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RESEARCH ARTICLE

Toward an Effective Community Energy Management by Using a Cluster Storage

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ABSTRACT The integration of renewable local energy generation in single households – turning the household into a ''prosumer'' – is an important way to support an ecological transition of the electric power system. However, due to the volatile and distributed nature of most renewable energy sources, the power system may face stability problems when integrating a large number of renewables. The paper at hand describes an approach to overcome these shortages in a two-fold manner: First, the effects of the installed renewables shall be limited locally to a group of households – a so-called ''energy community''. To do so, all the participating households are using existing self-consumption optimization tools. However, when a household has excess energy which can not be consumed locally, this energy is shared among the other participating households by using a cluster storage device, thus enabling a community self-consumption before feeding into the low-voltage distribution grid. Second, the connected operator may request flexibility from the participating households. For that, additional loads or load sheds are triggered by the requesting grid operator, depending on the current situation in the grid. The households decide autonomously about the amount of granted flexibility, receiving respective financial incentives. This work introduces an energy management concept and a prototypical control infrastructure used for the aforementioned functionalities. In a number of simulations and field tests, the proposed approach was successfully evaluated. The article provides a comprehensive overview of the gained results and the conclusions derived from them.

INDEX TERMS Cluster storage, energy community, energy management system, flexibility, optimization, renewables, self-consumption, volatility.

I. INTRODUCTION

The electric power system is currently undergoing a phase of transition towards a so-called smart grid. An important driver hereby is the integration of renewable energy sources [1], like Photovoltaic Systems (PVs), which support decarbonization of the power system and thus allow for an ecologic ''energy transition'', i.e., the change of the power grid to a ''green'' and sustainable infrastructure. However, most renewable energy sources face two important disadvantages: First, they are very often used with small-scale plants (e.g., roof-top installations on single houses) where many small and highly distributed installations have to be coordinated to ensure the security of supply, as well as the stable and efficient operation of the power grid [2]. Second, they are not controllable, and sometimes even hardly predictable; therefore, means have to be taken to use the energy when it is present, or to store energy (electrically or maybe thermally) for later use [3].

A. CUSTOMER ENERGY MANAGEMENT SYSTEMS

At single household level, Customer Energy Management Systems (CEMSs) [4] perform this by either using

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controllable loads (electric vehicles, heat pumps, air conditioning, etc.) at appropriate times – thus adhering to a "load follows generation" paradigm – or by utilizing energy storage devices to decouple production and consumption times. In both cases, the goal is to maximize self-consumption and thus minimize the energy exchange with the providing Distribution System Operator (DSO). This triggers economic benefits for households, as sales prices usually are much lower than purchase prices. For DSOs, a minimal exchange with prosumer households eases the control in the Low Voltage (LV) grid, as the power shares of volatile sources in the LV grid are then reduced due to less feed-in.

Beyond that self-consumption maximization, CEMSs additionally allow for providing flexibility [5] to the associated DSO. In the case of a lack of energy in the LV grid which is connected to households equipped with CEMSs, the DSO operating the LV grid may request a load shedding from the respective households. Conversely, when excess energy is present in the LV grid, additional consumption may be requested by the DSO. In both cases, the several households' CEMSs decide autonomously if and to which extent these requests are fulfilled. The amount of shifted load can be measured, and financial incentives can thus be given by the DSO to the households dependent on the amount of shifted energy – a strategy called demand side management (DSM) [6]. More details about that can be found in Section III.

B. ENERGY COMMUNITIES

The power optimization possibilities in LV distribution grids are even higher, when not just considering independently controllable households (i.e., utilizing CEMSs), but coordinated energy communities [7]. Without coordination, the exchange of energy between the households and the associated LV grid equals the sum of the single exchanges of all households. The more participants are considered, the smoother the consumption curve will be due to the simultaneity factor; i.e., consumption peaks of single households will not have that big effects anymore.

For the generation side, things turn out to be more complex: Usually, power generation is done with roof-top PV installations; in a local community, it can be expected that weather and shadowing conditions are almost similar and thus also the production curves will not differ widely. A difference is yet to emerge in the business model. In some cases, some of the households will feed into the LV grid, whereas others are consuming from the grid. In such a case, the producing and consuming households can be (logically) balanced, before the exchange with the LV grid is done (even when having multiple real connections).

When considering a much higher purchase price than selling price for the single households in their respective contracts with the DSO operating the LV grid, an internal balancing [8] using an internal transfer price in the middle of the DSO prices would let both selling and purchasing households benefit. However, this effect may reduce the amount of energy exchanged between the LV grid and the energy community, but does not change the total consumption and/or generation of the community at a certain point in time.

When additionally adding community storage(s), this may be changed. Producing households may feed into the storage up to a certain technically given upper limit, whereas consuming households may use stored energy up to a certain technically given lower limit. In this case, all households may feed in or use stored energy at the same time, as long as the upper and lower limits are kept. This may lead to an additional time shift in the usage of self-produced energy, which can not be accomplished just with a local storage system. Such effects are described in Section V-C.

C. RESEARCH QUESTIONS AND METHODOLOGY

In this work, results of a simulative and practical assessment of energy optimization in an energy community are presented. An appropriate prototypical implementation was realized to answer several Research Questions (RQs) in the context of managing energy communities with a high share of renewable Distributed Energy Resources (DERs), which are listed in the following:

- RQ1: To what extent can energy communities of multiple consumer/prosumer households contribute to the stability of LV grids? Which metrics can be used to assess these flexibility offers also quantitatively?
- RQ2: How realistic are the measurements of these contributions, considering the natural volatility of both electric consumers and renewable energy sources? Can a realistic baseline be defined to assess the effects of the control algorithm, and can this baseline be validated against real environments?
- RQ3: Which additional stability and economic effects can be gained by using a cluster storage in the multi-household community?
- RQ4: Which performance of the underlying Information and Communication Technology (ICT) infrastructure is needed to allow a smooth operation of the intended flexibility system? What timing requirements are needed for the controller? Which hardware resources are required? How can a scalable architecture be set up?
- RQ5: Which coupling strategies can be used in that architecture? What effects do these strategies have on the installation effort of new appliances? How can necessary state information be handled in the controller?

Some preliminary simulation results on these RQs have already been published in [9]. In opposition to that paper, in this work, a more realistic simulation environment is being used. First, a Matlab/Simulink [10] model has been utilized which contains close-to-reality physics for the simulations presented here, in opposite to very basic linear models as used in the work-in-progress paper (e.g., for environmental parameters as room temperature). Second, the simulation scenarios have been adopted to more realistic input patterns for the simulation; this regards usage patterns for the considered appliances and other input parameters like weather conditions.

After successfully finishing the simulations, several field tests have been conducted to complete the validation of the realized Proof of Concept (PoC) implementation. For this purpose, a real-world testbed has been set up in a mixed commercial and private building in the village of Stegersbach, South Burgenland, Austria, as described in Section IV-A. More details on the simulations and field tests can be found in Sections V and VI respectively.

The remaining parts of this article are structured as follows: Section II gives an overview of the current state of the art in the areas of electric power grids and related ICT infrastructures. The algorithmic basis of the controller application is given in Section III. In Section IV, the system architecture of the testbed in Stegersbach, South Burgenland, Austria, is briefly described, accompanied by a short depiction of the controller application. The validation tests of the controller and its system context are explicated in Sections V and VI respectively; also, the scenarios for the validation and evaluation of the realized controller are defined here. In Section VII, a discussion of the gained results and an evaluation of the system behavior is done; finally, conclusions and outlooks to further possible research and development activities are given here.

II. RELATED WORK

As the work at hand combines ICT infrastructures with smart grid applications, the discussion of relevant academic and industrial research and development undertakings can be split into (i) an "energy part", dealing with the necessary functionalities for distributed control logic for several appliances of interest, and (ii) an "ICT part", dealing with the calculatory power of participating nodes (which is to a great extent depending on the used software stack on the respective devices), as well as with connectivity issues of the underlay and overlay network infrastructures. These two aspects are considered in the following subsections; followed by a particular consideration of Quality of Service (QoS) issues, as these are crucial for many grid-related applications. Thus, the actual benefit and challenge of the current work is to utilize interdependences between these fields. For instance, timely and secure transport of control commands to actuators allows for distributed control strategies. Much existing research is done in one of these fields, but lacks the consideration of interdependences, especially in practical environments – as will be discussed in the following.

A. CHALLENGES FOR FUTURE POWER SYSTEMS

The integration of volatile and distributed renewable energy sources is one of the big challenges to the evolving smart grid [11]. Control of these DER is explored in [12]. Reference [13] shows how renewable energy forms can be integrated on a local level. In [14], the integration of renewable energy sources into a cooling, heating, and power grid in urban areas is explored in order to be able to derive statements about how and under which conditions the share of renewable energies can be increased. The volatility of renewable energy sources such as PV and wind presents particular challenges to DSOs. To keep the LV distribution grid stable, it is common to rely on Demand Side Management (DSM), i.e., influencing consumption depending on the energy currently being generated [15]. In addition to direct control of the devices by the DSO, there is also the possibility to leverage energy flexibilities by utilizing local control facilities of suitable devices in individual households [16].

In this context, a basic prerequisite is to avoid loss of comfort, for example by optimizing charging times of electric cars while ensuring timely charging [17]. Due to decreasing feed-in tariffs, optimization of self-consumption is an essential topic [18]. The concept of renewable energy communities is considered to be of immense importance. This concept is not very new – as early as 2015, more than 1000 projects were dealing with the topic of energy communities [19]. The constellations investigated are primarily concerned with bilateral exchange and the storage of energy in order to increase the self-consumption rate of the community [20]. In addition, energy communities allow DSOs additional room for maneuvering. Further projects deal with the optimization in an energy community taking into account the current energy price [21].

Besides control and flexibility issues for DSOs, another important aspect of the integration of renewables is self-consumption optimization. This is a central motivation for private households as well as energy communities, as the feed-in tariffs to sell energy to a DSO are usually much lower than purchase tariffs. This has been an important research topic over the last decade (e.g., [22]), but also commercial developments (e.g., from PV vendors) have incorporated appropriate technologies as offers for their customers. Machine Learning (ML) technologies [23] play an important role in this context. In many cases, demand and/or supply prediction is utilized for these optimization purposes (e.g., [24]), allowing for time-shifting the use of appliances that provide sufficient flexibility.

All of these smart grid applications turn the grid into a complex and multi-vendor system of systems, which needs appropriate mechanisms for interoperability; especially, communication between different subsystems has to be ensured [25]. For that purpose, a plethora of standards have been developed for different use cases and applications, as shown in [26]. Interoperability hierarchies have been developed to structure the collaboration issues and standards, like the GridWise Architecture Council (GWAC) stack [27]. Mappings to existing layered abstraction models like the Open Systems Interconnection (OSI) protocol stack [28] defined by the International Organization for Standardization (ISO) are thus possible, as depicted in Figure 1. Yet, the GWAC model extends the OSI model to even higher abstraction levels regarding business and application interoperability, which go beyond the possibilities of technical communication protocols as covered by the OSI stack.

