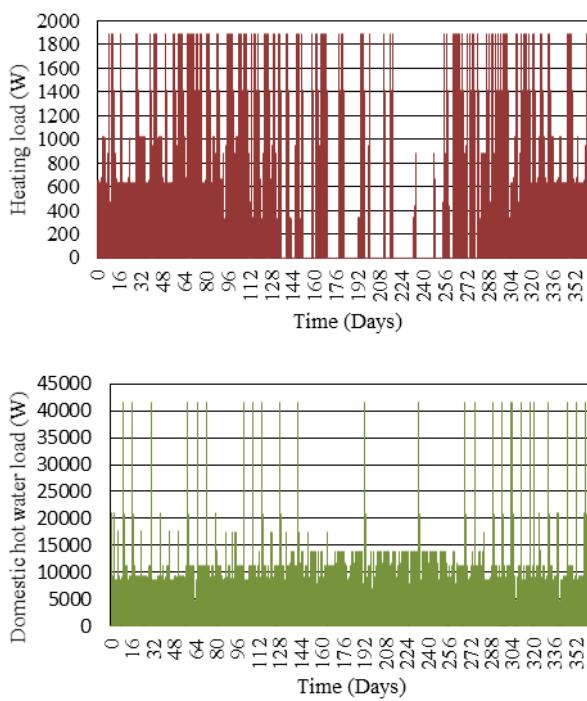

Fig. 4. Annual heating load profile (above) and annual domestic hot water load profile (below), each normalized to an annual heating/ domestic hot water demand of 1,000 kWh (own presentation based on the VDI [18])

C. Definition of application cases

In this analysis, two different building types are considered as possible application cases for combined micro CHP plus battery energy storage systems in single-family houses. A distinction is made between a new building and an old building. The parameters of the buildings are summarized in Table I.

The characteristics of the buildings are taken from the IWU building typology [20]. As a new building, the building with the TABULA-Code DE.N.SFH.12.Gen was chosen from the IWU database in the heating system variant, "Gas" (EFH_L). The living space of the building is 160 m², with a specific heating demand of 46.3 kWh$_{th}$/(m²·a). The heating demand is related to the building standard, "KfW-Effizienzhaus 55" (see Loga et al. [20] for further details). As an old building, the building with the TABULA-Code DE.N.SFH.05.Gen is chosen from the IWU database. The

living space of the building is 110 m², with a specific heating demand of 180 kWh$_{th}$/(m²·a). No modernizations of the building envelope are assumed. The demand for hot water and electricity is calculated based on the VDI [18] and depends on the number of persons living in single family houses (see chapter B). It therefore further distinguishes between a two- and four-person household. The resulting demand for hot water and electricity is summarized in Table I and is independent from the building standard. The normalized load profiles in chapter B are scaled according to the specified energy demand in Table I and used as input time series for the simulation of the building energy system (see chapter A).

TABLE I.   PARAMETERS OF SELECTED ARCHETYPE BUILDINGS.

Building type		New building (KfW 55 Standard)		Old building	
Age class	-	2016		1958-1986	
Living space	m²	160		110	
Heating demand (specific)	kWh$_{th}$/(m²·a)	46.3		180	
Heating demand (absolute)	kWh$_{th}$/a	7,410		19,740	
Persons	-	2	4	2	4
Domestic hot water demand	kWh$_{th}$/a	1,000	2,000	1,000	2,000
Electricity demand	kWh$_{el}$/a	4,000	7,000	4,000	7,000

Different energy supply concepts are considered to fulfill the demand for electricity, heating and domestic hot water. The building energy system configuration discussed here is summarized in Table II.

TABLE II.   CONSIDERED BUILDING ENERGY SYSTEM CONFIGURATIONS.

Building type	New building	Old building
CHP Type	PEM-FC	SOFC
Primary heating system	Boiler	Heat Pump
Storage type	Combined heat storage tank*	Combined heat storage tank*
Battery type (optional)	Lithium-Ion	Lithium-Ion

*Combined storage tank for heating and domestic hot water

Both building types are equipped with a CHP system, in combination with a primary heating system. The integration of a heat pump in the building energy system increases the total electricity demand in comparison to the electricity demand values provided in Table I. Both building types are equipped with a combined heat storage tank for heating and hot water. Furthermore, a battery energy storage system, in combination with the CHP systems, is considered in the analysis on the basis of a parameter variation of the battery storage capacity. The detailed technical parameters of the system components are summarized in the following chapter.

D. *Technical parameters of the system components*

Table III lists the technical parameters of the selected CHP systems. For CHP applications in single-family houses, the most suitable technology is fuel cells. Fuel cells offer the advantage of high CHP coefficients, high efficiency and the availability of systems with low nominal electrical power according to the energy demand requirements in single-family house applications. This analysis further distinguishes between polymer electrolyte membrane fuel cell (PEM-FC) and solid oxide fuel cell (SOFC) CHP systems. The technical parameters of both CHP types are based on the specifications of two commercially-available systems (see Table III).

TABLE III.   PARAMETERS OF SELECTED CHP SYSTEMS.

CHP Type		PEM-FC	SOFC
Modulation	-	Yes	No
Electric power	kW_{el}	0.25 – 0.70	1.5
Thermal power	kW_{th}	0.21 – 0.95	0.62
CHP coefficient	-	0.74	2.42
Electric efficiency	%	30.2 – 37.7 [a]	63
Thermal efficiency	%	25.3 – 51.4 [a]	27
Sources	-	[21, 22]	[23]

[a]Own calculation based on data in Staffell [21].

The PEM-FC is a modulating system. According to Staffell [21], the electrical efficiency of a comparable PEM-FC system with 1 kW electrical power, drops over the modulation range (35-100%, based on the nominal power) up to about 80%. This value is therefore considered as a lower efficiency limit in the modeling of the part-load efficiency of the selected CHP system. The in-between efficiencies are determined by linear interpolation. The PEM-FC is operated according to the thermal energy demand (heating and domestic hot water) of the building's energy system. The SOFC is a non-modulating system and is continuously operated at nominal electric power (1.5 kW), reaching a very high electrical efficiency. The feed-in of surplus electricity generated from the CHP system into the public electricity grid is possible.

