Ideas and Concepts for an Efficient Decentralized Energy Transition in Germany

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***Abstract*—The German energy transition is facing several systemic design flaws that hinder the optimal integration of decentralized renewable energy resources such as residential photovoltaics and battery storage systems. This paper analyzes technical and regulatory barriers within the current smart metering infrastructure, grid pricing models, and inverter grid codes. It further proposes a set of practical and technically grounded solutions — including a pricing scheme, simplified metering architectures, local powerline communication, and improved inverter grid code requirements — to enable a more robust, decentralized energy system.**

***Index Terms*—Keywords—Smart Metering, Energy Transition, Distribution Grid, Dynamic Pricing, Grid Codes, Battery Storage**

I. Introduction

Germany's ambitious energy transition ("Energiewende") relies heavily on distributed renewable generation [1]. However, despite widespread photovoltaic (PV) installations and storage deployments, current system-level designs create several inefficiencies:

1. **Unfavorable Battery Charging:** Home storage systems often reach full charge before PV peak generation, leading to curtailment or full power grid feed-in during PV peak.
2. **Overengineered Smart Metering:** Germany's smart metering solution (Digital Meter + Gateway + Control Box) is more complex than Powerline Communication (PLC) based electricity meters used in other countries, which include most of the German features in a single device.
3. **Lack of Real-Time Power Measurement Access:** Official smart meter data is not timely enough to enable zero-grid-import operation using a battery system. A power sensor is often required separately, as Smart Meter Gateway (SMGW) data is delayed and digital meter infrared interfaces have an update rate that is too low for real-time control.
4. **Absence of Locational Pricing:** Germany lacks zonal or nodal pricing, resulting in inefficient market signals and suboptimal investment behavior, leading to high redispatch cost [2].
5. **Grid Codes Emphasize Current Instead of Voltage Quality:** Inverter regulations focus on sinusoidal current, while the system goal should be clean sinusoidal voltage.
6. **Poor Low-Load Inverter Efficiency:** Many residential battery inverters have a poor system efficiency under low nighttime load conditions.
7. **Disproportionate Market Favor for Centralized Storage:** Large battery systems receive favorable conditions despite not necessarily installed in a beneficial area for grid load reduction, competing for agricultural land and requiring thermal management, because of high power density.
8. **Overemphasis on Grid Expansion:** Massive grid upgrades are planned [2] without fully utilizing decentralized flexibility and storage.

II. Observed Technical Deficiencies and proposed solution concepts

1. **Optimized Battery Charging:** During battery operation, premature charging increases battery degradation due to high State-of-Charge (SoC) stress [3]. Battery charging behavior can be improved by introducing zonal or nodal pricing. A first step towards efficient battery usage was implemented by the German Solar Peak Act (Solarspitzengesetz 2025) which sets the feed-in remuneration in hours with negative price to zero. This gives the battery system an incentive to store the midday PV peak. A more transparent and predictable method would be the implementation of a power access fee, ensuring that the predominantly power-driven grid costs are fairly assigned to the responsible parties. A proposal will be presented in section III. Although PV systems with 20-year feed-in tariffs cannot adjust their pricing, offering a grid-support bonus could encourage the investment in additional batteries.
2. **Needs-based Smart Metering:**
While other countries use PLC-based electricity meters, also known as "Smart Meter", the German approach needs three devices (Digital Meter + SMGW + Control Box) for metering and curtailment of loads or PV inverters, as shown in Fig. 1. For multi-family homes, this solution may offer financial benefits by using a single SMGW to connect up to 50 (electricity) meters. However, the required installation space, wiring overhead, and hardware costs are too high for single-family homes, which usually need just one electricity meter. Thus, a compact device is proposed for this use-case, shown in Fig. 2. The device directly offers the real-time power measurement for the energy management system (EMS) or battery inverter. The curtailment functionality of the control box can be implemented using simple electrical contacts or through the VDE-AR-E 2829-6-1 (EEBUS) specification. The latter supports additional

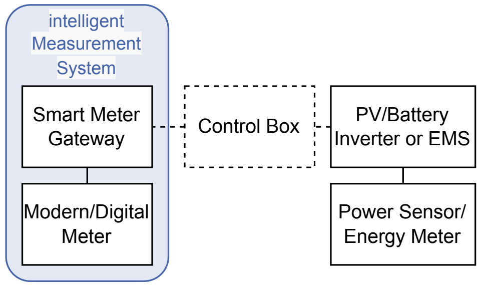

Fig. 1. Metering concept today.