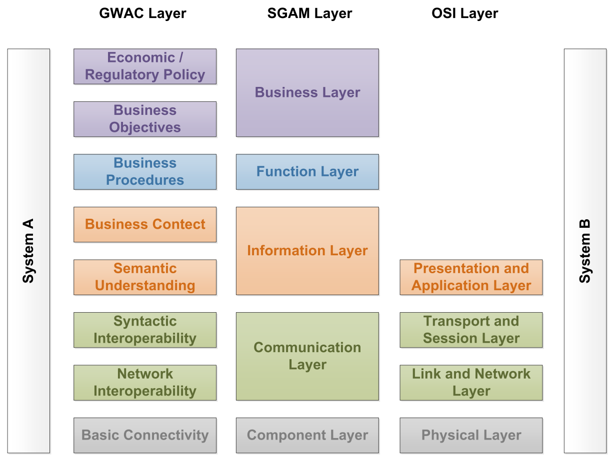

FIGURE 1. The mapping between GWAC and SGAM layers can already be found in [29]; additionally, a mapping of the "network interoperability" GWAC layer to the lower OSI layers can be identified, as well as a mapping of the "syntactic interoperability" GWAC layer to the higher (end-to-end) OSI layers.

Based on that, meta-architectures like the Smart Grid Architecture Model (SGAM) [29] have been defined; the SGAM complements the interoperability hierarchy with domains along the power distribution chain, as well as zones representing different roles in the automation pyramid [30]. To ease the interoperability on a practical level, collaboration platforms as Common Object Request Broker Architecture (CORBA) [31] and automation protocols as Open Process Control Unified Architecture (OPC UA) [32] have been developed. Yet, they do not allow for an application layer-specific course of actions – e.g., OPC UA implementations just allow for simple request/response communication patterns. On local level, frameworks such as OpenHAB [33] enable the integration of several hardware and software components, but do not enable cross-platform communication.

B. GRID-RELATED ICT INFRASTRUCTURES

The focus of the aforementioned work is mainly set on algorithmics and control logic. Other projects aim at a flexible and expandable infrastructure, e.g. to acquire the necessary sensor data. Also, this topic has been researched for many years, e.g. in [34]; however, still, no generic infrastructure suitable for the whole variety of grid applications has been developed so far [35]. Rather, tailor-made approaches have been developed for several application domains such as grid control, metering, etc. Some of these approaches are discussed in the following.

The first and basic requirement on the ICT infrastructure is to provide connectivity between participating nodes (the Intelligent Energy Devices (IEDs)). Traditionally, dedicated lines have been installed for that purpose, i.e., copper or (in newer installations) fiber cables along the high and medium voltage lines. On top of that physical infrastructure, often protocols like International Electrotechnical Commission (IEC) 60870-5-104 [36] are used for coordination at operation level (as depicted by the SGAM model [37]) of operating DSOs or Transmission System Operators (TSOs). Newer installations (especially with DSOs) often use IEC 61850 [38] for substation communication. Wide area coordination, even with dedicated systems, is usually based on Internet Protocol (IP) stacks, i.e., Transmission Control Protocol (TCP) [39] or User Datagram Protocol (UDP) [40] over IP [41], whereas on local levels (e.g., at station level) also field buses may be used for communication, using other address formats than IP to address IEDs.

For the LV grid, usually, no communication lines have been installed. This makes the coordination in the LV grid particularly challenging, as the demand for distributed control increases with the number of participants (especially due to the volatile and highly distributed nature of home installed PV systems). Also, applications like smart metering require appropriate infrastructure to be able to deliver meter data in timely and secure manner. Smart grid applications do not only need an exchange protocol; furthermore, the data definition itself has to be specified in advance. Standards are important here obviously; however, the plethora of different applications results in a variety of associated standards, as outlined by [25]. In the case of metering, the Device Language Message Specification (DLMS)/Companion Specification for Energy Metering (COSEM) suite [42] provides a very widespread and common solution for data definition as well as protocol actions.

For ensuring connectivity in the LV grid, three approaches are common: First, infrastructure may be newly set up to meet the communication requirements – in most cases, this is done via cellular mobile radio. Second, the existing power line infrastructure is used for communication purposes also (Power Line Communication (PLC)). Third, other existing connections (home Internet) are used for power applications such as metering. In the latter case, a public communication infrastructure like the Internet is used as an underlay network, which hosts a private overlay network. The traffic of this overlay network has to be encrypted and strictly separated from other kinds of traffic in the underlay to ensure the required security and QoS.

In Local Area Networks (LANs), the simplest approach for traffic separation is the use of Virtual LANs (VLANs), as described in [43]. As VLANs are working only locally (in a switched infrastructure), this is feasible for instance in intra-substation communication. However, for use in Wide Area Networks (WANs), extensions are necessary. Virtual eXtensible LANs (VXLANs) [44] provide an overlay approach as mentioned above; i.e., LAN frames are encapsulated and tunneled over the underlying public Internet. This is an easy way to provide traffic separation in a wide area network, and with encrypted payload also security can be provided to a sufficient level (at least for the transport – the end systems have of course to be secured additionally). However, the big downside of this lightweight approach is the lack of QoS support, especially concerning real-time data.

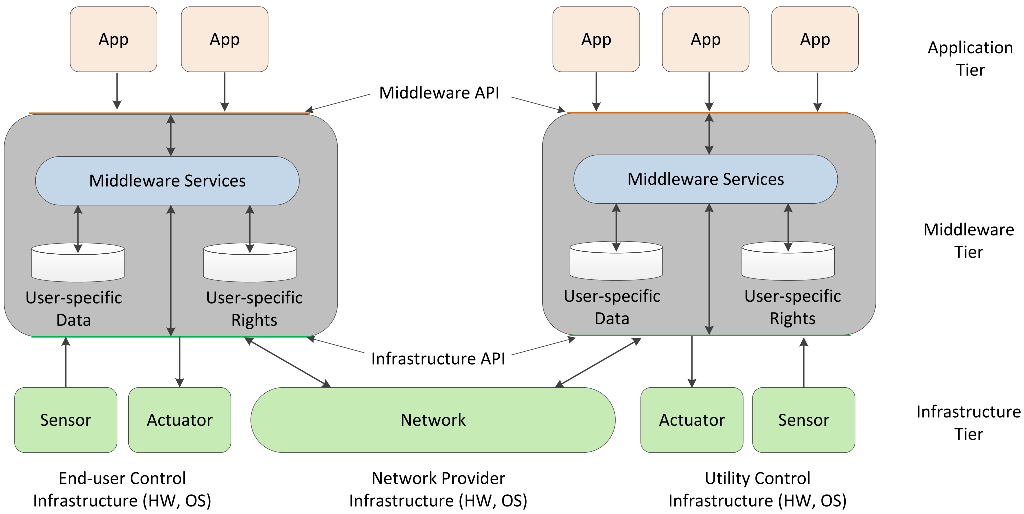

FIGURE 2. X-Architecture model depicts a common middleware layer that provides standardized services over a dedicated API to diverse applications; moreover, infrastructure elements such as communication means and hardware access are utilized by the convergent middleware layer.

C. QUALITY OF SERVICE ISSUES

The usual way to handle QoS requirements in Internet-based environments is the use of Multi-Protocol Label Switching (MPLS) [45]. Thereby, MPLS paths are defined in advance and can be associated according to QoS requirements. These requirements are encoded in different "Differentiated Services Codepoints (DSCPs)", representing different traffic classes. Routers can thus implement their respective strategies (Per Hop Behavior (PHB)) to forward packets depending on the DSCP. The setup of MPLS paths can also be used for Traffic Engineering (TE), allowing grid operators to have better control of their respective traffic flows (using a technology called MPLS-TE). However, as MPLS paths have to be ordered from service providers in advance, a lack of flexibility remains the biggest issue in using that technology for future grids.

Software Defined Networking (SDN) [46] is seen as a solution to overcome this issue, while providing the same potentials regarding security and QoS. SDN comes along with a separation of forwarding plane (being responsible for forwarding packets, as determined by a set of forwarding rules) and control plane (being responsible for defining the forwarding rules and sending them to the forwarding plane devices, i.e., the SDN switches). For the control plane, central devices (SDN controllers) are used; often, only one controller is servicing a whole SDN network. Yet, if availability is an issue, at least one backup controller should be used in order to minimize downtimes.

The rules are based on frame and packet headers; i.e., header fields like Medium Access Control (MAC) addresses, IP addresses, TCP port numbers, etc. can be used as distinguishing parameters by the rule set. Application-specific data (payload) however is not evaluated by SDN. To allow for forwarding based on payload data, "Programming Protocol-independent Packet Processors (P4)" [47] could provide an alternative; yet, the number of devices supporting that technology is still exiguous. In summarizing, SDN provides sufficient support of QoS for power ICT infrastructures, but still lacks some desired flexibility features. Additionally, as usually public underlay infrastructure is used, the security topic has to be taken into account. In this context, much literature already exists (e.g., [48]); this is not in the focus of the work at hand, yet best practice solutions such as encryption (e.g., [49]) are of course considered.

From an architectural point of view, many existing frameworks and approaches are based on an X-Architecture model (e.g., [50]) as depicted in Figure 2. These approaches define a convergence layer in the middle, which may be used by a number of applications over well-defined interfaces [51]. Often, these applications are sandboxed, i.e., they are running in a closed environment and can then communicate only via these system interfaces, allowing for a controlled environment and thus assuring security and privacy guarantees. A more detailed overview of infrastructural research can be found in [52] (focusing on connectivity issues) and in [35] (focusing on interoperability frameworks).

The work at hand now tries to combine these algorithmic and infrastructural approaches to a comprehensive PoC solution and to validate this PoC in simulations as well as in field trials. The innovation of this work lies in the usage of a general purpose infrastructure (Internet as a public underlay technology, Message Queuing Telemetry Transport (MQTT) as messaging protocol) for specifically distributed control logic, which can be tested in real-world scenarios including long-term tests, stress tests, and scalability tests.

III. ENERGY MANAGEMENT ALGORITHM

The proposed algorithm for the envisaged solution is planned to act on different scenarios and their respective requirements, which are set by the cluster operator. This cluster operator

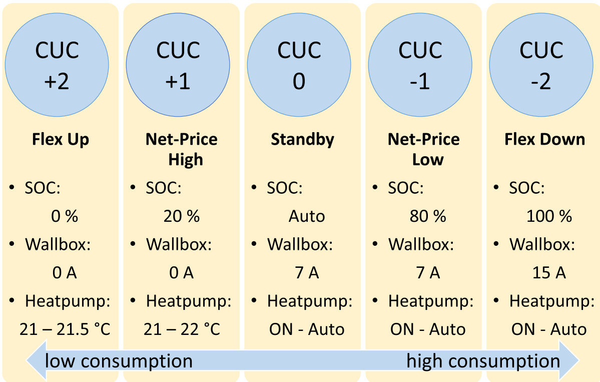

FIGURE 3. **Cluster Use Cases are defined in the basic control algorithm, having a defined state of charge of the battery (SOC), maximum allowed charging current at the wallbox and room temperature levels to be maintained by the heat pump.**

can be a human, organizational or technical actor that acts independently from the households and usually pursues maximum profitability in cluster operation.