As the CHP system is not usually designed to cover the complete thermal energy demand of a building, a primary heating system is typically used in combination with a CHP system. As a primary heating system, a boiler or, alternatively, a heat pump is considered. In order to avoid over-dimensioning of the primary heating system due to the high load peaks in the load profiles with 1 minute resolution (see chapter B), the sum of the hourly averages of the heating and domestic hot water load profiles is calculated and considered as the thermal building energy demand. The maximum required thermal power of the primary heating system is determined on the basis of the calculated hourly thermal energy demand values. The thermal energy demand and thus the related thermal power of the primary heating system depends on the building type and number of persons in it. The efficiency and nominal volume flow are static. The latter is determined for a spread of 10 K. The technical parameters of the systems are summarized in Table IV (boiler) and Table V (heat pump).

TABLE IV.   PARAMETERS OF SELECTED BOILER TYPES [24].

Building type		New building (KfW 55 Standard)		Old building	
Persons	-	2	4	2	4
Modulation	-	Yes		Yes	
Max. Thermal power	kW_{th}	4.05	6.64	9.36	10.46
Min. Thermal power	kW_{th}	2.1	2.1	1.9	1.9
Thermal efficiency[1]	%	90		90	
Nominal volume flow[2]	l/h	353	579	816	912

For the old building, the parameters of the heat pump are based on a commercially-available system, which meets the performance requirements with regard to the maximum thermal power demand (see Table IV). As the thermal power demand of the old building differs only slightly for a 2- and 4-person household, only one heat pump system is considered for each household type. The technical parameters of the heat pump are listed in Table V. The performance values relate to the dimensioning-relevant design time, which is defined by the coldest day in the selected time series. The efficiency is calculated using grid points for various combinations of outdoor temperature and flow temperatures; see Vela Solaris [25] for detailed information.

TABLE V.   PARAMETERS OF THE SELECTED HEAT PUMP [26].

Building type		Old building
Persons	-	2 4
Designation	-	ELCO AEROTOP S12M-IR
Modulation	-	No
Testing standard (DIN EN)	-	14511
Th. Power at -7 °C/55 °C	kW_{th}	10.69
El. Power at -7 °C/55 °C	kW_{el}	5.12
COP -7 °C/55 °C	-	2.09
Nominal volume flow	l/h	2,000

The use of micro-CHP systems is accompanied by the use of thermal energy storage tanks, or so-called buffer storage [27]. These tanks buffer heating water, enable the temporal decoupling of heating demand and the generation of thermal energy. In this way, longer running times of the CHP system can be realized, which contributes to an improvement in the overall efficiency. The storage type considered is a combined storage tank for heating and domestic hot water. The parameters of the storage tanks are listed in Table VI.

TABLE VI.   PARAMETERS OF COMBINED HEAT STORAGE TANKS [28].

Building type		New building (KfW 55 Standard)	Old building
Volume	l	300	500
Diameter	mm	600	658
Height	mm	1,061	1,455
Insulation thickness	mm	75	118
Volume/Surface	mm	117	134

The battery storage system is considered to be AC-coupled and consists of the battery and battery inverter. The battery inverter determines the maximum charge and discharge power of the system. The technical parameters of the battery are derived from a commercially-available system that is based on a lithium iron phosphate cell chemistry [29]. In the analysis, the battery storage capacity is considered to be variable and increased from 0 kWh (no battery) to 6 kWh, with an increment of 1 kWh.

The efficiency of the battery inverter is considered on the basis of a power-dependent performance curve by applying the PerModAC model [30], which is directly integrated in Polysun. The PerModAC simulation model is generally used to evaluate the performance of AC-coupled PV battery systems. In the context of this work, only parts of the model are used to evaluate the AC-coupled battery storage inverter performance. The parameterization of the PerModAC model is carried out using uniform measured data of battery storage systems, in accordance with the "Efficiency Guide for PV Storage Systems" [31]. In turn, model parameters are derived from the measured data. For the battery storage system, the parameters are: AC2BAT.a, AC2BAT.b and AC2BAT.c, which describe the charging process of the battery. The discharging process is represented by the parameters BAT2AC.a, BAT2AC.b and BAT2AC.c. These parameters form the factors of a second degree polynomial, which gives the specific power loss in W per kilowatt of rated power. For further details, reference is made to Weniger and Tjaden [30]. In this work, the inverter parameters from a commercially-available battery storage system are considered [32]. It is further assumed that the part load behavior of the measured inverter remains unchanged for inverters with different nominal power ratings. This allows for the adoption of the power-dependent performance curve for different inverters. In the context of this work, the battery inverter power is limited to 2 kW with respect to an efficient system. Up to a battery capacity of 2 kWh, a linear increase in the battery inverter power is assumed. This results in a battery inverter power of 1 kW for a capacity of 1 kWh. Battery degradation over the lifetime is not considered. All technical parameters of the battery storage system are summarized in Table VII.

TABLE VII. PARAMETERS OF BATTERY STORAGE SYSTEM [29] AND BATTERY INVERTER (ADAPTED VALUES BASED ON TJADEN ET AL. [32]).

Battery type	Lithium ion	
Cell chemistry	Lithium iron phosphate	
Charge-/ Discharge efficiency	%	99
Self-discharge	% per month	3
Depth of Discharge (DoD)	%	100
Storage capacity	kWh	0 – 6 (increment 1)
Cyclic lifetime	Full cycles	10,000
Service life	a	20
PerMod AC parameters for battery inverter (AC coupled system)		
AC2BAT.a	-	54.5926
AC2BAT.b	-	23.0135
AC2BAT.c	-	4.7813
BAT2AC.a	-	35.0175
BAT2AC.b	-	11.9006
BAT2AC.c	-	7.2390

E. Economic evaluation and economic framework

The economic efficiency of technical building installations is calculated on the basis of the VDI standard 2067 [33]. In order to compare the investment possibilities, the NPV is determined at the end of the observation period. Replacement investments and residual values are taken into account. The number of replacement investments of the components are determined by dividing the observation period by the component's service life. To determine the lifetime of the battery, the cycle life is taken into account. As the calendar life is assumed to be 20 years and thus equal to the observation period, a shortened battery lifetime is always due to number

of full load cycles being exceeded. The residual value is determined by linear depreciation of the initial investment or the last replacement investment. For further information about the calculation, reference is made to VDI [33].