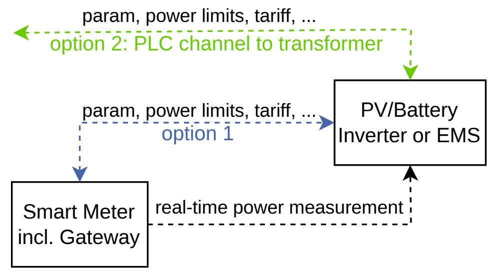

Fig. 2. Proposed metering concept for single-family homes.

use cases, such as Limitation of Power Consumption (LPC) during overload situations, Time of Use Tariff (TOUT), and Demand Forecast (PODF), among others.

Currently, the control box is not available at some distribution grid operators until 2026 [4]. Thus, new PV plants have to limit feed-in to 60 % of the PV power until the control box is installed, according to the German Solar Peak Act.

In the future concept, the inverters could communicate with a PLC-gateway in the distribution grid transformer station. To avoid any connection between the inverter and the Smart Meter, a PLC-modem could be integrated directly into the inverter as an option. The power stage of the inverter may be used for the PLC functionality [5].

The inclusion of the distribution transformer offers several advantages:

(a) Resilience: Independent control in case of a failure of other communication systems. The control unit in the grid transformer can always calculate backup control signals based on its current temperature and power flow. It can take into account the parameters of the other transformers to calculate the nodal price or direct control signals. In the event of a cyber attack, the inverters are programmed to ignore limitation signals if the grid frequency and voltage drop below their nominal values.

(b) Registration: If a residential PV plant is installed, the system parameters have to be sent to the grid operator. This process produces a lot of paperwork and is error prone. New inverters can send system parameters directly to the grid operator, using either the direct PLC channel to the transformer, or using the Smart Meter as a gateway, as shown in Fig. 2. Most inverters offer a WLAN or LAN connection already. This second channel can be used for the initial setup or to provide a second channel for two-factor authentication (2FA), whereby the security key or grid access keys of the inverter can be updated. A configuration of reactive power behavior can be set individually for each inverter by the grid operator.

3. **Real-Time Access to Power Measurement:**

Alongside all the intelligent measurement system devices, an extra power sensor is necessary for residential battery systems, because the power consumption cannot be accessed with the official system in real-time. The SMGW records consumption values every 5, 15, or 60 minutes only. More frequently, the local home area network (HAN) Ethernet port of the SMGW offers the current power based on the difference between two consecutive energy sum registers [6, p. 37]. If the power exchange with the grid is to be controlled to zero, the registers remain unchanged. However, this results in a loss of information regarding the current power mismatch, rendering the method useless for achieving exact zero-consumption control.

In contrast, the optical infrared interface of the digital electricity meter provides new power values every second, once unlocked with a 4-digit key. But this rate is still too low for exact zero-consumption control, since the energy registers of the electricity meter count in 0.1 Wh steps typically [7]. Thus, commercially available systems require an additional power sensor in order to achieve a settling time of, for example, 0.1 s. [8].