A. CLUSTER USE CASES

The different scenarios in the cluster and the adherent LV distribution grid are called Cluster Use Cases (CUCs) throughout the concerned research project and represent different control strategies for all the devices within all households of the concerned cluster community. Triggers of the DSO are used to either increase the power consumption and/or decrease the power generation because of an energy surplus in the LV grid, or to decrease the consumption and/or increase the generation because of an energy lack. In addition to that, there is also the standby level, which represents an equilibrium in the adherent LV distribution grid. This CUC triggers no action on the cluster participants, as the DSO has no flexibility requirements for the time being. Hence, it may be used for self-consumption optimization of every participating household in the cluster. Depending on the situation in the LV grid, the CUCs have been defined (sorted from energy lack in the LV grid to energy surplus) as shown in Figure 3.

The CUCs are defined in such a way that in CUCs +1 and +2 the energy demand of the household should be reduced as much as possible, whereas in CUCs −1 and −2 the opposite should be the case. The main difference between the price-controlled CUCs (+1, −1) and the flexibility-controlled CUCs (+2, −2) is the capacity provided by the energy storages including the batteries of Electric Vehicles (EVs), as well as the possible temperature band for space heating.

By means of presetting the ''Flex'' CUCs, the flexibility potential is allowed to be used for as long and as intense as possible. Also, more profound interventions to counteract the imbalances are possible (e.g., direct load shedding with technical means for devices allowing this technology, triggered by the DSO). However, in order to prevent loss of comfort, the used control algorithm is free to not or only partially implement the requested flexibilities. Of course, this will lower the incentives given by the DSO to cooperative customers.

Algorithm 1 The Base Algorithm Consists of an Endless Loop, Which Is Executed Once per Minute. The Actual Logic Is Implemented in the *calculate* Part. It Is Dependent on the Strategy, Which Is Again Defined by the Current CUC. The CUC Changes and Wallet Calculations Are Done Only in the First of 15 Loops Within a 15 min Timeslot

```
while true do
  for all datapoint ∈ sensors do
    dv ← read(value(datapoint))from broker
  end for
  for all datapoint ∈ config do
    sv ← read(value(datapoint))from file
  end for
  for all datapoint ∈ actuators do
    value(datapoint) ← calculate(strategy, dv, sv)
    write(value(datapoint))to broker
  end for
  if first loop in timeslot(n) then
    strategy ← read(value(CUC))from broker
    Pzero ← Pcurr
    Pcurr ← Average(Ptotal ∈ timeslot(n − 1))
    update(wallet(Pzero, Pcurr))
  end if
  wait(1min)
end while
```

B. BASE ALGORITHM

The base algorithm cyclically (once in a minute) checks the sensor inputs from the respective devices in a (sub-) household, calculates the set values for the actuators and sends them back. The calculation strategy depends on the current CUC. CUCs are updated in 15 min intervals, so the strategy has to remain the same within this 15 min timeslot. That does not mean, however, that the set values for actuators have to keep their values. If other inputs change (e.g., the room temperature exceeds a limit), the controller will react on that, even when using the same strategy. As the controller has no notion of the exact time, when input values are arriving, these values are stored locally and used only when the controller is active. Thus, it is possible that values are overwritten within the 1 min waiting time, such that only the latest measurements per datapoint are used. This has no influence on the controller's basic functionality; however, as values are also persisted in a database for later validation (as described in Section IV), it may cause performance issues when too many sensor values are transmitted.

In Algorithm 1, an overview of the basic loop is depicted in pseudocode. Hereby, the *broker* is the central communication instance for the MQTT data exchange with the controller (as described in Section IV), the *calculate* function derives the set values for actuators based on measurements and the current CUC (as described above). P_{zero} and P_{curr} are used for the ''wallet'' calculation, as described in Section III-C, P_{total} is the total measured power at a given measurement time, *dv* are the locally stored dynamic measurement values, and *sv* are the static configuration values, which are also stored locally in a *config file*.

The depicted algorithm is simplified for ease of understanding. Especially, the reading of measurement values is done independently from the main loop (as an own thread) in reality. As MQTT is working on a publish/subscribe basis, the reading occurs whenever the broker sends out values in subscribed MQTT channels. Yet, due to the limitations on the broker side mentioned in Section IV-A, these sensor measurement messages are sent exactly once per 1 min cycle. The CUCs are specified by the DSO in 15 min intervals; the new CUCs are sent out at the beginning of each timeslot. The control strategies for each of the named CUCs are defined as follows:

1) CUC +2 *("Flex Up"):* The energy supply network is in a strong imbalance; in this case, the demand is much higher than calculated. Load shedding should be performed wherever possible.
2) CUC +1 *("Net Price High"):* In this case, the power grid is only slightly skewed. When this CUC is sent to the households, the participating customers should decrease consumption in order to purchase less energy from the DSO or increase the feed-in. Balance is to be created based on the current electricity price.
3) CUC 0 *("Standby"):* No requirements are transmitted to the individual households. Accordingly, the specific subscriber systems do not adapt their mode of operation to a higher-level requirement. Self-consumption optimization, initiated by devices like inverters or energy storages, may take place; otherwise, the devices are operating under their usual parameters.
4) CUC −1 *("Net Price Low"):* This is the opposite use case to CUC +1 and means that there is a slight energy surplus in the LV grid. Controllable consumers should be turned on, or operated with higher power (e.g., by increasing the charging power of EVs).
5) CUC −2 *("Flex Down"):* Here, the production is much too high; i.e., consumption in the LV grid should be drastically increased. Every flexible energy sink (such as batteries and thermal storages) should be operated at maximum power. Additionally, a lowering of production in DER sites could be considered.

Changing DER production is considered to be the ultimate mechanism. In the tests with our prototype, we did not implement this control strategy, as connected PV systems have to provide such control by default (such that no additional value can be derived for the prototype at hand). Furthermore, production could only be limited, but the natural value of power production could not be further exceeded; thus, the treatment would be asymmetric. However, in this work, we used equal treatment for both imbalance directions, by delaying or advancing power consumption, as far as possible. Nevertheless, some appliances (especially EV charging) can not be advanced easily, as they usually start consumption right after plugging. Thus, the behavior may be not completely identical for power shortage and power overflow.

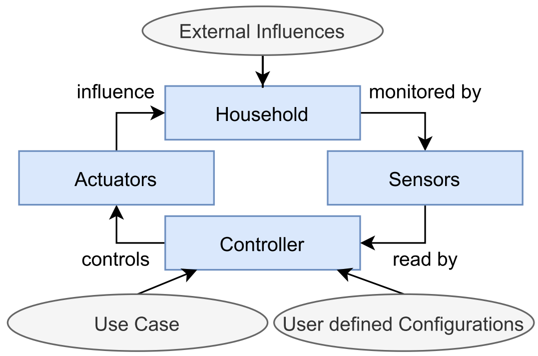

FIGURE 4. Control algorithm reads the current state of a household using sensors and adapts it using different actuators based on cluster commands and user-defined configurations. In addition to the controllable actuators, there are also external influences on a household that affect its state, such as the ambient temperature or the position of the sun.

Also, we did not implement self-consumption optimization, as this is an additional research question, which is not the main focus of this work (as depicted in Section I). Yet in the community simulation, we considered common storage for all participating households, which can be used for intra-community trading. Thus it allows for dealing with local imbalances, without interfering with the DSO. Electric energy storage devices hence by nature provide optimization to a certain extent. Finally, our prototype never overrides the built-in limits of the household appliances. Especially, safety measures (e.g., temperature limits of hot water storages) are kept fully functional; i.e., control is done only within normal operating parameters of the participating appliances.

C. CONTROLLER

The controller is the instance used to apply these cluster-wide control strategies, as well as user-defined configurations for an associated household. From a software side perspective, it is a monolithic component representing the control algorithm, as shown in Figure 4. It reads multiple sensors, which monitor the current state of the household. Based on the sensor values, the current CUC, and additional user-defined configurations, the controller sets different actuator values, which in turn affect the household's state. Of course, external influences such as the ambient temperature or the position of the sun also have been considered.

This is especially important for the simulations, as these external influences have to be modeled as accurately as possible. As many system parameters show some inertia, i.e., the influence of actuators may show only after a certain delay, the controller is executed only once per minute. In practical tests, this granularity turned out to be sufficient (see Section VI). Due to the fact that the appliances of a household offer different actuators, the controller needs to be able to control each appliance based on its type. Therefor, the system needs to know the following information:

- Which devices are available in the household?
- Which sensors and actuators can be accessed?

- What are the current values of the accessible sensors?
- What is the current state of additional configurations (e.g., preferred charging times for EVs)?
- What is the current CUC?
- How shall the appliances be controlled (based on the current state information)?

Based on the aforementioned CUCs, concrete control strategies are implemented as follows. As mentioned, no actions are taken for CUC 0; i.e., the native appliance control logic implemented by the respective vendors applies. Native (vendor defined) safety and security limitations of appliances also apply to each CUC.

D. USE CASE STRATEGIES

For the CUC +2, electric storages are discharged with 2 kW to 0% State of Charge (SOC). Wallboxes are interrupting all charging processes with the only exception of ''urgent charging'' (for user convenience, activation takes place in order to have a charged EV available at a user-defined departure time on individual user requirements). When the room temperature is within the user-defined tolerance band, the heat pump is set on pause mode and the room temperature is untouched by the heating system until it is as low as the pre-defined lowest tolerable limit.

For the CUC +1, electric storages are discharged to a pre-defined lower limit; the default value for that limit is set to 20% SOC. Wallboxes are deactivated again with the exception of immediate charging processes triggered by EV users. When the room temperature is in the defined band, the heat pump is again paused, as in CUC +2; however, the upper limit is slightly higher than in CUC +2, thus keeping the heating mode for a longer time (this allows for a bigger hysteresis).

For the CUC −1, electric energy storages are charged with 2 kW up to a pre-defined upper limit; the default value for that limit is set to 80% SOC. Wallboxes are triggered to charge with a defined charging current. Depending on the current SOC, cars may use flexible values lower than calculated by the controller. Heat pumps are enabled for heating operation. The concrete heating cycles are performed according to the internal control algorithm; i.e., in that case, the controller does not influence the heating (just like with CUC 0).