In the following, the general economic framework conditions will be examined. The observation period is assumed to be 20 years at an interest rate of 2 %. The electricity price and CHP index are assumed to be constant over the observation period. No heat pump tariff (reduced electricity price for heat pump operation) is assumed and the calculation of the NPV takes place, including the value added tax. In this paper, only the economic efficiency of an additional battery storage system to the CHP plant is considered. The specific costs for the battery storage system are assumed to be 1000 €/kWh, with the battery accounting for 50 %. The annual cost degression of the battery pack is assumed to be 5 %/a and the operational costs of the entire battery storage system is assumed to be 2 %/a of the initial costs (CAPEX), see also Table VIII.

TABLE VIII. ECONOMIC PARAMETERS.

Economic parameters		
Observation period	a	20
Interest rate	%	2
Electricity price | CHP-Index	ct/kWh$_{el}$	29.44 | 3.42
CHP-Premium	ct/kWh$_{el}$	8
Self-consumption Premium	ct/kWh$_{el}$	4
Payment after promotion	ct/kWh$_{el}$	2
Grid fee reimbursement	ct/kWh$_{el}$	1
CAPEX battery storage system	€/kWh	1,000 (excl. VAT)
CAPEX share battery pack	%	50
CAPEX degression battery pack	%/a	5
OPEX battery storage system	% CAPEX/a	2

The economic framework conditions, which are specified by the legislator, are distributed across several laws. In Germany, the basic law for the promotion of CHP systems, which also affects the economic efficiency of a battery storage combined with a CHP system, is the CHP Act [34]. This law imposes surcharges for own consumed electricity and electricity fed into a public grid. Furthermore, it determines the claim to the CHP-Index that is calculated as the mean value of the EEX (European Energy Exchange) electricity base load price for the last three months. Due to the yearly calculation of the NPV, the mean value from 2017 is taken for the CHP-Index [35]. The duration of the surcharges amounts to 60,000 full load hours of the CHP system. After the subsidy period has expired, the CHP electricity can still be marketed, but without legally-guaranteed remuneration. Further provisions concerning CHP plants are laid down in the Renewable Energies Act (EEG), the Energy Tax Act, the Electricity Tax Act and the Grid Charges Ordinance. Only the EEG, the Electricity Tax Act and the Grid Charges Ordinance are relevant for calculating the economic efficiency of the battery. According to the EEG Act, a levy, called the EEG levy, must be paid for self-consumed electricity that is produced by a CHP system. The EEG levy is not applicable for up to 10,000 kWh of self-consumed electricity if the maximum electrical power of the CHP system does not exceed 10 kW. From a quantity of 10,000 kWh, 40 % of the EEG levy must be paid [36]. The Electricity Tax Act allows for the exemption of electricity tax on self-consumed electricity produced in CHP plants with an electrical output of less than

2,000 kW [37]. In general, the reimbursement of grid fees based on grid feed-in from a CHP system is considered based on the amount of avoided work (electricity feed-in) and the avoided power. However, the avoided power is only considered in the calculation if a recording electricity metering (e.g. via smart meter) is available, see also [38]. According to the Measuring Point Operating Act (Messstellenbetriebsgesetz), a recording metering is only mandatory if the installed electrical output of a generator exceeds 100 kW [39]. Due to the electrical power output of the CHP systems of less than 100 kW in the considered application cases, no recording power measurement is assumed, and only the amount of avoided work is taken into account for the calculation. It should also be noted, that supplements under the CHP Act and benefits under the EEG Act are only granted for CHP plants that meet the high efficiency criterion. The claim to the CHP index for plants with an electrical output of up to 50 kW and the abolition of the electricity tax remain unaffected.

III. RESULTS AND DISCUSSION

In chapter A, the simulation results for the new building and in chapter B the results for the old building are presented.

A. *New building*

The building energy system operating parameters for a single-family house equipped with a PEM fuel cell and boiler are presented in Table IX, dependent on the storage capacity of the battery storage system.

TABLE IX.   BUILDING ENERGY SYSTEM OPERATING PARAMETERS DEPENDENT ON THE STORAGE CAPACITY OF THE BATTERY STORAGE SYSTEM FOR A SINGLE-FAMILY HOUSE WITH A TWO-PERSON (ABOVE) AND FOUR-PERSON HOUSEHOLD (BELOW) EQUIPPED WITH A PEM FUEL CELL AND BOILER.

Two-person household							
$C_{battery}$	kWh	1	2	3	4	5	6
$P_{el,inv}$	kW	1	2	2	2	2	2
n_{flc}	1/a	754	448	300	225	180	150
$W_{inv,l}$	kWh/a	90	121	122	122	122	122
$\eta_{inv,ch}$	%	93.7	92.6	92.6	92.6	92.6	92.6
$\eta_{inv,dch}$	%	94.7	94.3	94.3	94.3	94.3	94.3
ØSOC	%	79.3	84.5	89.4	92.1	93.7	94.7
$t_{operate,CHP}$	h/a	8,760		$\omega_{el,CHP}$				36
$\tau_{flh,CHP}$	h/a	7,593		$\omega_{th,CHP}$	%			23.7
$n_{starts,CHP}$	—	1		$\omega_{tot,CHP}$				59.7
$t_{operate,b}$	h/a	2,492		ω_b	%			76.6
$n_{starts,b}$	—	416						

