Modeling Grid-Friendly Clean Energy Communities and Induced Intra-Community Cash Flows

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Modeling Grid-Friendly Clean Energy Communities and Induced Intra-Community Cash Flows

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Abstract

In the context of decarbonizing the energy sector, energy communities play an increasingly important role. However, the German energy transition has reached a point where it is now necessary to look at electricity generation and consumption in a holistic, systemic manner. Building on the qualitative work of Gui and MacGill (2018), the present paper quantifies how the inception of different types of clean energy communities (CECs) changes the grid-friendliness of a community and how it induces intra-community cash flows. In detail, the paper creates three residential reference networks, representing a countryside, village, and suburb setting. To simulate the residential load, the model employs a behavior-based load profile generator. Moreover, it uses meteorological data to model the electricity generation via photovoltaic (PV) systems and wind energy converters (WECs). In the model, CECs can conduct four measures: improve the energy efficiency, buy PV systems in bulk, introduce peer-to-peer (P2P) trading, and install a WEC. The results indicate that by conducting only a single measure, CECs often create a tradeoff in the community’s grid-friendliness. In contrast, combining a measure with a second measure nearly always improves the community’s grid-friendliness. This shows that the measures complement each other well from a grid-friendliness perspective. With regard to intra-community cash flows, the paper estimates a realistic volume for local P2P trading as well as its upper bound. In this regard, the extent of the realistic cash flow alone may not be enough to justify the purchase of P2P-enabling infrastructure. From a grid perspective, the paper highlights the importance of exploiting the complementarity of CEC measures as well as the necessity to provide CECs with access to sufficient funding.

Keywords: Citizen community; Microgrid; Peer-to-peer trading; Germany

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## List of abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>BaU</td>
<td>Business as Usual (scenario)</td>
</tr>
<tr>
<td>CEC</td>
<td>Clean Energy Community</td>
</tr>
<tr>
<td>CON</td>
<td>Conservative (scenario)</td>
</tr>
<tr>
<td>DWD</td>
<td>Deutscher Wetterdienst (German Meteorological Service)</td>
</tr>
<tr>
<td>EEG</td>
<td>Erneuerbare-Energien-Gesetz (Renewable Energy Sources Act)</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>FiT</td>
<td>Feed-in Tariff</td>
</tr>
<tr>
<td>FLH</td>
<td>Full-Load Hour</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
</tr>
<tr>
<td>kVA</td>
<td>Kilovolt-Ampere</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilowatt-hour</td>
</tr>
<tr>
<td>kWp</td>
<td>Kilowatt peak</td>
</tr>
<tr>
<td>LPG</td>
<td>Load Profile Generator</td>
</tr>
<tr>
<td>MaStR</td>
<td>Marktstammdatenregister (German ledger for master data of electricity and gas generators)</td>
</tr>
<tr>
<td>MAX</td>
<td>Maximum (scenario)</td>
</tr>
<tr>
<td>MMV</td>
<td>Monthly Market Value</td>
</tr>
<tr>
<td>MP</td>
<td>Market Premium</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatt</td>
</tr>
<tr>
<td>MWh</td>
<td>Megawatt-hour</td>
</tr>
<tr>
<td>MWp</td>
<td>Megawatt peak</td>
</tr>
<tr>
<td>NCL</td>
<td>Net Community Load</td>
</tr>
<tr>
<td>P2P</td>
<td>Peer-to-Peer</td>
</tr>
<tr>
<td>PV</td>
<td>(Solar) Photovoltaics</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable Energy Sources</td>
</tr>
<tr>
<td>SLP</td>
<td>Standard Load Profile</td>
</tr>
<tr>
<td>SP</td>
<td>Supply Premium</td>
</tr>
<tr>
<td>STC</td>
<td>Standard Test Conditions</td>
</tr>
<tr>
<td>V</td>
<td>Volt</td>
</tr>
<tr>
<td>VCB</td>
<td>Virtual Community Battery</td>
</tr>
<tr>
<td>VPP</td>
<td>Virtual Power Plant</td>
</tr>
<tr>
<td>VTBA</td>
<td>Value To Be Applied</td>
</tr>
<tr>
<td>WEC</td>
<td>Wind Energy Converter</td>
</tr>
<tr>
<td>$A_{PV,Total}$</td>
<td>Total surface area of a PV system</td>
</tr>
<tr>
<td>$A_{Rotor}$</td>
<td>Area of the rotor disc (WEC)</td>
</tr>
<tr>
<td>$C_{P,Temp}$</td>
<td>Temperature-dependent performance coefficient (PV module)</td>
</tr>
<tr>
<td>$C_{P,Wind}$</td>
<td>Wind performance coefficient</td>
</tr>
<tr>
<td>$E_{Global,PV}$</td>
<td>Global irradiance on an inclined and oriented PV system</td>
</tr>
<tr>
<td>$P_{Air}$</td>
<td>Kinetic power of an air flux</td>
</tr>
<tr>
<td>$P_{PV}$</td>
<td>Output power of a PV system</td>
</tr>
<tr>
<td>$P_{WEC}$</td>
<td>Output power of a WEC</td>
</tr>
<tr>
<td>$T_{Ambient}$</td>
<td>Ambient temperature</td>
</tr>
<tr>
<td>$T_{Cell,Actual}$</td>
<td>Actual cell temperature</td>
</tr>
<tr>
<td>$T_{Cell,STC}$</td>
<td>Cell temperature under STC</td>
</tr>
<tr>
<td>$v_{Wind,at\ hub}$</td>
<td>Wind speed at hub height</td>
</tr>
<tr>
<td>$\alpha_{PV}$</td>
<td>Azimuth angle of a PV module</td>
</tr>
<tr>
<td>$\beta_{PV}$</td>
<td>Inclination angle of a PV module</td>
</tr>
<tr>
<td>$\eta_{Inverter}$</td>
<td>Inverter efficiency</td>
</tr>
<tr>
<td>$\eta_{Module,STC}$</td>
<td>Module efficiency under STC</td>
</tr>
<tr>
<td>$\eta_{PV,System}$</td>
<td>Overall system efficiency of a PV system</td>
</tr>
<tr>
<td>$\eta_{Temp}$</td>
<td>Temperature-dependence of the PV module efficiency</td>
</tr>
<tr>
<td>$\rho_{Air}$</td>
<td>Air density</td>
</tr>
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</table>
1. Introduction