For the CUC −2, electric storages are charged up to 100% SOC. Wallboxes are operated at the maximum charging current and thus also at the maximum charging power (as the voltage is fixed in LV grids). This of course depends on the electrical installation, as well as on the capabilities of the EV. Usual values for home installations are 22 kW/32 A or 11 kW/16 A. Finally, the heat pump is enabled for heating operation (again, heating cycles are performed according to internal control).

As mentioned, users may manually override the settings of the controller in some cases for convenience reasons; especially, the urgent charging of EVs may have a big impact on the effects of the controller. Also, all the band limits for temperature and SOC are given by the system customers. Thus, an incentive system called ''wallet'' has been created, which rewards cooperative users while doing nothing when users counteract the control goals. Hereby, not the absolute power consumption is considered, but the changes in power consumption of users' appliances as a reaction to the flexibility request.

For each 15 min timeslot, an average power value is calculated ex post (P_{curr}). When the new timeslot starts with a changed CUC (such changes are only possible at the beginning of a new timeslot), the current value of P_{curr} is stored as a reference value P_{zero}. P_{zero} is valid for the time being without further changing the CUC. After finishing new timeslots, again new P_{curr} values are calculated, and the differences to the reference value P_{zero} are determined.

Differences in the ''wrong'' direction (load shedding in negative CUCs, load adding in positive CUCs) are ignored (no penalties are given); however, differences in the ''right'' direction are rewarded with a pre-defined amount of money per changed energy. Hereby, fluctuations within a timeslot are also ignored; i.e., constant power is assumed within a timeslot, allowing direct calculation of the energy changes (in kWh) out of the power differences:

$$E_{flex} = |P_{curr} - P_{zero}| * 0.25 \tag{1}$$

Here, E_{flex} is the energy flexibility provided to the DSO in exchange for the flexibility incentive (the ''wallet''). P_{curr} and P_{zero} are used as defined above. The factor 0.25 is derived from the duration of a CUC timeslot (which is a quarter of an hour) in h.

IV. CLUSTER ARCHITECTURE

This section describes the different architectural considerations of the presented community energy management system in the following terms:

- The system architecture (the structure of the intended storage cluster) contains the system components and their interrelation.
- The communication architecture depicts the communicating nodes of that system and their used protocols.
- The energy grid architecture contains the consumers, producers, and storage elements of the community at hand, as well as the energy flows in-between these power nodes.
- The software architecture of the central logic component (i.e., the controller device) holds the logic of the distributed control system.

A. STORAGE CLUSTER SYSTEM ARCHITECTURE

Storage clusters as described in this work are used to manage the power consumption as well as the generation of multiple controllable households depending on the grid's energy prices and demands. A household may in turn be separated into multiple sub-households. This concept is introduced (i) to be able to map multi-family households with different optimization goals and (ii) to separate devices that can actively be controlled (e.g., heat pumps, battery energy storage systems)

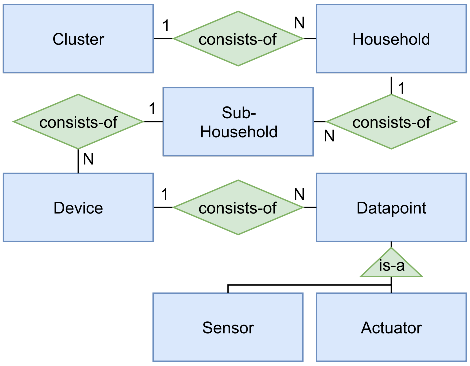

FIGURE 5. Structure of a storage cluster can be represented in form of an EER diagram that consists of multiple households, each of which may be separated into sub-households. A sub-household represents a set of devices with readable and/or writable datapoints in form of sensors and actuators.

from other power consumers that can only be monitored, usually using smart meters (e.g., TV, washing machines). Sub-households however usually share one CEMS; i.e., one central instance which is containing the controller logic as well as the gateway for external communication.

Every sub-household is a set of controllable or non-controllable units that offer different datapoints. They usually represent a readable sensor value or a setpoint writable to an actuator. However, some static configuration parameters (e.g., type of participating EVs and their battery capacities) or user preferences (room temperatures, preferred charging times, etc.) also have to be considered. Finally, the current CUC and wallet-related data (P_{zero}, P_{curr}) are relevant to the controller and have to be communicated in a proper (i.e., secure and timely) manner. In Figure 5, the most important components and their logical interrelations are shown in form of an Enhanced Entity Relationship (EER) [53] diagram.

The main system components and the used communication links between them are outlined in the following. Basically, a backend infrastructure (the "SPC Test Server") is connected to a number of test households (for the field test bed, two households have been considered; for simplicity, only one is depicted in the figure) via a public cloud. Each test household comprises a number of (controlled) devices, as well as an edge device implementing the CEMS functionality. As edge device, a `Simatic IOT2050` Internet of Things (IOT) gateway has been used; it is equipped with an `ARM TI AM6528 GP` dual-core processor, and holds 1 Gigabyte (GB) of Random Access Memory (RAM). This edge device contains the actual controller, which manages the devices within a household, as outlined in Section III.

Additionally, the edge device holds device drivers for all controlled devices in order to receive sensor information and to set actuator values, usually utilizing technologies like Modbus, ZigBee, etc. The device drivers translate these data exchange formats to MQTT messages, which are sent to and received from the controller via an MQTT broker which may be located anywhere in the cloud.

In later implementations, the broker instance is planned to reside within the edge device to avoid unnecessary cloud communication; however, for testing purposes, one central broker instance had been utilized. This has been done for simplicity reasons, as the central broker instance is also used for forwarding necessary central data from and to the backend (e.g., the indication of the current CUC, changing user preferences, or also wallet data).

In older implementations, a usual standard Personal Computer (PC) had been used to hold the CEMS functionality, which worked without problems. For the edge device, however, we faced difficulties when processing all MQTT messages that the broker provided, especially due to the fact that some sensors produced many more measurements than actually needed. As we identified the limited RAM as main origin of these difficulties, we limited the sensor data to one message per datapoint and cycle. As we are storing measurement data in local variables and using these variables as input for the calculations in each cycle, only the latest measurement per cycle is used. Thus, this limitation had no effect on the functionality of the control algorithm.

The backend server contains an MQTT client to communicate with the MQTT cloud broker (which could optionally also reside at the backend itself). An appropriate user interface allows households to define user settings like charging times or temperature preferences. Furthermore, a cluster operator can set the current CUCs for the households in a cluster in order to request energy flexibilities from the participating households. These CUCs are distributed using MQTT cluster command messages, which have to be acknowledged by the household controllers.

Both for end users and for operators, Web interfaces are available at the test server. The system thus allows adding additional services like a monitoring service, time series databases, or visualization dashboards to show temporal differences of the measured values. Specifically, Prometheus [54] is used for the monitoring of the system, as well as an InfluxDB time series database [55] together with Grafana [56] as visualization tool for later validation and evaluation of measurements from households' appliances.

Furthermore, some environmental data (e.g., outside temperatures) are used as input for simulations; again, the simulations can store their results in the time series database. In Section V, a couple of simulations are sketched which have been performed based on that simulation environment. Some of the components mentioned here have been realized as Docker containers [57] in order to allow for a later porting to other system components. This does not affect the functionality, however. Figure 6 gives a brief overview of the mentioned system components and the communication protocols used for their interactions.

B. COMMUNICATION INSTANCES AND FLOWS

In this work, a loosely coupled architecture for a storage cluster system is proposed; i.e., the inner logic of the controller should not reflect the way, appliances are connected to the

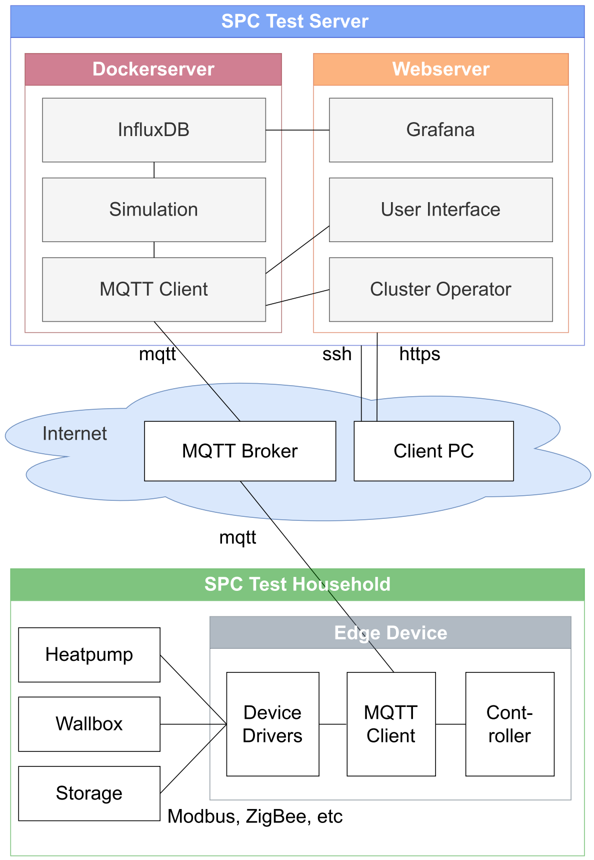

FIGURE 6. This figure outlines the main components of the field testbed in Stegersbach. Only one test household is depicted here; a second household has been connected in an identical way. The system architecture contains physical devices (e.g., the heat pump) as well as controlling devices; the protocols of the main communication paths are also given.

system. However, at least the datapoints must be known to the controller, as the appliance control is based on them. Yet, further details should be hidden to the controller communication. Also, best practice solutions for secure communication should be used, even when security is not the primary focus of this work.

As mentioned, this is ensured by using the messaging protocol MQTT [58]. MQTT is a publish/subscribe network protocol that allows broadcasting messages for given topics via an additional decoupled message broker. These topics can in turn be subscribed by other communication participants to receive the published messages from the MQTT broker. MQTT also provides sufficient security by using Secure Socket Layer (SSL) connections as well as client authentication and authorization.

To be able to clearly identify the different types of messages that are broadcasted in the system, the following hierarchical topic structure has been developed:

`<prefix>/<clusterid>/<type>/<gateway>/<subhousehold>/<asset>/<datapoint>`

Such, an MQTT topic reflects the cluster structure shown in Figure 5 and builds up on different placeholders, where `prefix` and `clusterid` uniquely identify the addressed storage cluster. The following subtopic `type` defines the message type and differentiates between sensor, actuator, actuator acknowledgment, cluster command, and cluster acknowledgment messages. The addressed edge device of a household is associated in `gateway`. An edge device may combine multiple sub-households, which are in turn represented by the `subhousehold` section. The last two parts link the message with the used `asset` and its concrete source or target `datapoint`.