Four-person household							
$C_{battery}$	kWh	1	2	3	4	5	6
$P_{el,inv}$	kW	1	2	2	2	2	2
n_{flc}	1/a	828	498	333	250	200	167
$W_{inv,l}$	kWh/a	96	133	134	134	134	134
$\eta_{inv,ch}$	%	93.8	92.6	92.6	92.6	92.6	92.6
$\eta_{inv,dch}$	%	94.9	94.4	94.4	94.4	94.4	94.4
ØSOC	%	35.5	20.5	13.9	10.5	8.4	7
$t_{operate,CHP}$	h/a	8,760		$\omega_{el,CHP}$				36.1
$\tau_{flh,CHP}$	h/a	7,651		$\omega_{th,CHP}$	%			24.5
$n_{starts,CHP}$	—	1		$\omega_{tot,CHP}$				60.6
$t_{operate,b}$	h/a	2,275		ω_b	%			77.7
$n_{starts,b}$	—	489						

The operating parameters show that the CHP system has a relatively low power (see Table III), which is expressed by a high number of operating and full-load hours. Due to the modulation capability, the low thermal output and buffer storage tank, the CHP system is operated year-round. The full-load hours of the CHP system increase slightly from 7,593 for the two-person household to 7,651 for the four-person one. This corresponds to the expectations due to the higher heat demand for domestic hot water with increasing household size. The remaining thermal energy demand of the building is covered by the boiler.

For the battery system, the number of full cycles decreases with increasing battery capacity. For a battery with 1 kWh storage capacity, high full cycle numbers with 754 (two-person household) and 828 (four-person household), can be observed. In general, the number of full cycles increases with increasing electricity demand (increasing household size). The charging and discharging efficiency results show that charging and discharging occur at different operating points. The maximum AC charging power is approximately 0.7 kW, while the maximum DC discharge power is 2 kW. The charging and discharging power of the battery depends on the electrical power of the CHP system and the electrical load of the building. For the average SOC, different trends can be observed dependent on the electricity demand. For the two-person household, the average SOC increases with increasing storage capacity. An increase in the average SOC indicates that the electrical CHP power is at a high level, in contrast to the electricity demand. The remaining electricity demand, which is covered by the battery, is not high enough to discharge the battery to lower SOC levels. In this case, batteries with higher capacity are operated at a higher average SOC. For the four-person household, the average SOC decreases with increasing storage capacity. This indicates that the electric CHP power is at a low level, in contrast to the electricity demand. The remaining electricity generation from the CHP system, which is available to charge the battery, is not high enough to charge the battery to higher SOC levels. In this case, batteries with higher capacity are operated at a lower average SOC.

Figure 5 shows the degree of self-sufficiency and self-consumption fraction dependent on the storage capacity of the battery storage system.

The results show that both parameters (degree of self-sufficiency, self-consumption fraction) increase with increasing battery capacity. Furthermore, battery capacities between 0 and 2 kWh have the biggest influence. The degree of self-sufficiency and self-consumption fraction are, without battery storage, 79.2 % and 59.5 % for the two-person household. With a 1 kWh battery, the degree of self-sufficiency can be increased to 96.7 % and the self-consumption fraction can be increased to 72.7 %. With a battery capacity of 2 kWh, a degree of self-sufficiency of 99.8 % and self-consumption ratio of 75 % can be reached. It is not possible to reach a degree of self-sufficiency of 100 % due to the limitation of the battery inverter power. For the four-person household, a degree of self-sufficiency of 61 % and self-consumption ratio of 80 % are reached without a battery storage system. With a 1 kWh battery, the degree of self-sufficiency can be increased to 72.3 % and the self-consumption fraction can be increased to 94.3 %. With a battery capacity of 2 kWh, a degree of self-sufficiency of 74.4 % and self-consumption ratio of 97 % can be reached. For higher battery capacities, both parameters remain almost constant. It can be stated that from a technical perspective,

only batteries with storage capacities of up to 2 kWh have a significant influence on the parameters. Larger batteries do not affect the parameters, although the cyclic battery lifetime is increased due to decreasing full cycle numbers.
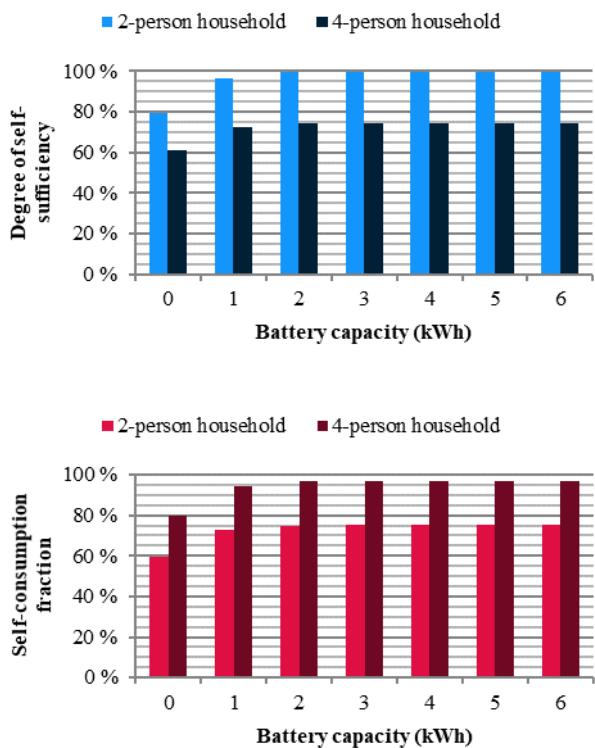

Fig. 5. Degree of self-sufficiency (above) and self-consumption fraction (below) dependent on the storage capacity of the battery storage system and the household size for a single family house with a PEM fuel cell and boiler.