To demonstrate the usage of the optical interface of the digital electricity meter, an inverter prototype has been developed. It operates as a hybrid inverter, enabling direct DC-side connection to both, the PV array and a battery. Details on the project and the inverter firmware source code are available in a github repository [9]. However, the system cannot be controlled exactly to zero-export, zero-import, for the reasons mentioned above. In Fig. 3, an import of 2 Wh and an export of 1.1 Wh occurs during the load jump at 23:20. In [7], it was shown that the mismatch generated by load jumps of a glass ceramic hob can sum up to 37 kWh per year. While this amount of energy import due to control mismatch does not pose a significant problem, the benefits of the obsolete extra meter plays a more important role. The reduced hardware cost, installation space and power offset to the official meter could be the decisive factors.

It should be guaranteed by legislation, that the current power value of the official measurement system provides a sufficient update rate to be able to achieve zero-consumption. If the step-size of the digital electricity meter would be changed from 0.1 Wh to 10 Wh, then a load step of e.g. 3.6 kW can be compensated within 10 seconds. Alternatively, the energy import and export can be summed over a complete 15-minute interval, as this is the typical billing interval of the energy system and compatible with the existing SMGWs.

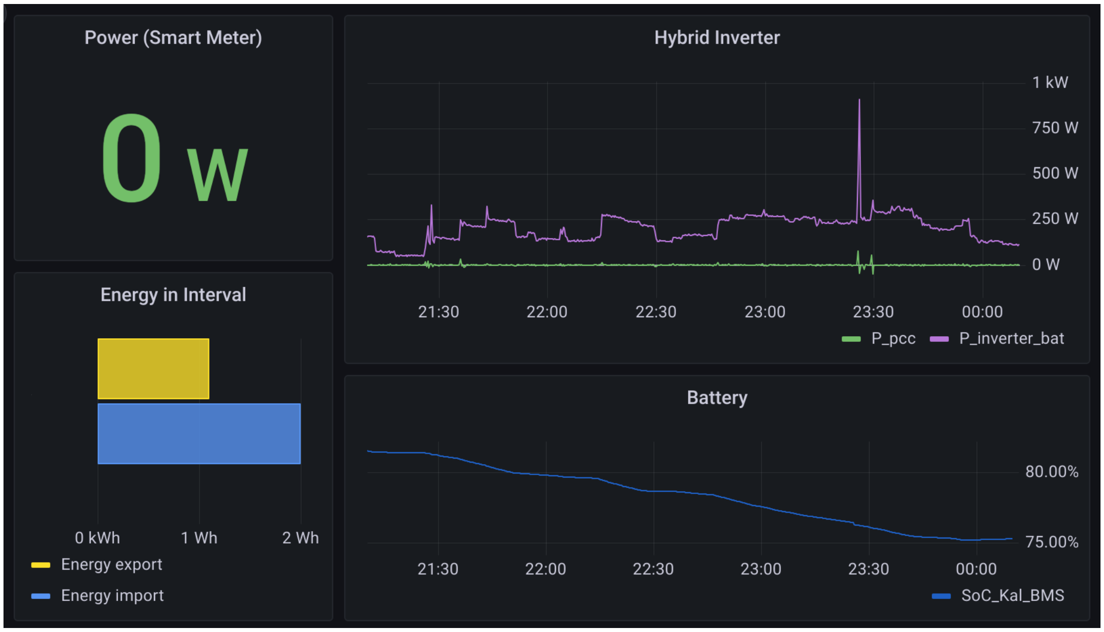

Fig. 3. Dashboard of the demonstrator PV battery inverter prototype with direct use of main electricity meter power measurement (P_pcc).