An asset thus aggregates multiple datapoints depending on the message type. While for cluster commands, the CUC may be the addressed asset, for sensors and actuators this placeholder is used for the actual physical appliance. Messages are exchanged within the system based on this topic structure. The message structure itself is again defined based on the JavaScript Object Notation (JSON) [59] exchange format. Every message contains two main entries: (i) the actual get or set value and (ii) a Coordinated Universal Time (UTC) timestamp containing the message's creation date. In addition to that, there may be additional metadata depending on the message type.

Besides MQTT, Web applications are used for supervising, evaluating, and maintaining the control logic, as mentioned above. Finally, field buses are used for the direct connection to the appliances in the households. Due to the inhomogeneity of the connected devices, there is a wide range of communication protocols within a household; for example, Zigbee [60], Modbus [61] or Controller Area Network (CAN) bus [62] are commonly used in this context. These field bus protocol stacks are connected to the system via drivers, which translate the respective field bus protocols to an MQTT messaging in order to hide appliance-specific details from the controller. Especially, specific MAC-Layer addressing can thus be avoided.

C. POWER COMPONENTS AND FLOWS

A single household, as it is used later in simulations (see Section V) and field tests (see Section VI), contains several power components as shown in Figure 7 and listed in the following itemization:

- *PV system:* The PV system feeds power to the household. In reality, this follows the respective weather situations. Especially, daylight duration and cloudiness have an impact on the output. These values are not measured and stored in our system; yet, the outside temperature is gathered with the sensory associated with the heat pump. For the latter, a statistical correlation with the PV output can be proven (daylight length and temperature are both dependent on the season). In the simulation, no curtailment limit is implemented. The feed-in is calculated according to a predefined weather data set (which may be aligned with measured values) or it is derived from a defined PV profile.
- *Battery:* The local battery energy storage systems can consume or produce power, depending on the balance

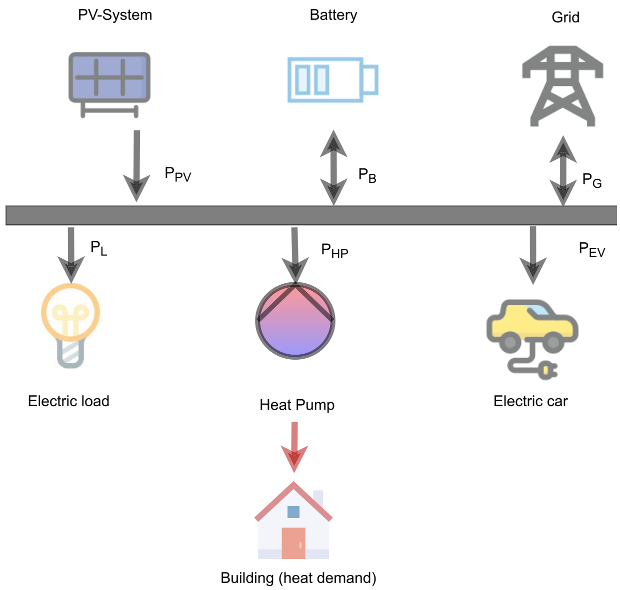

FIGURE 7. In this overview of devices and main power flows within a simulated or real household, the red arrow represents the thermal power invested to heat the building, whereas the gray arrows represent electric power. The component ***Electric load*** comprises all non-controllable loads of the household; the ***Building*** stands for a thermal energy consumer here.

of PV production and consumption in the household. It can either be working in autonomous mode (self-consumption optimization), which is for example the case in CUC 0, or be controlled by the household controller. In the latter case, upper and lower limits are used dependent on the current CUC. For the simulation, the battery is modeled as a limited integrator with continuous power dissipation and a capacity of 13 kWh. In the field tests, two different batteries have been utilized: A `Siemens Junelight SB-13,2` with a capacity of 13.2 kWh and an inverter power of 3.5 kW, and a `Neoom Kjuube Light HV-SO` with a capacity of 14.2 kWh and an inverter power of 8 kW. Additionally, in multi-household simulations, cluster storage with a capacity of 90.6 kWh is used.

- *EV charging station:* The EV charging station is of type `Keba KeContact P30`. It represents a controllable load where the maximum charging current can be set. By its nature, it is only available when a car is connected. The power can be scaled up to 22 kW depending on the fuse rating and the capability of the connected EV. In a Vehicle to Grid (V2G) scenario, negative values for the charging power could be set. In this case, the wallbox control would be similar to battery control, provided that an EV is connected that is capable of providing energy to the grid. It the field tests as described in Section VI, no such car had been used for obvious economic reasons.
- *Heat pump:* The type `iDM Terra SW 30S` heat pump also represents a controllable load with a nominal electrical power of 10 kW and a strong restriction on maintaining comfort within the building. Again, it can be operated in an autonomous mode for CUC 0. For the positive CUCs, the restrictions are user-defined. The basic idea is to keep the inside temperature derived by the room sensor of the heat pump within a defined band. In the Net-Price High CUC, a hysteresis from 21 to 22 °C is used for the on/off control. In the Flex Up CUC, this hysteresis is kept smaller (21 to 21.5 °C) to shorten or delay the operation time and thus save electric power for the time being.
- *Household load:* The electric household load consists of all appliances, which are not directly controllable by the household controller/CEMS. However, indirect control may be possible, if humans in the household get appropriate energy feedback to change their power consumption behavior. Yet, this has not been researched in this project context.
- *Building:* The building is representing a thermal energy sink, as can be seen in Figure 7. This is resulting from heating demands in the winter season; cooling in summer has not been researched, however. As the heating is performed with a heat pump in the considered household, this can be used as a controllable consumer. As thermal effects in the building have comparably high inertia, it is well suited for short-term power shifts. In the simulation, a close-to-reality model has been applied (see Section V).
- *Grid:* The grid finally represents the connected LV grid. After balancing production and consumption, the imbalance is tried to compensate with the (local or cluster) battery storage. If this is impossible due to battery limits, the remainder has to be exchanged with the grid. The main goal of the control strategy has been to minimize this exchange.

Heat pumps, batteries, and wallboxes have been chosen due to their controllability and their ability to provide a substantial amount of flexibility, compared with appliances like dishwashers, etc. For the real-world test-bed, existing households and their appliances have been used for economic reasons, but also to demonstrate the system's ability to co-operate with all given appliances which provide a common control interface (in many cases, but not necessarily, this is realized via Modbus). As mentioned, the edge device contains a gateway functionality to translate the individual control interfaces to the controller's MQTT based communication. The effort for this translation varies significantly. Standard compliant control interfaces like Modbus SunSPEC [63], which is common for PV systems, can be integrated much easier as appliances which use proprietary control protocols. However, if comparable appliances use different internal semantics (e.g., one storage device uses just charge/discharge control, while an other device also allows controlling the used power), the controller would need to provide different logics to cope with that. To keep the effort reasonable, we used semantically compatible devices, such that the customization is only affected by syntactic issues (names and structures of comparable datapoints).

D. CONTROLLER SOFTWARE ARCHITECTURE

The actual control logic (as described in Section III) can be mapped into the system realization using object-oriented paradigms, where an abstract `UseCase` class supports a base control method to apply the control algorithms for all devices. This base method needs to iterate all devices of the household and apply a type-specific control method, that in turn can be separated into three single steps for pre- and post-controlling, next to the actual control process. Pre-processing is reserved for plausibility checks for sensor values, yet not used in the current implementation. Post-processing is used for checking violations of side conditions.

Besides the base algorithm mentioned above, the controller may also call combined control algorithms for multiple devices of different types. Based on this foundation, there may exist multiple implementations for the different CUCs, as shown in the upper part of Figure 8. This creates a ''Per Controller Behavior (PCB)'', just like the PHB in routers allowing for different implementations of given QoS requirements.

Next to the actual control algorithm, the controller needs also connectivity components to be able to exchange information with the remaining system. For this purpose, an `MqttManager` class is required that is able to react on MQTT specific events, like getting connected to the broker or losing the connection. In addition to that, it must also be able to subscribe to household relevant topics in order to allow to react on cluster commands, but also to get notified when new sensor values are available and forward those to the `Controller` class.

The `MqttManager` must also be able to broadcast actuator messages based on CUC specific optimization strategies, that are applied within the injected `Controller`. This task is performed in a loop with a definable interval, to be able to map inert systems, where a reaction to an executed action is not immediately measurable (e.g., the changing water temperature after adapting the target value of the heat pump). The software structure of the controller, as well as the MQTT component, are shown in the bottom half of Figure 8.

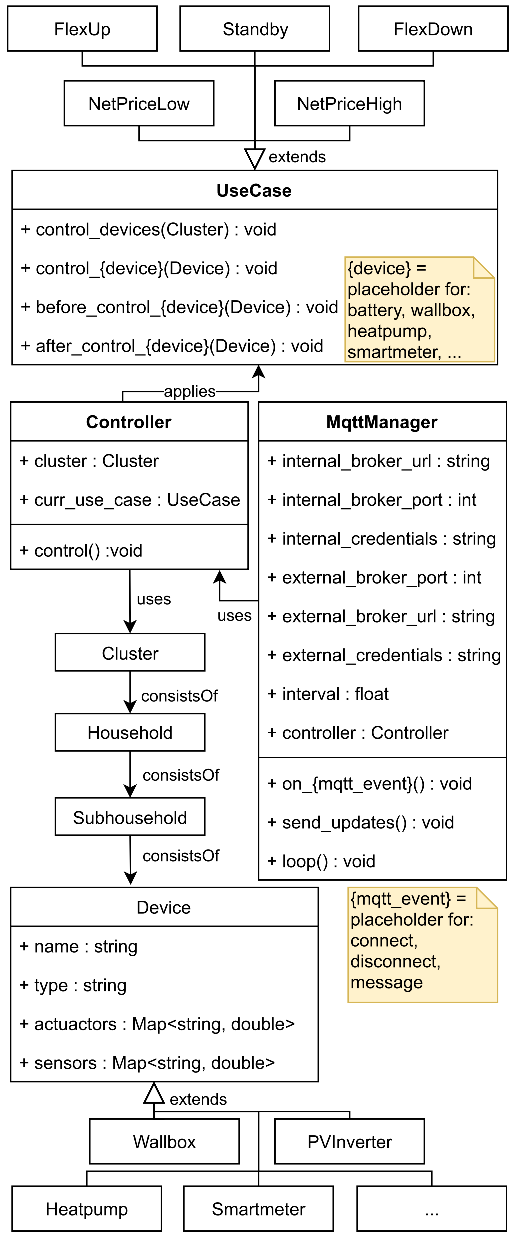

FIGURE 8. Software architecture of the household controller shows the use of MQTT to receive sensor values, as well as cluster commands, and to send cluster acknowledgment and actuator messages to control the devices of a household based on the current CUC.

V. HOUSEHOLD SIMULATIONS

This section describes the simulation environment for a single household as well as for a group of households with similar equipment. The scenarios, the executions, and the corresponding results of all the simulations in a single-household environment and in a multi-household environment are also given here. The aim of this simulation environment is to test the algorithm, find potential errors in the control outputs, and see the influence of the control mechanism before implementing in the field. The simulated scenarios shall also demonstrate the potential of smart energy management.