To further analyze the battery system's operation, the course of the battery state of charge (SOC) over the day for one year is shown in Figure 6 and Figure 7.
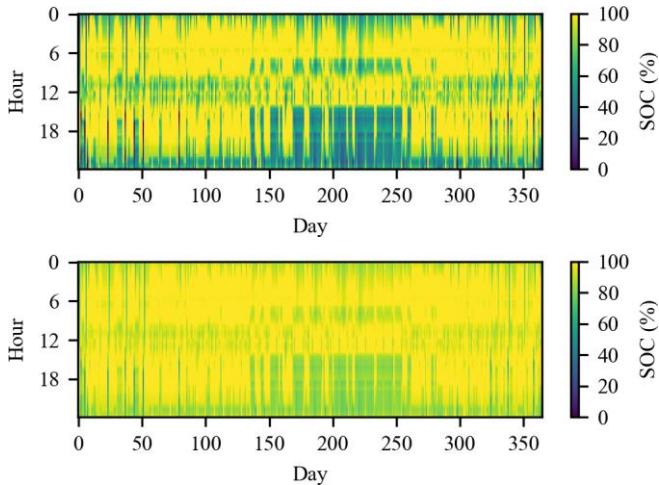

Fig. 6. Daily course of the state of charge (SOC) for one year for a battery storage capacity of 2 kWh (above) and 6 kWh (below) integrated in a building energy system equipped with a PEM fuel cell and boiler for a two-person household.

For the two-person household (Figure 6), two periods with a high SOC and two periods with a low SOC per day can be seen in the SOC diagram. For the 2 kWh battery, this results

in about 1.23 full cycles per day. In addition, the summer months are clearly visible. These are characterized by a low thermal demand. As a result, the operating time of the CHP system is reduced and the SOC decreases because the battery is not charged or not fully charged. For batteries with a larger capacity of 6 kWh, the higher average SOC level and lower utilization of the capacity can clearly be seen. The 6 kWh battery is mostly operated between 60 and 100 % SOC, which indicates that the electricity demand is not high enough to discharge the battery to lower SOC levels. It must be mentioned that operation at high SOC levels could be limited by applying an intelligent, forecast-based battery operating strategy. The general operating pattern for different battery capacities remains unchanged, as the operation of the CHP system and the electrical load profile does not change.

The effect of a higher electricity consumption on the battery utilization can be seen from Figure 7, which shows a battery operation at significantly lower average SOC levels. The 6 kWh battery is mostly operated between 0 and 40 % SOC, which indicates that the electricity from the CHP system that is available to charge the battery is not sufficient to fully charge it. The general operating pattern remains essentially unchanged and is not significantly affected by the higher annual electricity consumption and higher domestic hot water demand. The higher annual electricity consumption mainly affects the average SOC level. The SOC pattern is directly coupled to the operation of the CHP system and therefore to the thermal demand. Due to the minor change of the domestic hot water demand of 1,000 kWh, the SOC pattern over one day is only slightly affected by household size.
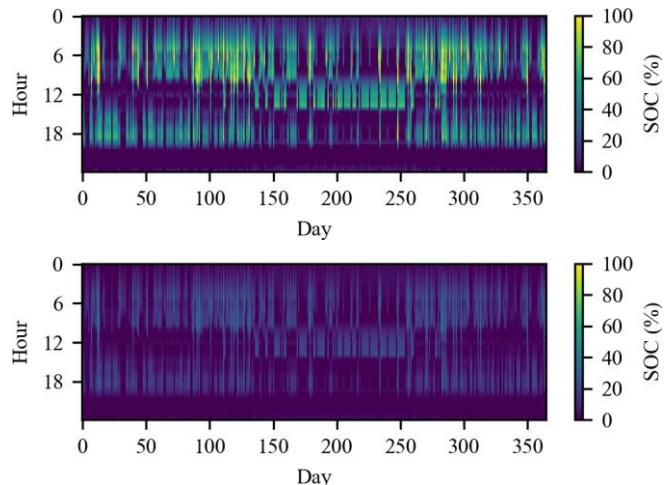

Fig. 7. Course of the state of charge (SOC) over the day for one year for a battery storage capacity of 2 kWh (above) and 6 kWh (below) integrated in a building energy system equipped with a PEM fuel cell and boiler for a four-person household.

Figure 8 shows the results of the economic evaluation. For the two-person household, a positive NPV is reached for a 1 and 2 kWh battery. For the four-person household, a positive NPV is also reached for a 3 kWh battery. For both cases, the highest NPV is reached for the 1 kWh battery. The 1 kWh battery is exchanged once in the observation period of 20 years, as the number of full cycles exceeds the cyclic lifetime. For all other battery capacities, a battery exchange due to cyclic lifetime limitations is not necessary.
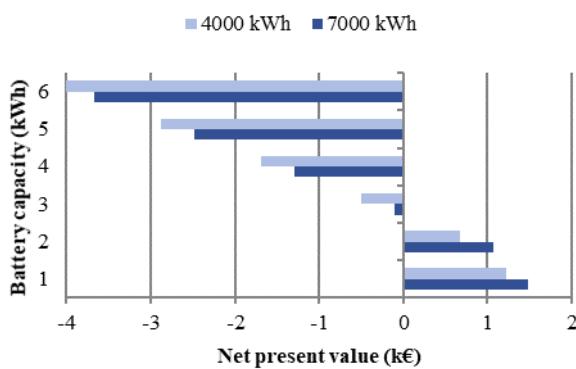
Fig. 8. Net present value of a battery energy storage system, in combination with a PEM fuel cell as a function of battery capacity.

B. Old building

The building energy system's operating parameters for a single-family house equipped with an SOFC and heat pump are presented in Table X dependent on the storage capacity of the battery storage system. The CHP system is non-modulating and continuously operated at nominal power throughout the year (see Table X). The heat pump is used as the primary heating system. The electricity demand of the building, including the heat pump, is covered as far as possible from the CHP system. The remaining electricity demand is supplied from the electricity grid. The annual electricity demand from the heat pump for the two-person household is 8,655.4 kWh.

TABLE X. BUILDING ENERGY SYSTEM OPERATING PARAMETERS DEPENDENT ON THE STORAGE CAPACITY OF THE BATTERY STORAGE SYSTEM FOR A SINGLE-FAMILY HOUSE WITH TWO-PERSON HOUSEHOLD (ABOVE) AND A FOUR-PERSON HOUSEHOLD (BELOW) EQUIPPED WITH AN SOFC AND HEAT PUMP.