4. **Nodal Pricing:**
Nodal pricing introduces localized price signals based on physical constraints. Though considered administratively complex, decentralized algorithms and modern embedded controllers make this feasible. Unlike Germany, which currently applies a uniform electricity price nationwide, countries such as the United States have implemented nodal pricing for electricity markets starting in 1998 [10].
In Germany, most of the customers still use a standard fixed price tariff, but more tariffs are offered now with flexible wholesale price. During hours of negative wholesale pricing, high tax and grid fee still result in an overall price per kWh, which is higher than for oil or gas. This leads to household oil boilers still operate during extreme PV energy production because there is no incentive to install an electric heating element in the boiler. Most of the grid fees in Germany are still time-independent. Some tariffs offer defined but inflexible time slot pricing [11] or to receive a fixed annually discount when a control box is installed to limit a larger load, such as an electric vehicle (EV) charger, during high grid load condition.
The current system with two price components, namely the dynamic wholesale price and the (dynamic) grid fee, and multiple companies involved is overly complex. In contrast, a nodal pricing model captures all relevant elements, reflects the physical behavior of the grid, and is easier for customers to understand.
5. **Grid Code Modification:**
The harmonic current limits in the grid code and power quality standards for inverters were suitable when the first PV inverters arise to ensure a clean sinusoidal grid current and avoid disturbances. Nowadays, many electronic devices use an intermediate DC link and come either with an active power factor correction (PFC) or use a simple bridge rectifier. While the PFC stage is relatively unaffected by the total harmonic distortion (THD) of the grid voltage, the rectifier actively causes distortion by drawing high-amplitude current pulses to recharge the DC link capacitor. These current cause voltage distortion, depending on the grid impedance. The primary issue associated with distorted voltage arises in electrical machines that are directly connected to the grid without a frequency inverter, such as fans and pumps. These loads, along with distribution transformers, suffer from increased losses as a result. Instead of providing the demanded current for the rectifier or other nonlinear loads locally, those currents are delivered by some generator far away in the grid. Instead, the currents should be provided by the inverters in the vicinity. To demonstrate this approach, the aforementioned hybrid inverter prototype [9] aims for a sinusoidal voltage instead of sinusoidal current. The inverter control lacks a current control loop and uses a voltage PLL and a model of the LCL-filter for feedforward control only. The conceptual inverter AC current is shown in Fig. 4 together with the current of some bridge rectifier loads, with an accumulated load of $320\,\mathrm{W}$.
In the first $20\,\mathrm{ms}$, the inverter charges its battery from the AC grid and the inverter current shows a flattened/distorted sine, because the grid voltage is flattened by the peak currents of the rectifier loads. The inverter has no current controller which tries to draw a sinusoidal current during the voltage peak. This behavior helps to restore a clean sinusoidal grid voltage.
In the range from $20\,\mathrm{ms}$ to $40\,\mathrm{ms}$, the inverter is disabled and the high-amplitude currents of the rectifier loads have

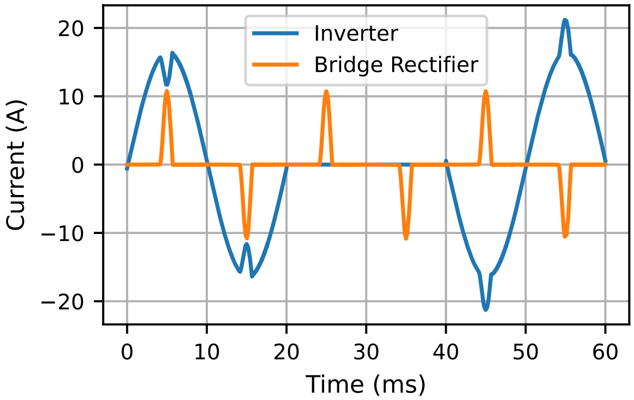

Fig. 4. AC current simulation during battery charging and discharging.

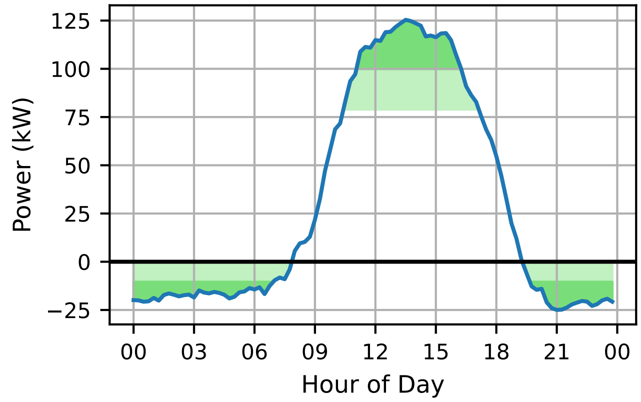

Fig. 5. Transformer power in a rural area during summer day.

to be provided by other sources in the grid, which causes those currents to pass the distribution transformer.