A. SIMULATION ENVIRONMENT AND SCENARIOS

The simulation environment was created in Matlab/Simulink [10]; a standard PC was used as hardware base for all simulations. For the appliances, component models have been built specifically for this project. Additionally, the thermal model has been derived from the Carnot toolbox [64]; yet solar gains have been modified according to existing measurements of PV power, as this correlates well with real weather conditions. Technically, an interface between Matlab and Python is used, such that direct communication between the simulation and the controller (see also Section III-C) is established. The cluster command is directly set in the simulation environment, according to the defined test scenarios.

Basically, the simulation thus builds a wrapper around the controller, which is included as an external function within a household. Thus, the MQTT broker is not necessary within the simulation; also the gateway function of the edge device (appliance drivers) is not needed for the simulation, as no communication to real hardware appliances is used. The single components in the simulation for both single-household and multi-household environments (appliances, controller, database) are the same as in the real-world tests, as described in Section IV-C.

To execute several simulation runs in this simulation environment, the respective scenarios had to be defined. The scenario definition has been based on the set of input parameters, i.e., the CUC, the ambient temperature, the power consumption of the non-controllable appliances, the cable state of connected EVs, and the instantaneous power of the connected PV system. As simulation output, the power demand of the participating appliances over time is derived. To be able to guarantee as realistic scenarios as possible, we have used stored values in our database, which have been collected by our sensors over more than a year, as inputs. By doing so, we are also able to retrace different context conditions due to seasonal effects or different usage patterns at weekends or holidays, etc.

For these simulations, we have used the autonomous behavior of the considered appliances as a baseline, and explored the effects of our control algorithm (see Section III) in contrast; i.e., for the baseline scenarios, no optimization is performed (also no self-consumption optimization), and each appliance works autonomously as foreseen in the respective given appliance controls. In comparison to the baseline, load shedding or load adding is performed by our control algorithm (as described in Section III), depending on the flexibility requests of the DSO. For single-household simulations, CUC 0 is identical to the baseline, since the DSO has no control requirements on the cluster participant. The effects of our algorithm on the power consumption can then be measured, while all other input parameters remain the same (ceteris paribus condition).

B. SINGLE-HOUSEHOLD SIMULATION

For evaluating the system reaction on our control logic, we simulated leaps from CUC 0 to all the others, while leaving all other input parameters the same. After issuing the non 0 CUCs, the implemented control algorithm overrides the autonomous behavior of the appliances. Thus, we could derive the changes which have been caused by the controller, and compare them with the required flexibilities. An illustrative example of these effects is shown in Figure 9, where the upper curve denotes the CUCs for a given time period, and the lower curves represent the power exchange with battery and heat pump respectively. It can be seen for instance, that in the morning of the first day, CUC +2 leads to an interruption of the heating period, as well as to a provision of energy stored in the battery. However, these effects can not always be observed in that clarity, as convenience conditions override the flexibility requests (see Section III).

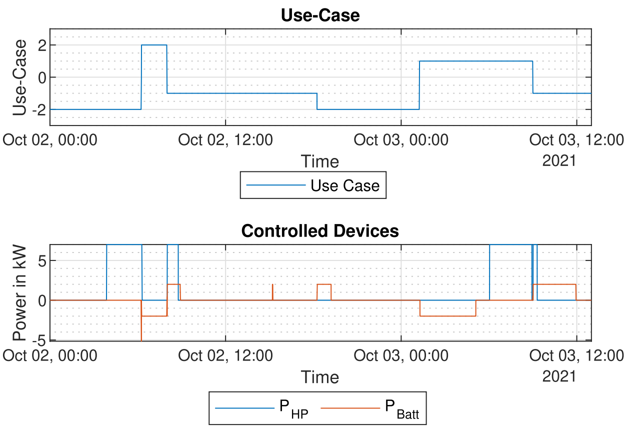

FIGURE 9. Simulation example shows the sequence of CUCs, and the reaction of controlled appliances on these flexibility requests, taking into consideration user-defined convenience limitations.

In order to quantitatively assess the provided flexibility, appropriate metrics had to be defined. In this work, we evaluated the Maximum Power Change (MPC) triggered by a changing CUC, the Duration of Change (DUR) (i.e., the time between the trigger and the return of the flex curve to the value of the baseline curve), and the Total Amount of Provided Flexibility (TAF) (i.e., the area between the baseline curve and the flex curve, calculated by the integral of the difference). With these metrics, an assessment of the provided flexibility can be performed, as exemplarily depicted in Figure 10. The upper curves show the power balance in the simulations of CUC 0 (the baseline) and CUC -1; the middle curve depicts their difference (which is the reaction of the system on the different CUC), and the lowest curve the integral of the middle curve (for calculating the TAF metric). Again, the example demonstrates the effects of the control under beneficial conditions.

C. MULTI-HOUSEHOLD SIMULATION

For the multi-household simulations, the environment for single-household simulations has been cloned several times, such that at the end, six households (with one sub-household each) could be used for the simulations [65]. Each of the clones then has been modified a little regarding the appliances present in the respective households. Additionally, a Community Energy Storage (CES) has been introduced, which is connected to each of the participating households. Each household is able to charge the CES, if the upper limit has not yet been reached, and discharge it, as long as the lower limit has not been reached. Both activities can be performed with the same CES tariff, which is an intermediate tariff between purchase and feed-in tariff when exchanging power with the DSO.

By doing so, the CES may be used by participating households as cost neutral extension of the internal storage; moreover, it can be used by different households to transfer energy from a household with an energy surplus to an other household with power demand. In comparison with a feed-in into

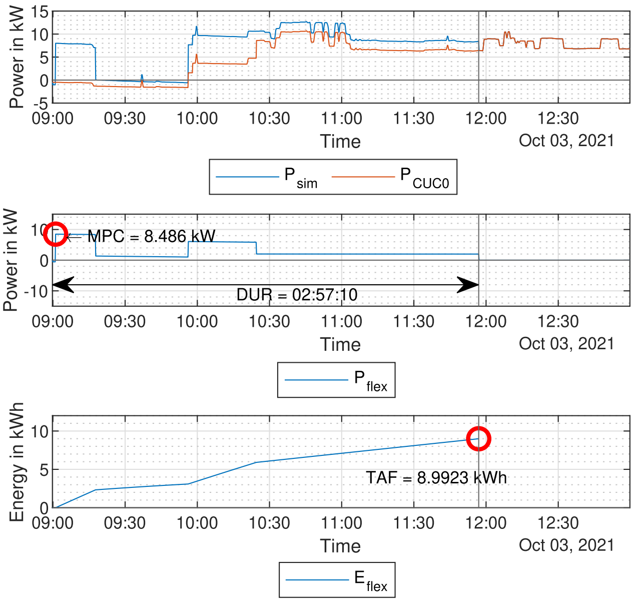

FIGURE 10. The metrics on flexibility requests are assessed in an illustrative example, showing the baseline (the simulation of CUC 0), the simulated reaction on issuing CUC -1, as well as the resulting values for the metrics.

the associated LV grid, or an energy purchase from the DSO, both the energy-providing party and the energy-consuming party profit from such an exchange. For the simulations, 0.21 € per kWh has been used as purchase tariff, 0.10 € as feed-in tariff, and 0.15 € as internal tariff. The CES allows for balancing the several households of the community before they exchange energy with the DSO; thus, it helps to relieve the power lines (in opposite to a just financial balancing of energy communities). However, it also provides additional storage capacity and thus strengthens the flexibility potential of the community.

Table 1 shows the electrical and financial effects of the CES on the community according to the simulated test households, for a simulated time of 30 days. The CUC has to be set to 0 throughout the whole multi-household simulation (since in the other CUCs, flexibility provision will override the autonomous behavior of participating appliances). The other input parameters known from single-household simulation are set to realistic values (which have either been directly derived from real-world measurements in a similar time period, or calculated by using the mentioned thermal model). Here, the purchase or selling is done either to the CES (if present), or directly to the DSO.

In the simulation, the limits of the CES have never been reached, such that no mixed purchases or sales have occurred. As it can be seen, the amount of purchased and sold energy for all households remains the same, i.e., the CES does not influence the appliance behavior. In the case of direct exchange with the DSO, the cost benefits are negative, i.e., the households have to pay the DSO, although the balance of energy is positive, which results from the different tariffs for purchasing and selling power. However, from a purely financial point

TABLE 1. Energy and cost effects of the usage of common cluster storage for an energy community consisting of six individual households, partly equipped with individual storages, heat pumps, EVs, and PV systems for a simulation of 30 days reveal some additional benefits [65].

	Without CES	With CES
Energy sold	94.86 kWh	94.86 kWh
Energy purchased	89.46 kWh	89.46 kWh
Revenues	9.486 €	14.229 €
Expenditures	18.786 €	13.419 €
Cost benefits	-9.30 €	0.81 €

of view, the effects of the CES from about 10 € per month for the whole energy community would not justify the investment of a CES. Yet, the additional flexibility, as well as a smoothing effect helping the connected LV grid for peak clipping and valley filling, might raise the interest of DSOs to provide such a device as an additional incentive.

VI. FIELD TESTS

For the tests in a real-world environment, there was no obvious baseline since environmental as well as usage patterns are never exactly identical, and we could either apply our control algorithm or not. To be able to assess the effect of our control, in reality, we thus used two reference scenarios for comparison:

1) The "wallet reference" is based on the assumption that usage and environmental influences stay constant for the duration of a use case. Consumption changes in the requested direction are thus a result of the applied control strategy and deserve a reward in form of financial incentives (i.e., the wallet, see Section III).
2) The "simulation reference" is based on the simulation scenarios, which are again derived from the collected historical data persisted in our database. If the simulation represents reality well, it can be used as a reference, that approximates reality without using our controller entity.

A. TEST SCENARIOS

The simulation reference is the same as used in the evaluation of the simulations. As a baseline for both, the simulation of CUC 0 is taken; yet, the evaluated curve here represents the real data in other CUCs and not the simulated data in other CUCs. The simulation reference is used only for evaluation purposes for the work at hand and has not been integrated into the calculation of incentives. For the following, we concentrated on the simulation reference, as it delivers more accurate results than the wallet reference when the simulation works well (see Section VII and Figure 10). However, the definition for E_{flex} from Equation (1) has to be adopted in this case, as flexibility can be measured now continuously, not only for 15 min timeslots, as follows:

$$E_{flex}(t) = \int_a^t P_{flex} \quad (2)$$

Here, P_{flex} is the difference between the flex curve and the baseline curve, t is the instantaneous time of the measurement, and a is the time of the flexibility request as described in Section V-B and visualized in Figure 10. When b is the time where the flex curve returns to the baseline curve, it can easily be seen that the TAF metric equals $E_{flex}(b)$.