Two-person household							
$C_{battery}$	kWh	1	2	3	4	5	6
$P_{el,inv}$	kW	1	2	2	2	2	2
n_{flc}	1/a	2,138	1,598	1,117	847	682	572
$W_{inv,l}$	kWh/a	294	370	388	392	395	397
$\eta_{inv,ch}$	%	91.7	93.7	93.7	93.7	93.7	93.7
$\eta_{inv,dch}$	%	98.9	98.9	98.9	98.9	98.9	98.9
ØSOC	%	68.2	54.7	52.1	50.6	50.6	50.6
$t_{operate,CHP}$	h/a	8,760		$\omega_{el,CHP}$				63
$\tau_{flh,CHP}$	h/a	8,760		$\omega_{th,CHP}$	%			7.1
$n_{starts,CHP}$	—	1		$\omega_{tot,CHP}$				70.1
$t_{operate,hp}$	h/a	2,726		COP_{hp}	%			2.44
$n_{starts,hp}$	—	3,062						

Four-person household							
$C_{battery}$	kWh	1	2	3	4	5	6
$P_{el,inv}$	kW	1	2	2	2	2	2
n_{flc}	1/a	2,051	1,413	965	732	589	494
$W_{inv,l}$	kWh/a	276	322	330	334	336	338
$\eta_{inv,ch}$	%	92	93.9	93.9	93.9	93.9	93.9
$\eta_{inv,dch}$	%	95.1	95.1	95	95	95	95
ØSOC	%	56.3	41.8	38.8	36.4	34.7	33.5
$t_{operate,CHP}$	h/a	8,760		$\omega_{el,CHP}$				63
$\tau_{flh,CHP}$	h/a	8,760		$\omega_{th,CHP}$	%			7.7
$n_{starts,CHP}$	—	1		$\omega_{tot,CHP}$				70.7
$t_{operate,hp}$	h/a	2,841		COP_{hp}	%			2.44
$n_{starts,hp}$	—	3,020						

Fig. 9. Degree of self-sufficiency (above) and self-consumption fraction (below) dependent on the storage capacity of the battery storage system and the household size for a single-family house with SOFC and heat pump.

The total electricity demand of the two-person household amounts to 12,655.4 kWh. For the four-person household, the electricity demand from the heat pump increases slightly to 8,997.8 kWh due to the higher domestic hot water demand. The total electricity demand of the four-person household amounts to 15,997.8 kWh.

For the battery system, the number of full cycles decreases with increasing battery capacity. For a battery with 1 kWh storage capacity, very high full cycle numbers of 2,138 (two-person household) and 2,051 (four-person household) can be observed. In contrast to the new building (see chapter A), the number of full cycles decreases slightly with increasing electricity demand. This can be explained by the continuous operation of the CHP system at nominal power, in combination with the non-modulating heat pump, which shows a clocked behavior. The charging and discharging efficiency results show that charging and discharging occur at different operating points. The maximum AC charging power is approximately 1.5 kW and the maximum DC discharge power is 2 kW. The charging and discharging power of the battery depends on the electrical power of the CHP system and the electrical load of the building. The average SOC generally decreases with increasing storage capacity for both household types. This indicates lower battery utilization with increasing storage capacity, which is also indicated by the decreasing number of full cycles.

Figure 9 shows the degree of self-sufficiency and self-consumption fraction dependent on the storage capacity of the battery storage system. The results show that both parameters (degree of self-sufficiency, self-consumption fraction) increase with increasing battery capacity. Furthermore, battery capacities of between 0 and 2 kWh have the biggest influence. The degree of self-sufficiency and the self-consumption fraction are without battery storage for the two-

person household at 53.3 % and 53.1 %. With a 1 kWh battery, the degree of self-sufficiency can be increased to 68.3 % and the self-consumption fraction can be increased to 68.1 %. With a battery capacity of 2 kWh, a degree of self-sufficiency of 76.0 % and a self-consumption ratio of 75.8 % can be reached. The maximum degree of self-sufficiency is significantly lower in comparison to the new building (see Figure 5) due to the significantly higher electricity consumption (heat pump). For the four-person household, a degree of self-sufficiency of 51.9 % and a self-consumption ratio of 65.0 % are reached without a battery storage system. With a 1 kWh battery, the degree of self-sufficiency can be increased to 63.5% and the self-consumption fraction can be increased to 79.4%. With a battery capacity of 2 kWh, a degree of self-sufficiency of 68% and a self-consumption ratio of 85.1% can be reached. For higher battery capacities, both parameters remain almost constant. From a technical perspective, only batteries with storage capacities of up to 2 kWh have a significant influence on the parameters. Larger batteries do not affect the parameters; however, the cyclic battery lifetime is increased due to decreasing full cycle numbers.

To further analyze the battery system operation, the course of the battery state of charge (SOC) over the day for one year is shown in Figure 10 and Figure 11. For the two-person household (Figure 10), a clear distinction can be made between the summer months without heating demand and the heating period. During the summer months, the heat pump is not operated and the remaining domestic hot water demand is covered by the CHP system. During this time, the electricity load of the building is not high enough to discharge the battery in comparison to the relatively high rated power of the CHP system (1.5 kW). The battery mainly remains fully charged at 100% SOC. From this, it can be stated that the CHP system is over-dimensioned for single-family building energy applications (comparable building standard) without a heat pump. It must again be mentioned that the operation at high SOC levels, especially during the summer months without heat pump operation, could be limited by applying an intelligent, forecast-based battery operation strategy.
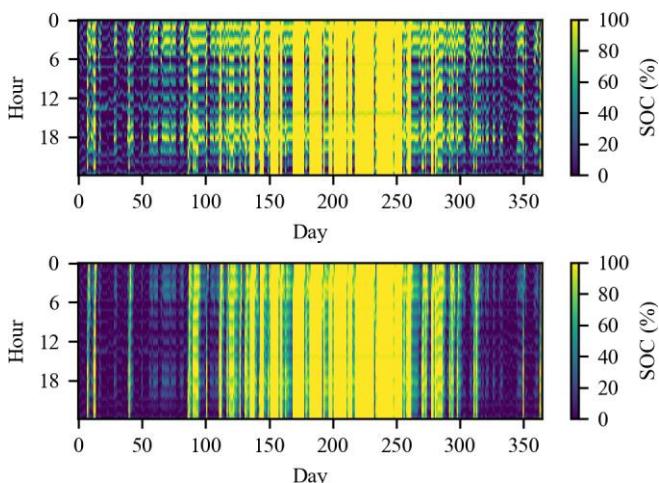

Fig. 10. Course of the state of charge (SOC) over the day for one year for a battery storage capacity of 2 kWh (above) and 6 kWh (below) integrated in a building energy system equipped with an SOFC and heat pump for a two-person household.