Globally, climate change mitigation is considered a main challenge of the 21st century. With 866 million metric tons (t) of CO₂ equivalents, Germany emits the most greenhouse gases (GHG) in Europe. Of these, the energy sector accounts for 34.5% (UBA, 2019). While the German energy sector has progressed towards decarbonization, many conventional power plants are still active. Thus, reducing GHG emissions in the energy sector remains a strong lever to meet emission reduction targets. Especially against the background of sector coupling (i.e., coupling the energy, heating, mobility, and industry sectors), providing low-carbon electricity becomes ever more important.

However, Germany faces several challenges in advancing its sustainable energy transition (Energiewende). First, the expansion of the transmission grid, responsible for transporting electricity over large distances, happens slowly. In 2013, the German government passed a law to accelerate its expansion. By 2019, however, only 600 km (out of 5,900 km) had received approval and only 300 km of new power lines were in operation (BNetzA, 2019a). Secondly, the interest in auctions for onshore wind energy converters (WECs) decreases: In 2019, only 50.3% of the envisaged new capacity were awarded (i.e., 1,847 MW) (BNetzA, 2019b). Two main causes for this are the lack of available areas for WECs and legal obstacles (e.g., active citizen resistance) (BMWi, 2019).

The European Union (EU) has recognized the importance of a citizen-supported energy transition. In May of 2019, it adopted the last pieces of the “Clean energy for all Europeans” package, aimed at increasing citizen participation in and acceptance of the energy transition. To this end, the EU included provisions regarding “renewable energy communities”, whose primary purpose is “to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates rather than financial profits” (RED, Art. 2(16c)). The potential of energy communities is substantial. By 2030, they “could own some 17% of installed wind capacity and 21% of solar” (EU, 2019: 13).

This study examines three types of “clean energy communities” (CECs), a term coined by Gui and MacGill (2018). It aims to quantify how the inception of CECs and their actions affect the energy system. To this end, the paper examines two research questions.

First, how do different CEC types influence the grid-friendliness of a community? This question aims at energy communities from a technological viewpoint. In the current phase of the sustainable energy transition, it is necessary to examine electricity generation and consumption in an integrated, systemic manner (BMWi, 2018a). For the German government and grid operators it will be instructive to quantify how CECs shape grid requirements and whether CECs show an intrinsically grid-friendly behavior, or if policy makers have to adapt their policies accordingly.