As a next step, the scenarios for the field tests have been defined for some appliances present at the used testbed in Stegersbach. We have concentrated on controllable energy-consuming appliances here. The non-controllable consumers can not be influenced by our algorithmic logic, such that only sensor readings could be tested. The energy-producing roof-top PV could yet be influenced, but should not be down-regulated for keeping purchased energy as small as possible unless stability reasons enforce a regulation. By doing so, we have defined scenarios for a heat pump, a wallbox, and the electric energy storage(s).

For each of these devices, we have defined 3 kinds of functional test scenarios:

- *Tests of base functionality:* Under given appliance-specific conditions, each CUC has been applied to the controller component, and the reactions of this component (in form of MQTT messages) have been measured and documented. Furthermore, the application of control commands to the appliances under test (MQTT actuator commands translated to the respective appliance interfaces) has been conducted, and again the reaction of the appliances has been observed and documented. Thus, it can also be verified that the actions have real-life effects as intended (which can not be validated in a simulation environment only).
- *Tests of stochastic CUC sequences:* These tests are designed as long-term tests in order to not only cover all CUCs, but also all possible CUC leaps (especially from CUC 0 to the others), and this under different environmental conditions. By doing so, white-box testing should be avoided, which is hard to define properly, as the environmental conditions are not predictable and can hardly be grouped into meaningful categories. These tests should reveal potential shortcomings of the applied logic which may occur very rarely in practical environments, but can nevertheless be theoretically possible. By examining these rare situations, we can prove that the applied control algorithms are robust against extreme conditions.
- *Tests of realistic CUC sequences:* In order to conduct tests in near realistic conditions, a sequence of cluster CUCs is derived from typical power price curves at the Austrian spot market. These price curves represent shortages and surpluses of electric power in transmission and distribution grids and can thus incorporate different technical conditions in the LV grid associated with the field test environment. A price curve of a typical weekday has been selected as a representative. The delimitation of CUCs has been done on the base of manually chosen limits at 49.9, 56.1, 61.9, and 72.7 €/MWh in order to support "higher" CUCs (which trigger energy savings) while keeping a reasonable distribution of all defined use cases. Prices and CUCs have been defined on an hourly basis here.

B. CONTROLLER VALIDATION

For the base functionality tests, the expected results of the control (see Section III) could be obtained after eliminating initial implementation difficulties. Hereby, scaling issues played the most important role; by limiting the number of messages (per controller cycle, only one value per datapoint has been transmitted), the controller hardware was then able to proceed as foreseen. This means, that the heat pump showed an on/off behavior according to the room temperature limits of the respective CUC; the storage kept the respective SOC limits, and the wallbox deferred charging as long as possible when required by the CUC.

For the heat pump, functionality tests have been conducted in different environmental situations, i.e., in winter tests with cold ambient temperatures have been conducted and in spring with medium ambient temperatures. For the wallbox, functionality tests have been conducted in different usage situations, i.e., with or without a car plugged; with a car plugged and additional user requirements set (immediate charging or charging shall be finished within 12 hours), as well as plugging or unplugging within a charging session. For the stochastic CUC sequences, the tests showed similar effects as in the simulation (mentioned in Section V and visualized in Figure 9).

After validation of the controller capabilities, some close-to-reality test sequences have been conducted. The daily sequence of CUCs is defined as mentioned above. Additionally, different environmental and/or usage patterns are issued again. Here, heat pump tests include different weather conditions (warm&sunny, warm&cloudy, cold&sunny, and cold&cloudy). The second parameter is as well important here, as the installed PV could be used for operating the heat pump in sunny weather conditions, serving as an electric power sink, if needed.

For the wallbox tests, besides the usual tests with given CUCs and different usage patterns, also an additional scenario with a higher power supply during the day (due to PVs production) is considered. Finally, for the storage, the CUC sequences are tested with different SOC values ($SOC < 20\%, 20\% \leq SOC < 80\%, 80\% \leq SOC$). Figure 11 shows a typical example of the conducted field tests with respective values of the evaluation metrics. Hereby, the parameters are the same as in Figure 10, except for the blue line in the upper part, which is the real power here.

VII. EVALUATION AND DISCUSSION

When analyzing simulations and field tests, the system's behavior is in focus. As the controller's main purpose is to provide flexibility to the DSO, the ability to shed or add loads

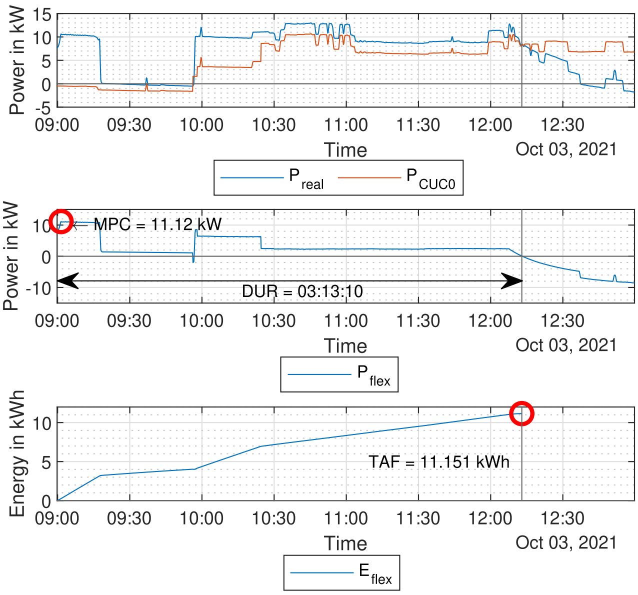

FIGURE 11. **Typical example of the conducted field tests reveals the evaluation metrics in a close-to-reality scenario (the CUCs are based on typical price curves and not real-time flexibility requests; all other parameters are resulting from real-world measurements and given user preferences).**

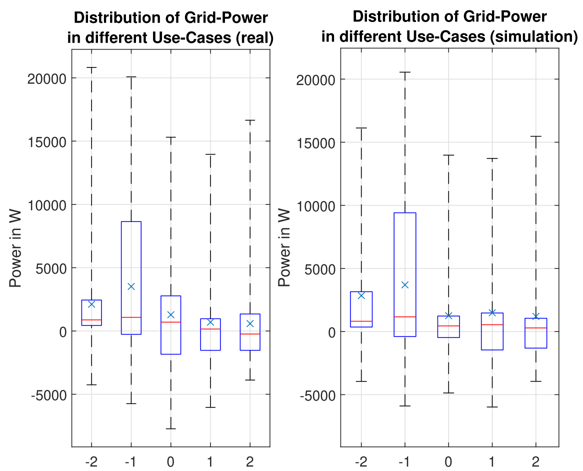

FIGURE 12. **Boxplot shows the mean value, the median, the quartiles, as well as the range of the power values which are fed into the LV grid, depending on the CUCs set by the grid operator. The left part shows the reaction of the system in real field tests, whereas the right part depicts the respective simulated values.**

on demand has to be proven. Concrete, the power consumption should have a clear dependence on the CUC, which will be shown in the following. Furthermore, a validation of the simulation model has to be done. As the simulation is used as a reference in Section VI, the validity of this reference has to be shown. For that purpose, a comparison of measured values with simulated values, which are derived by using the same input parameters, has to be performed.

A. INFLUENCE OF CLUSTER USE CASES

Figure 12 shows the distribution of grid power values between the CUCs in the simulation and in the field test. Here, the red line represents the median of all power values in a certain CUC. The blue box represents the 25th and the 75th percentile, and therefore 50% of all power values in the respective use case are within those borders. The mean power value is depicted with a cross. Considering the CUC definitions, high consumption should take place in the negative CUCs, whereas the power values should be lower in the positive CUCs.

In fact, the CUCs -2 and -1 show higher power values than $+1$ or $+2$, as intended. However, the "flex" CUCs, especially CUC -2, appear to have less influence. Here, we are evaluating time series with realistic CUCs sequences (see Section VI) in order to derive meaningful results; yet, this means that leaps from CUC 0 to the "flex" CUCs are very rare. As we only adapt the limits (battery SOC, etc.) when changing from a "net price" CUC to a "flex" CUC (e.g., if CUC $+2$ comes after $+1$), the remaining flexibility potential might be too low to still receive a remarkable effect. Thus, flexibility effects might have already been exploited.

However, when considering the power provided to the DSO, the CUCs -1 to $+1$ work as expected. For a roll-out in real world, either the used limits should be adapted (in order to keep a higher reserve), or the strategies should be changed (e.g., by providing appliances that are only touched in the "flex" CUCs). Simulation and field test measurements show similar behavior here, indicating a well-modeled system; however, this has to be explored in more detail.

B. VALIDATION OF SIMULATION RESULTS

To provide the required validation, we have chosen a time series showing the most important energy-related values for 10 days in spring, as it is depicted in Figure 13. As the ambient temperature is highly fluctuating these days, leading to an on/off behavior of the heat pump, the period seems adequate for the analysis. As can be seen, the simulation results and the measurements show a good match. The upper line shows temperature values and the CUC. The second line represents the simulated and real grid power, where the simulation only deviates slightly from the measurement, indicating a well-modeled battery energy storage system and wallbox. Lines 3 and 4 present the respective power data for the appliances heat pump and wallbox, and line 5 again for the battery and the PV system.