During the heating period, the 2 kWh battery is frequently charged and discharged with several full cycles per day due to

the clocked behavior of the heat pump (non-modulating system). The clocked behavior is expressed by the high ratio between the number of starts of the heat pump in relation to the operating hours. A modulating heat pump would significantly affect the SOC's operational profile of the battery. For the battery with a larger capacity of 6 kWh, the lower average SOC level and lower utilization of the capacity can be clearly seen. The general operating pattern for different battery capacities remains unchanged, as the operation of the CHP system and the electrical load profile does not change. In particular, the clocked behavior of the heat pump and battery is retained. However, in comparison to the 2 kWh battery, the 6 kWh battery is typically not fully charged during a charge-discharge cycle, which indicates that the available electricity from the CHP system to charge the battery is insufficient due to high direct self-consumption.

The effect of higher electricity consumption on the battery utilization can be seen in Figure 11, which shows a battery operation at lower average SOC levels. However, the general operating pattern is also oriented on the operation of the heat pump and is not significantly affected by the higher annual electricity consumption and higher domestic hot water demand.
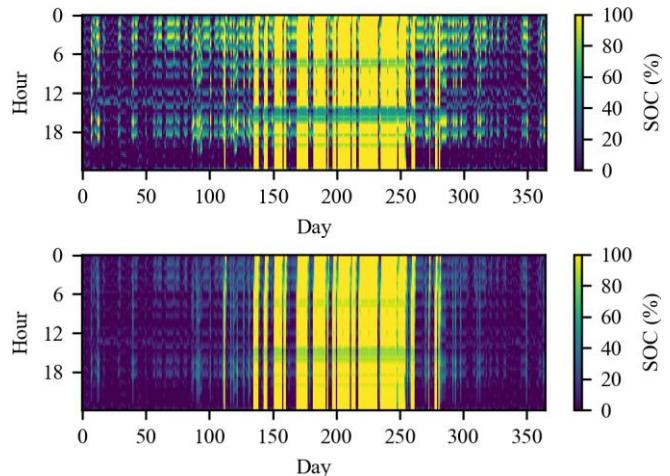

Fig. 11. Course of the state of charge (SOC) over the day for one year for a battery storage capacity of 2 kWh (above) and 6 kWh (below) integrated in a building energy system equipped with an SOFC and heat pump for a four-person household.

Figure 12 shows the results of the economic evaluation. For all cases, a positive NPV is reached. For both household types, the highest NPV is reached for the 2 kWh battery. Due to the high number of full cycles, regular battery replacements are necessary. The 2 kWh battery is exchanged three times in the observation period of 20 years, for instance, as the number of full cycles exceeds the cyclic lifetime. Only for the 6 kWh battery in the four-person household is it not necessary to exchange the battery. The NPV of the battery is generally higher for the two-person household in comparison to the four-person one. The reason for this is the lower battery utilization in the four-person household, which is expressed by a lower number of full cycles. The main impact factor is the heat pump with a higher ratio between the operating hours and starts of 0.94 for the four-person household in comparison to a ratio of 0.89 for the two-person one (see Table X). This behavior again shows that the clocked behavior is the key driver for the high battery utilization and high NPV of the battery energy storage system.
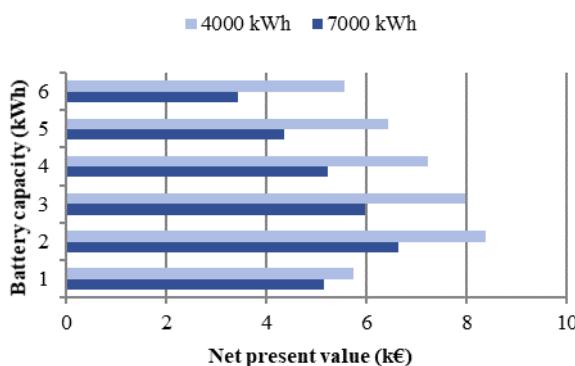
Fig. 12. Net present value of a battery energy storage system in combination with an SOFC and heat pump as a function of battery capacity.

IV. SUMMARY AND CONCLUSION

In this paper, a simulation model was applied to analyze the design of battery storage systems in combination with micro CHP systems for use in single-family houses. For the analysis, a distinction was made between two application cases: a new building with a low energy standard and an unrenovated old building with a high energy demand for heating. The new building was equipped with a PEM-FC, in combination with a boiler, while the old building is equipped with an SOFC in combination with a heat pump. For both building types, a further distinction was made between two- and four-person households, which influences the demand for domestic hot water and electricity demand. The results of the analysis show that the degree of self-sufficiency (autarky) and self-consumption fraction generally increase with increasing storage capacity. However, only batteries with a capacity of up to 2 kWh have a significant impact on the parameters for all the application cases considered. The operation of batteries, in combination with CHP systems, significantly differs from the operation of batteries in combination with PV systems, which is expressed by significantly higher full cycle numbers and a different battery utilization pattern with a strong seasonal influence.