Second, how high are the induced intra-community cash flows? Here, the focus lies on CEC-dependent cash flows between community members. Among others, increasing the local electricity
generation via renewable energy sources (RES) can create new income sources for community members (RED, 2018). In particular, intra-community cash flows can help retain capital in the community.

The model consists of three elements. Firstly, it simulates the electricity generation of solar photovoltaic (PV) systems and WECs. Secondly, it generates load data for different household types using a behavior-based load profile generator. Thirdly, the household types are combined to form a community. The paper then analyzes how the inception of a CEC changes the status quo.

By design, the model exhibits several restrictions. The main restrictions include the use of only household loads, the focus on PV and wind energy, and using a simplistic model of the electrical grid. All restrictions are explained in the corresponding sections. Despite these restrictions, the model was deemed the best approach for several reasons. First, the input data has a high resolution and several years of data are available. Secondly, the model can easily be applied at other locations. Thirdly, the results are replicable using the MATLAB® code (available from the authors upon request). Hence, the model meets all requirements of a system-analytic approach (i.e., its results are transparent, comprehensible, and verifiable) (BMWi, 2018a).

The paper is structured as follows. Section 2 introduces the CEC types. Section 3 gives an overview of the political framework and Section 4 presents the reference networks. Section 5 then explains the measures that CECs can implement. Section 6 analyzes and evaluates the results. Section 7 concludes the paper by summarizing the findings and giving an outlook for future research.

2. Clean energy communities

Gui and MacGill identify three CEC types based on how communities interact with the energy system: centralized, distributed, and decentralized CECs. In general, CECs are “social and organizational structures formed to achieve specific goals of [their] members primarily in the cleaner energy production, consumption, supply, and distribution, although this may also extend to water, waste, transportation, and other local resources“ (Gui and MacGill, 2018: 95). This paper focuses only on electrical energy in the context of citizen energy. To illustrate this, in the following we examine the concept of community, the current state of citizen energy in Germany, as well as potential benefits and challenges of citizen energy.

We follow Walker’s (2011) concept of community, who identifies six different meanings: (1) Community as actor, (2) Community as scale, (3) Community as place, (4) Community as network, (5) Community as process, and (6) Community as identity. The literature finds that participation is often heterogeneous in communities (Bauwens and Devine-Wright, 2018). Moreover, the members “may play different roles, such as producers, consumers, or prosumers [members who
produce and consume electricity], investors, asset owners, or a combination of these.” (Gui and MacGill, 2018: 96)

Citizen energy already plays an important role. In Germany, there may be up to 1,712 citizen energy companies (Kahla et al., 2017). In 2016, private citizens owned the largest share of RES capacity (31.5%), while farmers owned 10.5% (AEE, 2017). Most citizen energy companies are energy cooperatives (54.6%), followed by limited liability companies and limited partnerships (36.6%) (Kahla et al., 2017). Of the 1,712 citizen energy companies, 1,516 are active in the field of energy generation. With 43.2% and 42.6% respectively, wind and PV energy are the most common technologies (ibid.).

Moreover, CECs have to provide their members with unique benefits, since there is “no purpose in having an organization when individual, unorganized action can serve the interests of the individual as well as or better than an organization” (Olson, 1965: 7). Although the members do not have identical goals, they share one or more community goal, making CECs communities of interest. In particular, Rogers et al. (2008) identify three categories of potential benefits from renewable energy projects: social, environmental, and economic benefits. Social benefits include improved energy literacy (Walker and Devine-Wright, 2008; Bauwens and Eyre, 2017) and combatting rural exodus (Walker et al., 2007; Yalcin-Riollet et al., 2014), among others. Environmental benefits include carbon reduction (Walker and Devine-Wright, 2008) and raising awareness of environmental issues (IZES, 2015), while economic benefits include the provision of electricity at lower costs (Doci and Vasileiadou, 2015) and the creation of employment (Walker, 2008). The ability of energy communities to share the gains can be analyzed by cooperative game theoretical frameworks (Abad et al., 2020). Still, communities can exclude citizens (Süsser, 2016). For example, not every household can afford to buy shares from an energy cooperative. Thus, non-members may not receive any benefits while having to bear, e.g., the visual intrusion of a WEC close to their home. To counteract this, communities can use community trusts or charities to serve more citizens (Interreg Europe, 2018).