Modeling the heat pump is more complex, as it requires a precise model of the building and the heating system. Both are strongly influenced by environmental variables (temperature, humidity, wind, solar radiation, etc.) and user behavior (presence, ventilation, hot water demand, etc.). The standby consumption of the heat pump ranging from 20 to 100 W in the measurements was not considered in the simulation model. The simulation model of the wallbox is even more dependent on user behavior (plugged or unplugged car status, driven distance, etc.). The model makes use of the logged, real plug state of the EV in order to allow a fair comparison between simulation and reality. It was assumed, that the longer the

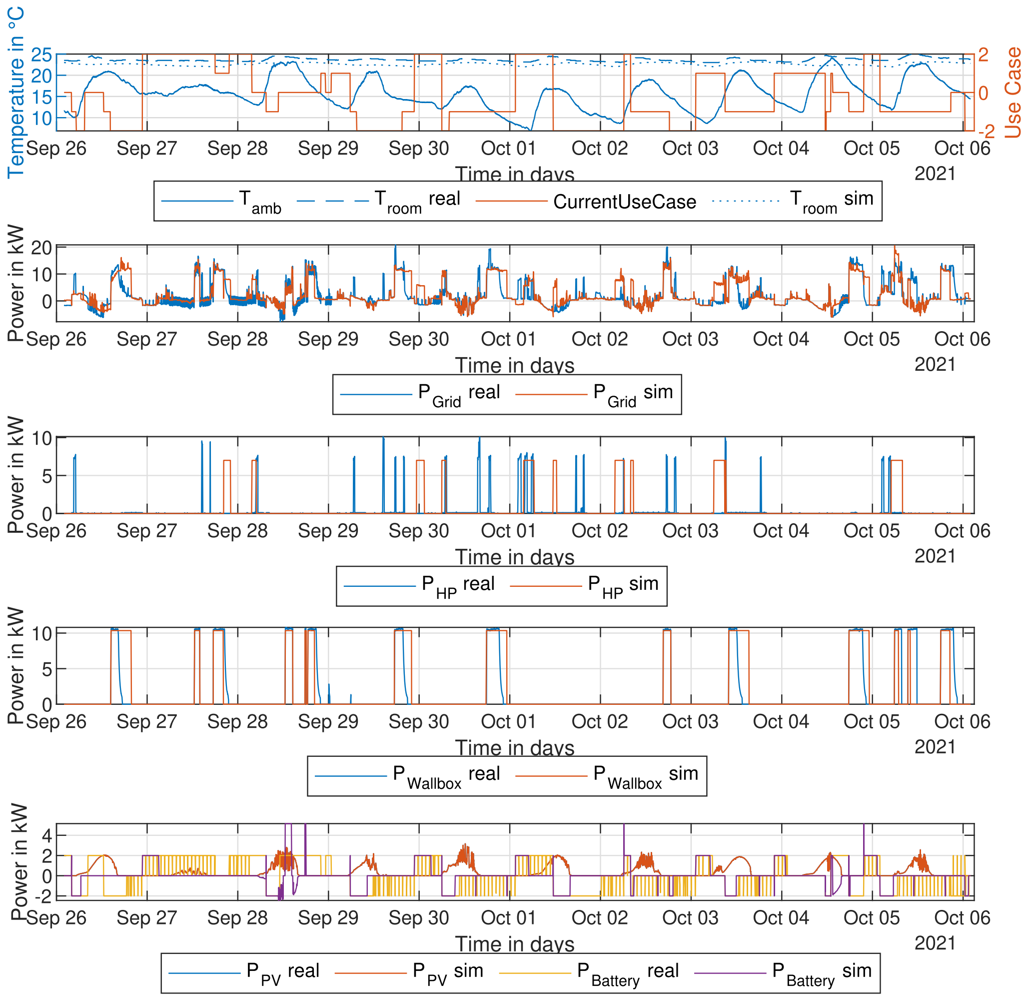

FIGURE 13. **Timeseries of the heat pump, the wallbox, the PV, and the electric storage device are compared with the power fed into the connected grid, both for the simulation and the real field test in the given period of time. The first row shows input parameters as the CUC and the ambient temperature, as well as the measured and simulated output parameter room temperature.**

car was not connected, the lower the SOC would be. With these inputs and assumptions, a good correlation between simulation and the wallbox consumption profiles could be reached.

As can be seen in the lowest graph, there was a communication problem with the battery leading to data quality issues; i.e., leaps in the measured battery power occurred. Alignment between the simulated and measured power can still be observed. The PV production measurement was directly used in the simulation as an environmental variable since it was not being influenced by the controller. Altogether it can be stated, that the simulation model gives a good estimate of the grid power. The thermal modeling of the building and heating system in order to simulate the heat pump behavior and electricity consumption is difficult. From a statistical point of view, the heat pump behavior shows many similarities (especially, average consumption over time); yet, the observed time shifts are stochastic.

C. COMPARISON AND DISCUSSION

After having validated the approach, an assessment of the afore-defined research questions can be given. A short summary is depicted in Table 2. The contribution of one household to one flexibility request (CUC change) seems promising; however, questions of scaling (regarding the number of households, or the number of requests) should be explored in a bigger real-world testbed. Thus, the effects of aggregated flexibility provision could be as well researched as architectural effects. However, by using distributed controller instances on the respective edge devices for the critical functionality, no devastating scalability effects in the ICT infrastructure can be expected. The community effects are negligible; additional stability effects could only result from the exceeded storage capacity by introducing cluster storage; however, the additional storage is just constituting one additional household, where the provided flexibility amount is again dependent on the storage capacity.

TABLE 2. Qualitative and quantitative assessments of the defined research questions listed in Section I demonstrate the validity of the chosen approach.

Issue	Assessment
RQ1	The defined metrics MPC, DUR, and TAF allow for a quantitative assessment of single flexibility requests. Under auspicious circumstances, a volume of more than 11 kWh (as visualized in Figure 11) can be shifted by one common household for a single request.
RQ2	The simulation reference (defined in Section VI) has turned out to form a useful baseline, which could be compared well with real-life measurements, as depicted in Section VII-B. As the most important parameter, the total electric load in the simulation usually differs by under 10% from the measurements, e.g. by 8.6% for a 20 days period in 2021.
RQ3	As stated in Table 1, the financial effect of intra-community trading for customers was only about 10 € after a 30 days simulation period for CUC 0. For the other CUCs, the appliances are controlled directly via the given CUC strategy (i.e., no trading between households occurs). However, the cluster storage provides an additional buffer for shifting power consumption to more suitable times.
RQ4	A controller using a loop time of 1 min provided a sufficient amount of flexibility on demand of a cluster operator. Public Internet as underlay network and utilizing MQTT over TCP/IP provided sufficient network performance, as well did standard PCs and embedded PCs (as depicted in Section IV-C) as endpoints.
RQ5	The use of MQTT allowed for loosely coupled systems with yet sufficient performance. The customization effort can thus be kept acceptable, as the control logic is set up on a generic topic system (however, translations to this topic system are still necessary, as pointed out in Section IV-A). State information is included in this topic system.

When comparing this work with existing literature, it can be said that there are more advanced strategies for controller algorithms than our simple rule-based approach; also, there are testbeds with many more participants than we used, and protocol suites may be better suitable for real-time requirements than the one we have used here. However, only very rare contributions combine these two approaches, resulting either in purely theoretical assessments of algorithmic advances while not having proven real-world capability, or in ICT infrastructures which have not been used with real grid-related control logic. To the best knowledge of the authors, those rare contributions which are trying to combine these approaches, mainly concentrate on issues like self-consumption optimization (e.g., [66]), taking into account the better simultaneity factors in energy communities. On the other hand, flexibility issues are explored in some new research papers, yet concentrating on user convenience aspects [67] or on market participation [68] rather than effects on the associated LV grid. However, the assessment of flexibility potentials is important for grid stability, such that a realistic assessment using a combined approach as in this work may impose a noteworthy contribution to grid management.

Another point that has not been sufficiently solved in existing literature, is the definition of a realistic baseline to compare the effects of the control with the initial situation. In literature, usually mathematical assessments are made instead of field tests (e.g., [69]); however, a practical assessment further increases the degree of realism and validity. Due to the volatility of energy consumption in households, measuring the difference to past situations is not satisfactory. To overcome this, we have made simulations additional to the field tests and validated these comparatively by using the same set of input parameters. We used these simulations to represent the situation without using our control with more degree of realism (the "simulation reference" mentioned in Section VI).

Finally, the uniqueness of this contribution has been rounded by providing a rigorous metrical assessment of flexibility, by defining the two dimensions of flexibility (represented by DUR and MPC), as well as the total amount (represented by TAF). Related approaches have been listed by [70]; however, the mentioned flexibility metrics are bound to concrete appliances there (mostly in combination with thermal storages), and utilized to assess appliances' capacities rather than measuring realized flexibilities. All these unique contributions may help operators with their stability goals, but they also support the scientific grounding of practical work in the field.

VIII. CONCLUSION

With the work at hand, it could be shown that energy communities have the potential to yield a remarkable impact on the flexibility market, even when applying very simple rule-based control strategies. Together with self-consumption optimization, which is much better explored in current research, such systems may be used in the future to gain financial benefits for participants of energy communities, while at the same time contributing to more stable and better balanced LV grids. The effectivity of such systems may be further enhanced by utilizing better optimizers, especially incorporating ML algorithms and predictions of relevant input parameters like weather conditions, etc.

Further research is also necessary to explore the practical differences between grid instabilities due to a surplus of power and those which are originating in a lack of electrical power. Especially for appliances that are starting their operation immediately when certain preconditions are fulfilled (e.g., EV charging systems usually start charging the car right after plugging it), additional logic (e.g., default idle times) may be required.

Also, it could be shown that a message-based infrastructure (in this case employing MQTT message queues) is capable of delivering control relevant data promptly and in sufficient quality to allow for control mechanisms that fulfill the requirements of LV grid control. Hereby, standard security mechanisms like encryption and authentication/authorization have been utilized. However, security will stay an important research topic in such an environment, as grids are critical infrastructures, and as much personal data are processed.

In future realizations, MQTT communication may be separated into two steps using an internal and an external MQTT broker. To be able to handle this, the `MqttManager` is already capable of managing multiple connections in form of a Unified Resource Locator (URL) and a port, as well as authentication credentials where required. Thus, the system is designed in a scalable manner allowing for a broader adaptation of the researched technologies in the field.

ACRONYMS

CAN Controller Area Network
CEMS Customer Energy Management System
CES Community Energy Storage
CORBA Common Object Request Broker Architecture
COSEM Companion Specification for Energy Metering
CUC Cluster Use Case
DER Distributed Energy Resource
DLMS Device Language Message Specification
DSCP Differentiated Services Codepoint
DSM Demand Side Management
DSO Distribution System Operator
DUR Duration of Change
EER Enhanced Entity Relationship
EV Electric Vehicle
GB Gigabyte
GWAC GridWise Architecture Council
ICT Information and Communication Technology
IEC International Electrotechnical Commission
IED Intelligent Energy Device
IOT Internet of Things
IP Internet Protocol
ISO International Organization for Standardization
JSON JavaScript Object Notation
LAN Local Area Network
LV Low Voltage
MAC Medium Access Control
ML Machine Learning
MPC Maximum Power Change
MPLS Multi-Protocol Label Switching
MQTT Message Queuing Telemetry Transport
OPC UA Open Process Control Unified Architecture
OSI Open Systems Interconnection
P4 Programming Protocol-independent Packet Processors
PC Personal Computer
PCB Per Controller Behavior
PHB Per Hop Behavior
PLC Power Line Communication
PoC Proof of Concept
PV Photovoltaic System
RAM Random Access Memory
RQ Research Question
QoS Quality of Service
SDN Software Defined Networking
SGAM Smart Grid Architecture Model
SOC State of Charge
SSL Secure Socket Layer
TAF Total Amount of Provided Flexibility
TCP Transmission Control Protocol
TE Traffic Engineering
TSO Transmission System Operator
UDP User Datagram Protocol
URL Unified Resource Locator
UTC Coordinated Universal Time
V2G Vehicle to Grid
VLAN Virtual LAN
VXLAN Virtual eXtensible LAN
WAN Wide Area Network

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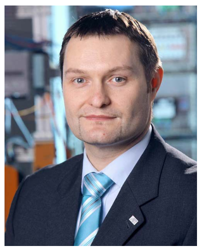

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