For the new building with two-person household, the degree of self-sufficiency, for example, can be increased from 80 % (no battery) to close to 100 % with a 2 kWh battery, which allows close to autarkic operation without an electricity grid connection. The related self-consumption fraction is increased from 60 % (no battery) to 75 % (2 kWh battery). High full cycle numbers of, e.g., 754 (two-person household) and 828 (four-person household) full cycles per year, respectively, for a 1 kWh battery in combination with a PEM-FC in the new building are reached. The number of full cycles decreases with increasing battery capacity. For a 2 kWh battery 448 (two-person household) and 498 (four-person household), respectively, full cycles are reached. The battery SOC distribution shows a strong seasonal influence due to the heating demand-driven CHP operation of the PEM system. In this case, the battery shows higher utilization during the winter months, with approximately two cycles per day. During the summer months, the battery shows lower utilization according to the more frequent part load operation of the PEM system (modulating system). During the summer months, the PEM system is mainly operated to cover demand for domestic hot water. The results of the NPV analysis shows that a clearly

positive NPV is reached for both household types for the 1 and 2 kWh batteries in the new buildings equipped with a PEM-FC. This underlines the techno-economic feasibility of only small batteries with capacities of up to 2 kWh, in combination with PEM-FC CHP systems.

The old building is equipped with a non-modulating SOFC system, in combination with a non-modulating heat pump. The heat pump is used as the primary heating system. The simulation results show that for the two-person household, the degree of self-sufficiency, as well as the related self-consumption fraction, for example, can be increased from 53 % (no battery) to 76 % with a 2 kWh battery. Higher degrees of self-sufficiency cannot be reached despite the higher nominal power of the SOFC in comparison to the PEM-FC, due to the additional electricity demand from the heat pump. Very high full cycle numbers of, e.g., 2,138 (two-person household) and 2,051 (four-person household) full cycles per year, respectively, for a 1 kWh battery are reached. The number of full cycles also decreases with increasing battery capacity. For a 2 kWh battery, 1,598 (two-person household) and 1,413 (four-person household) full cycles, respectively, are reached. The very high full cycle numbers limit the cyclic battery lifetime and require several battery exchanges across the observation period of 20 years.

The battery's SOC distribution in the old building also shows a strong seasonal influence. During the heating period, the batteries generally show a high utilization, with several full cycles per day due to the clocked operation of the heat pump. During the summer months, the heat pump is not operated and the battery is only infrequently used with shallow charge and discharge cycles. During this period, the battery typically remains in a high state of charge.

The results of the NPV analysis show that for all cases, a positive NPV is reached. The highest NPV is reached for the 2 kWh battery for both household types. The clocked behavior of the heat pump is the key driver for the high battery utilization (high full cycle numbers) and the high NPV of the battery energy storage system. In future, it is planned to analyze a system with a modulating heat pump in a sensitivity analysis regarding the impact on battery NPV and operation. In general, a frequent battery exchange due to cyclic lifetime limitations does not negatively impact the NPV due to the assumption of decreasing battery pack cost over time. For applications that require frequent battery exchanges, a plug and play design is recommended for the battery storage system, as this allows for the easy replacement of battery packs.

In the future, it is planned to analyze building energy systems for single- and multi-family houses with combined micro CHP, PV and battery storage systems. Furthermore, the development of an intelligent, forecast-based battery operation strategy could be a subject for future research. An intelligent battery operation strategy could be favorable, especially to limit long stand-by periods of the battery system at high SOC levels. A shift towards lower average SOC operation could significantly improve battery lifetime, as higher SOC levels promote battery ageing. To analyze this effect, a model coupling with a battery-ageing model is required.

ABBREVIATIONS AND SYMBOLS

Abbreviation	Significance
CAPEX	Capital Expenditures
CHP	Combined Heat and Power
COP	Coefficient of Performance
DIN	Deutsches Institut für Normung (German Institute for Standardization)
DoD	Depth of Discharge
DWD	Deutscher Wetterdienst (German Metrological Service)
EEG	Erneuerbare-Energien-Gesetz (Renewable Energy Act)
EEX	European Energy Exchange
EN	European Norm
IWU	Institut Wohnen und Umwelt
KfW	Kreditanstalt für Wiederaufbau
NPV	Net Present Value
OPEX	Operational Expenditures
PEM-FC	Polymer Electrolyte Membrane-Fuel Cell
PerModAC	Performance simulation model for AC-coupled PV batter systems
PV	Photovoltaic
RES	Renewable Energies
SFH	Single Family House
SOC	State of Charge
SOFC	Solid Oxide Fuel Cell
TABULA	Typology Approach for Building Stock Energy Assessment
TRY	Test Reference Year
VDI	Verein Deutscher Ingenieure (Association of German Engineers)

Symbol	Unit	Significance
AC2BAT.a	-	AC to Battery Inverter Parameter
AC2BAT.b	-	AC to Battery Inverter Parameter
AC2BAT.c	-	AC to Battery Inverter Parameter
BAT2AC.a	-	Battery to AC Inverter Parameter
BAT2AC.b	-	Battery to AC Inverter Parameter
BAT2AC.c	-	Battery to AC Inverter Parameter
$C_{battery}$	kWh	Battery Capacity
COP_{hp}	-	Coefficient of Performance of Heat Pump
n_{flc}	-	Number of Full Load Cycles
$n_{starts,b}$	-	Starts Boiler
$n_{starts,CHP}$	-	Starts CHP System
$n_{starts,hp}$	-	Starts Heat Pump
$P_{el,inv}$	kW	Maximum AC/DC Inverter Power
$t_{operate,b}$	h/a	Operating Hours Boiler
$t_{operate,CHP}$	h/a	Operating Hours CHP System
$t_{operate,hp}$	h/a	Operating Hours Heat Pump
$W_{inv,l}$	kWh/a	Battery Inverter Losses
$\eta_{inv,ch}$	%	Average Battery Inverter Charging Efficiency
$\eta_{inv,dch}$	%	Average Battery Inverter Discharging Efficiency
$\tau_{flh,CHP}$	h/a	Full Load Hours CHP System
ω_b	%	Average Annual Efficiency of Boiler
$\omega_{el,CHP}$	%	Average Annual Electrical Efficiency of CHP System
$\omega_{th,CHP}$	%	Average Annual Thermal Efficiency of CHP System
$\omega_{tot,CHP}$	%	Average Annual Total Efficiency of CHP System

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