In the last 20 ms, the inverter discharges its battery and the inverter current shows a peak in the area of the sine maximum, because the inverter delivers current for the rectifier loads. Although the current appears to be highly distorted, it results in an improvement of the grid voltage THD, as the nonlinear load is partially compensated. The concept of a grid-forming inverter includes this voltage-source behavior [12] among other features and should be incorporated into a grid code.

6. **Low-Load Inverter Efficiency**:
A typical 10 kW residential inverter cannot reach peak efficiency at a load of 50-200 W in typical households during the nighttime. The dynamic pricing approach allows the inverter to be switched off then, because the electricity price may be lower than the inverter operation at bad efficiency. Another approach is an energy packet control algorithm, which exploits the step-size of the electricity meter. A typical energy meter sums the energy in 0.1 Wh steps [7]. This equals 360 W for 1 second. If the household consumes e.g. 60 Watt, the inverter can turn off the semiconductor gate signals for 5 seconds and deliver 360 W for 1 second. The energy meter does not count anything and the efficiency of the inverter increases, because no switching losses occur in 5 of 6 seconds. The exact scheme has to be tuned for each inverter, to avoid increased $I^2 \cdot R$ losses. The prototype inverter [9] uses this algorithm. The inverter dashboard (Fig. 3) shows no zero gaps, as the curves display values averaged over 10-second intervals.

7. **Equal Market Access:**
According to § 118 (6) of the German Energy Industry Act (Energiewirtschaftsgesetz), battery storage systems are exempt from grid fees for 20 years. However, decentralized, smaller battery systems are not eligible for this exemption, even though they offer certain advantages. For example, distributed batteries do not require complex thermal management because their lower system power density allows them to be installed in locations like basements. They can be combined with PV systems, reducing the amount of required AC inverter power and the peak power on the distribution transformers.
In Fig. 5, the power curve during one day in July of a 400 kVA distribution grid transformer in a rural area is shown. Although the transformer has not yet reached its capacity limit, potential peak power reduction methods are analyzed to enable the integration of additional PV power plants in this exemplary grid located in the south-west of Germany. In order to reduce the maximum transformer power peak caused by PV plants of 125 kW to 100 kW, a battery capacity of 87 kWh (corresponding area is shaded in dark green) is required in the local distribution grid. In this scenario, a battery comparable in size to a typical electric vehicle battery could reduce the transformer's peak power by 20 %.
When the battery is sized to buffer the energy required for nighttime, a combined battery size of 216 kWh (corresponding area is shaded in light+dark green) is required. This battery capacity could reduce the PV peak power to 79 kW, which results in a reduction of the transformer peak power by 37 %.
Beyond peak power reduction, storing energy to cover nighttime consumption can also help to reduce losses in transformers and transmission lines. A smart control approach can also enable decentralized inverters to compensate for reactive power directly within distribution grids, thereby relieving the transformer from the currents, which are caused by this service. Furthermore, decentralized batteries are beneficial in terms of community participation.

8. **Rethink Grid Expansion:**
To show how decentralized resources can reduce grid reinforcement needs, grid load scenarios are analyzed. During summer, decentralized batteries could prevent the curtailment of PV power and replace fossil power plants during nighttime. During winter, dynamic pricing enables load shift and uniformly usage of the distribution grid transformers. Lower ambient temperatures during winter allow transformers and overhead lines to operate with

increased loading capacity. Thus, massive grid expansion plans (€ 110 billion by 2033 [2]) for the distribution grids (not transmission grids) may be avoidable with smarter local solutions. Given Germany's 41 million households, this investment could alternatively fund about 10 kWh of battery storage per household, yielding decentralized flexibility. The cost of battery capacity were assumed to be 268 € per kWh.