Energy communities face several challenges, notably financing. RES projects often require significant upfront investment, limiting CECs in the number and size of their projects. Thus, determining who may invest is a key decision for energy communities. If the community cannot raise the necessary funds on its own, it can acquire external financing. Yet, receiving a bank loan is difficult for communities who are not able to offer adequate securities (Victoria State Government, 2015). Also, energy communities face strong competition in the energy sector regarding limited resources (e.g., attractive wind sites) (Bauwens et al., 2016; Koirala et al., 2016).

2.1 Centralized CECs
Centralized CECs are “cohesive [networks] of households and businesses that collectively own or participate in energy-related projects, such as solar, wind and other clean energy generation projects, energy efficiency, demand-side management, community bulk-buying, etc.” (Gui and MacGill, 2018: 100) Their members are directly connected and share social rules. Yet, they do not necessarily form a community of locality.

Energy cooperatives are a prime example of centralized CECs. In Germany, they “constitute the organizational form that has become the most relevant regarding active participation in local energy policy” (Yildiz et al., 2015: 61). Hence, the paper uses energy cooperatives to exemplify centralized CECs. In general, cooperatives “are intended to primarily benefit their members.” (Interreg Europe, 2018: 6) While this can mean financial benefits, cultural and social concerns and needs can also motivate the establishment of a cooperative (GenG, 2018). Thus, cooperatives differ from investor-oriented firms insofar as they do not focus only on maximizing their profits (Kahla et al., 2017). Parties interested in becoming cooperative members usually need to buy cooperative shares. For example, a share of Greenpeace Energy eG costs €55 (Greenpeace, 20 January 2020). Hence, citizens with small financial means can become active in the energy transition. Furthermore, cooperatives apply the “one member – one vote” principle, giving all members the same voting rights regardless of their investment.

Taking action collectively allows to divide transaction costs and to distribute the risk (Dóci and Vasileiadou, 2015). For centralized CECs, this represents a key reason to exist. If a centralized CEC forms a community of locality, it is “well-placed to identify local energy needs, take proper initiatives and bring people together to achieve common goals such as self-sufficiency, resiliency, and autonomy.“ (Koirala et al., 2018a: 573) As mentioned above, centralized CECs can conduct different energy-related measures. While Section 4 explains the implementation in detail, in the following the three measures community-scale RES, energy efficiency measures, and community bulk-buying are briefly described.

Most community-scale RES projects involve mature technologies like PV and wind energy. Thus, the technology risk is relatively low. Community-scale PV systems often have a rated power of several hundred kilowatts while community-scale WECs typically have a rated output of several MW. Since the generators usually achieve a positive net present value over their lifetime, community members expect a financial return on their investment (C4CE, 2017). In Germany, the average dividend payment of energy cooperatives amounts to 3.89% (DGRV, 2016). Non-members may furthermore also profit from such projects. For example, installing a community-scale RES can reduce the (local) electricity prices, leading to overall lower electricity bills. Although this is a secondary effect, it is a particularly important one for economically marginalized citizens (Interreg Europe, 2018). Moreover, centralized CECs may be treated favorably by the municipality in which
they are active (e.g., gaining access to areas for RES installation), which can be an important advantage over competitors from the “outside” (C4CE, 2017).

Centralized CECs can also conduct efficiency measures. These are comparatively easy to implement and require less capital than community-scale RES. Centralized CECs can raise member awareness regarding energy efficiency and help to replace existing devices with newer, more energy-efficient ones.

Lastly, centralized CECs can conduct bulk purchases for their members. If members want to purchase a certain product they will have higher bargaining power when purchasing together. For some members, bulk buying may unlock an investment which they would not have been able to make if they had not profited from the bulk-buying quantity discount.

2.2 Distributed CECs

*Distributed* CECs are “a network of households and businesses that generate or own distributed generation individually, connected through a controlling entity either physically or virtually, and sharing the same rules in supplying and consuming electricity within the network” (Gui and MacGill, 2018: 101).

In contrast to centralized CECs, most members of distributed CECs are not connected in a direct manner. Moreover, here, the controlling entity can be referred to as the hub organization, a role often occupied by technology companies. They may, for example, provide a platform to coordinate electricity supply and consumption and to enforce the community rules.

While community members can be homogeneous in some regards (e.g., sharing the role of electricity consumer), they can also be heterogeneous (e.g., living at different locations). To exemplify distributed CECs, we assume peer-to-peer (P2P) electricity trading. P2P electricity trading describes the direct exchange of energy and money between producers and consumers. The producers “[exchange] remaining electricity with other consumers in the power grid.” (Park and Yong, 2017: 4)

In this context, consumers owning RES are also referred to as prosumers, since they are both consumers and producers of electricity. Our study focuses on local P2P trading (i.e., within the same low-voltage grid), allowing “local money to remain within the local economy” (Koirala et al., 2016: 731).

2.3 Decentralized CECs

A *decentralized* CEC is “a community of households, businesses or a municipality that generates and consumes energy locally for self-sufficiency that may or may not connect to the main grid” (Gui and MacGill, 2018: 102). The capacity for energy autonomy distinguishes decentralized CECs from centralized and distributed CECs.
The paper follows the energy autarky definitions of McKenna et al. (2014), who differentiate between “soft” and “strict” autarky. A region exhibits 100% soft autarky if, for a certain period, it generates as much energy as it consumes. It may use supra-regional energy infrastructure to export excess electricity (in times of over-production) or draw electricity from the wider grid (in times of under-production). In other words, the community does not have to meet its energy demand at all times. By contrast, communities with 100% strict autarky may not use supra-regional energy infrastructure to temporarily cover their demand. A community with 100% strict autarky needs to cover its demand at all times and under all circumstances. Consequently, the paper considers only communities with 100% strict autarky as truly energy autonomous and thus as decentralized CECs. Subsequently, the term “autarky” always refers to strict autarky.

In order to reach 100% autarky, communities need to take strategic, long-term decisions. Hence, the build-up of decentralized CECs requires a lot of time. They need to determine a cost-efficient combination of generation and storage infrastructure as well as load reduction and shifting strategies. Decentralized CECs “benefit from the development and growth of both distributed and centralized CECs” (Gui and MacGill, 2018: 104), which can provide energy generation and management infrastructure. Also, efficiency measures conducted by centralized CECs may have already reduced the electricity demand. By nature, decentralized CECs are communities of locality. In order to compare the different CEC types, the paper uses microgrids to exemplify decentralized CECs.

A microgrid is “an integrated energy system consisting of DER [distributed energy resources] and interconnected loads that can operate in parallel with the grid or in an intentional island mode.” (Ho and Le-Ngoc, 2013: 116) In rural and remote areas, they can represent a cost-efficient alternative to connecting communities to the national grid (UBA, 2013).

3. Political framework

In Germany, the central piece of legislation for RES is the Renewable Energy Sources Act (“Erneuerbare-Energien-Gesetz,” EEG). Its goal is to advance the German energy transition while setting the necessary rules to guarantee a cost-efficient, reliable, and sustainable energy supply (“energy trilemma”). This section summarizes current technical and financial provisions that potentially regard CECs. Unless stated otherwise, all references to legal sections in this section refer to the EEG 2017.

3.1 Technical provisions

With regard to connecting an RES to the grid, Section 7 is a key element of the EEG, dictating the most suitable connection point. If a connection point already exists on the property where an RES shall be located, this connection point is usually the most suitable one for RES up to 30 kWp.
Moreover, operators of RES larger than 100 kW\textsubscript{p} have to equip their generators with a special technical device, allowing the grid operator to remotely reduce the feed-in in case of grid overload and to retrieve the actual feed-in of the generators (Art. 9 (1)). Operators of PV systems smaller than 30 kW\textsubscript{p} have to either equip the generators with the aforementioned technical device (however, it only needs to satisfy one of the two functions) or to limit the active power feed-in to 70\% of the installed power (Art. 9(2)). The latter is also referred to as “peak shaving” and is the preferred method for small PV systems in Germany (BMWi, 2018b).

3.2 Financial provisions

When deciding how to sell their electricity, RES operators can choose between market premium, feed-in tariff, landlord-to-tenant supply premium, and any other form of direct selling. All premiums and tariffs are expressed in €-ct/kWh.