Investments in the transmission grid appear beneficial to enable the use of offshore wind power in southern Germany. However, the estimated investment in distribution and transmission grid together of € 560 billion by 2045 [13] of which 50 % will get invested in grid expansion, rises the question of alternative solutions. Additional investments are required in backup power generation to ensure energy supply during so-called "dark doldrums", periods of low wind and solar generation. Currently, plans are in place to build 20 GW of gas-fired power plants in Germany [14].

A renewable alternative to fossil-fueled backup power could be the use of biogas or hydrogen. Hydrogen can be produced in the summer during periods of excess PV generation and stored in underground gas caverns in northern Germany or in porous rock reservoirs in southern Bavaria [15]. In winter, this hydrogen can be used not only for material and chemical applications but also for electricity and heat generation. In federal states where no efficient long-term storage options exist for now, wood-based backup systems for electrical and thermal energy production could be considered as an alternative.

III. Redefined Pricing Model

The proposed solutions for reducing curtailment, such as nodal pricing or smart meters with included control box capabilities, require time to achieve widespread market adoption. Currently, some renewable energy plant operators incur significant additional costs due to the mandatory SMGW, while receiving no proportional benefit. Conversely, other participants cannot benefit from dynamic pricing schemes because they do not yet have a SMGW installed. Moreover, the present system of installing a control box to be able to limit loads like an EV charger for a static annual grid fee reduction of, e.g., € 167 [11], according to § 14a or the additional use of defined but inflexible time slot pricing [11] fails to incorporate intelligent operation strategies, particularly for residential battery storage systems. This highlights the need for a more adaptive and incentive-compatible pricing scheme.

A revised pricing model is proposed to address these shortcomings. A new component, the *Power Access Fee* (PAF), is introduced. This fee would better reflect the household's impact on grid bottlenecks and provide grid operators with improved predictability. The basic cost of grid access of approximately € 120 [11] are typically paid via the energy supplier, and are not analyzed in this chapter.

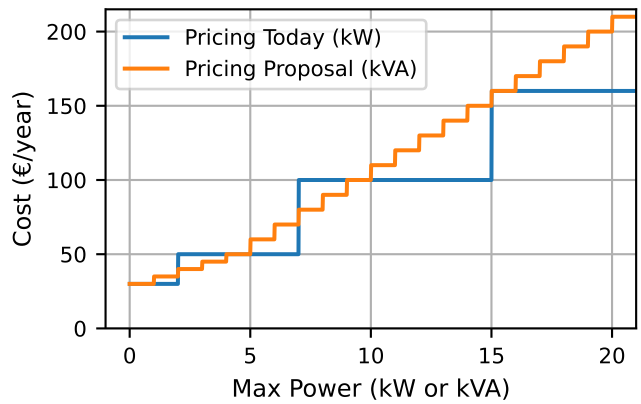

Fig. 6. Annual smart meter cost for customers.

A. Current Cost Scenario

Consider a single-family home equipped with a 12 kWp PV system and a 12 kVA inverter. Under the current scheme, the annual costs comprise € 50 for the electricity meter and SMGW as well as € 50 for the control box. This configuration provides no direct incentive for the household to limit its maximum grid power draw or feed-in power.

The actual cost of the smart metering infrastructure are estimated to be around € 180 annually, according to § 30 (6) of the German Act on Metering Point Operation and Data Communication (Messstellenbetriebsgesetz, MsbG). The additional € 80 is currently supported by the grid fees, indirectly increasing the price per kWh.