The market premium (MP) is the mandatory selling form for RES generators with a capacity of 100 kW\textsubscript{p} or more. In Germany, this affects around 90\% of onshore WECs and 20\% of PV systems (BMWi, 2018b). To receive the MP, the plant operator or a third party have to sell the electricity in a direct manner (Art. 20 (1)). The MP is the difference between the value to be applied (VTBA) and the monthly market value (MMV):

\[ MP = VTBA - MMV \]  

The idea behind the MP is to guarantee a minimum selling price for renewable energy, while limiting the direct financial support. The VTBA is like a fixed minimum price that plant operators receive, while the MMV is the volume-based, technology-specific average hourly EPEX spot market price in one month. If the MMV is smaller than the VTBA, the MP covers this difference; if the MMV is larger than the VTBA, the MP is set to zero.

For generators with a capacity less than 750 kW\textsubscript{p}, the VTBA is determined by law. For larger plants, the Federal Network Agency conducts pay-as-bid auctions. Each successful bid is then granted its bid price (i.e., the award value). An exception exists for successful bids of citizen energy companies, whose award value is equal to the highest successful bid from that auction round (Art. 36g(5)). For PV systems, the award value is equal to the VTBA. For onshore WECs, multiplying the award value with a location-dependent corrective factor yields the VTBA.

Alternatively to the MP, generators smaller than 100 kW\textsubscript{p} can receive a fixed feed-in tariff (FiT). For PV generators, the FiT is equal to the legally determined VTBA in the MP model less 0.4 €-ct/kWh (Art. 21(1)). Since the FiTs are fixed, they are a market-independent support scheme; consequently, the cash flows are more predictable (Kahla et al., 2017). This is particularly important for risk-averse entities with small project (e.g., energy cooperatives) (Bauwens et al., 2016).
Operators of building-mounted PV systems smaller than 100 kW_{p} may furthermore choose to receive a landlord-to-tenant supply premium (SP). For this model, a final consumer has to take and consume the PV electricity directly, either within the building or in close proximity. This is important, since consuming electricity from a battery previously charged with PV electricity does not entitle the plant operator to the SP. Also, the operator does not receive the landlord-to-tenant SP for electricity that enters the grid before reaching a final consumer (Art. 21(3)). Instead, she receives the FiT according to the generator capacity (BMWi, September 3, 2019). For the landlord-to-tenant SP, the VTBA is equal to the VTBA determined by law. From this, 8.5 €-ct/kWh are deduced for PV generators with a total capacity smaller than 40 kW_{p} (8 €-ct/kWh for systems between 40 and 750 kW_{p}) to determine the landlord-to-tenant SP (Art. 23b(1)).

4. Electrical reference networks

This section presents the basic network model. In the analysis, we consider a German low-voltage grid (230/400 V), able to supply houses or small commercial enterprises (Konstantin, 2017). There are different approaches to set up a network model. While gathering data from a single, real low-voltage grid ensures a realistic model, it does not ensure representativeness. Instead, the present model reverts to the findings of Kerber and Witzmann (2008), who analyzed 87 low-voltage grids in Bavaria (Germany). According to them, it is possible to generate typical reference networks by combining typical transformer outputs with an average number of connection points. Hence, statements derived from such reference networks should be applicable to a broad range of real networks.

4.1 Transformers

Kerber and Witzmann (2008) differentiate between three settings: countryside, village, and suburb. The results show that the rated transformer power significantly depends on the setting. In the countryside, the most frequent rated transformer power is 100 kVA (44%). In villages and suburbs, respectively, 400 kVA (50%) and 630 kVA (48%) transformers are common. The paper assumes that these values are representative for low-voltage networks at any location in Germany.

Subsequently, the paper considers three reference networks: a countryside network, a village network, and a suburb network. For each network, it uses the most often used rated transformer power. Also, Witzmann and Kerber’s (2007) assumption of pure active power feed-in is extended to all network components, not only PV systems, which represents a key limitation of the model.

4.2 Network structure

The next step is to determine the number of connection points. With a 95% confidence, Kerber and Witzmann (2008) find that the maximum power per connection point is around 15 kVA (countryside), 25 kVA (village), and 32.5 kVA (suburb). The model assumes that each building has one connection point and that no connection point is utilized only for RES. Before being able to determine how many
buildings to place in each setting, it is necessary to first determine the connection power of the buildings.