The prevailing cost allocation model, as defined in § 30 (6) (MsbG), alongside the proposed model, is illustrated in Fig. 6. An annual energy import below 6000 kWh is assumed. Notably, the price step at a capacity threshold of 15 kW is disproportionately high, with an annual increase of € 60. This creates a disincentive for households with existing PV installations of, e.g., 12 kWp on south-facing roofs to expand capacity by an additional 5 kWp on east- or west-facing roofs, despite the potential benefits of increased morning or evening production. Consequently, valuable generation potential remains unused due to a discontinuous pricing step.

B. Proposed Pricing Scheme

In the proposed model, the functionalities of the electricity meter, SMGW, and control box are integrated into a single device, as shown in Fig. 2. Thus, the total smart metering cost should be significantly below the previously mentioned € 180 annually. Additional income of the smart meter pricing is used for reduction of grid fees, not the other way around.

The central element is the introduction of a PAF designed to improve grid utilization efficiency. The fee structure is based on the following principles: a base charge of € 25; € 5 per kVA of annual power access up to 5 kVA; € 10 per kVA of annual power access above 5 kVA; measurement intervals of one hour, subdivided into four sliding 15-minute intervals.

As the control box functionality does not incur additional costs—since the smart meter already provides the required interface (see Fig. 2)—users can voluntarily register for load curtailment during grid overload situations. The annual PAF is then reduced in proportion to the potential load reduction. In congested grids, the grid operator may require participants with higher power access or substantial loads, such as EV chargers, to register for load curtailment. However, the grid operator is required to provide transparent information on the utilization of the affected grid elements. The process for production curtailment must also be clearly defined, because the current approach of suspending the solar remuneration during negative prices adds another step function to the system.

C. Benefits

This pricing mechanism provides several operational and economic advantages. It encourages battery charging during midday PV generation peaks rather than in the early morning, thereby reducing grid stress and benefit from reduced PAF. It reduces the incentive to install oversized PV inverters while maintaining the economic viability of overpaneling. Furthermore, it introduces economic signals that limit peak power usage, a capability not reliably achieved through dynamic energy pricing. For example, even a high energy price of €0.8 per kWh may fail to prevent peak loads such as EV charging, whereas exceeding the targeted power access capacity triggers immediate, tangible financial consequences. The PAF also mitigates extreme power fluctuations induced by volatile energy price signals, thus enhancing system stability. With smart energy management systems, most households can optimize power usage without compromising comfort, thereby increasing both efficiency and welfare.

D. Drawbacks

Potential drawbacks include a reduced incentive to operate flexible loads during periods of high renewable generation when a lower power access is targeted. However, aggregate flexibility across the system is likely to remain substantial, and the PAF effectively prevents unpredictable extreme load changes in response to price volatility. By registering for willingness to curtail flexible loads, a higher grid power can be used most of the time, without an increase of the static cost, as it is described in III-B.

E. Edge Case Analysis

The new pricing model is analyzed for a household that could potentially suffer from it, while not being able to benefit from renewable energy generation. For a rental apartment with a 22 kW electric boiler, the PAF seems like a high financial burden. However, the acquisition interval of one-hour offers the possibility to reduce the PAF. With four individuals showering for approximately six minutes each at 22 kW heating power, the resulting average grid load is 8.8 kW over the relevant one-hour interval. Thus, a capacity of 12 kVA seems sufficient to allow concurrent appliance use.

IV. Conclusion and Outlook

The current design of the German energy system lacks the flexibility and local control necessary for an economical and ecological energy transition. Simplified metering, local communication via PLC, updated pricing models and reformed inverter grid codes towards grid-forming converters can unlock the potential of existing technologies. A capacity-based tariff was proposed as a replacement for the currently step-based increase of smart metering cost. A paradigm shift from centralized control to distributed autonomy can minimize grid expansion while increasing resilience and participation.

It is essential that the term *installed power* is clearly defined in all relevant legislation. For most regulatory and operational purposes, the installed inverter capacity in kVA is more appropriate than the installed PV capacity in kWp. This approach would align cost allocation more closely with actual grid impact and could foster grid-friendly operation patterns, particularly if incorporated into the Renewable Energy Act (EEG).

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