The model considers two building types: detached houses and apartment buildings. While detached houses exist in all three settings, apartment buildings only exist in the village and suburb settings. Based on this assumption, detached houses are modeled as having a connection point that can support up to 15 kVA, the maximum transformer output per connection point in the countryside setting.

The model allows for one household in a detached house, while two or more households can live in apartment buildings. The exact number of apartments per building is important since buildings with more apartments draw more power. In Germany, 93.1% of buildings with more than one apartment have between 2 and 12 apartments (Destatis, 2016). Hence, these buildings represent the majority of apartment buildings. Since the data is only available in intervals (e.g., number of buildings with 7-12 apartments), one can only estimate the average number of apartments to lie between 4.2 and 7.2 apartments.

Building on the notion that less space is available in suburbs than in villages, suburban apartment buildings likely contain more apartments than village apartment buildings. The paper assumes that suburb (village) apartment buildings consist of eight (four) apartments. These buildings will be referred to as medium-sized and small apartment buildings, respectively. In accordance with the DIN 18015 standard, the connection points in medium-sized (small) apartment buildings shall have a minimum apparent power of 50 kVA (35 kVA) (Baade, 2007). The model adopts exactly these values.

The last step is to determine the building compositions. To this end, the model combines the building types such that the average connection power matches the maximum average connection power as reported by Kerber and Witzmann (2008). Using a 100 kVA transformer, six detached houses constitute the countryside network, yielding a specific transformer output of 16.67 kVA per connection point. The village reference network consists of eight detached houses and eight small apartment buildings, yielding a specific transformer output of 25 kVA per connection point. In the suburb setting, nine detached houses and nine medium-sized apartment buildings yield a specific transformer power of 32.5 kVA per connection point. Table 1 summarizes the building composition of all three settings.

<table>
<thead>
<tr>
<th></th>
<th>Detached houses</th>
<th>Small apartment buildings</th>
<th>Medium-sized apartment buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Countryside</strong></td>
<td>6</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1: Building composition of the three settings
4.3 Residential load

This section deals with the residential load (i.e., the household electricity consumption). For reasons of simplicity, the model neglects industrial and commercial loads. Since the latter two can be significantly higher than the residential load (UBA, 2013), their omission represents an important limitation. To model the residential load, two approaches are considered.

The first approach is to use measured load data. However, measured load data is restricted in several dimensions; most importantly, it is location-specific and thus may not be representative. Also, the data may not show all seasonal influences if it is available for less than a year. The second approach is to generate load data, either via standard load profiles or load profile generators.

Standard load profiles (SLPs) are created by aggregating the loads of many households to calculate an average household load. Consequently, SLPs are smoother than single load profiles. This has important implications for data analysis. For example, brief peak loads are less visible in SLPs. In Germany, the H0 profile is likely the most prominent SLP for household loads. Although many engineering studies employ SLPs, they exhibit several drawbacks. First, they may not represent modern households. The H0 SLP was published in 1999; in the meantime, significant efficiency advances have been achieved and new appliances (with new usage and power consumption patterns) were developed. Secondly, SLPs are static. It is impossible to modify an SLP based on behavioral or structural changes since the data is only available at an aggregated level. Thirdly, often only one SLP exists for residential loads, making it impossible to model different community compositions or household types.

In contrast, load profile generators (LPGs) simulate the load of individual households. This paper uses a behavior-based LPG (Pflugradt, 2016), subsequently referred to as the LPG. The LPG is available for free and is being developed continuously. Based on time allowances, it simulates the behavior of the household members (e.g., cook a meal, watch television) using the corresponding devices. Thus, the LPG effectively simulates the activation and deactivation of single devices. As a result, the generated load profiles show characteristic spikes. Figure 1 compares the H0 SLP and an LPG-generated load profile, scaled such that they have the same average load. The LPG profile clearly contains more information than the H0 profile. This has important implications since, for example, using the SLP could lead to a miscalculation of how much locally generated PV electricity the household consumes directly.

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1 See https://www.bdew.de/energie/standardlastprofile-strom/.
2 See https://www.loadprofilegenerator.de/.
Several parameters influence the shape of a household’s load profile. These include the available devices, the number of dwellers, their daily routines, and their occupation status, among others. For instance, “[load] profiles vary widely between […] office workers, shift workers, retirees, singles or families.” (Pflugradt and Muntwyler, 2017: 655) Also, “[residential] electricity demand is highly synchronized around the work-day, work-week, and the seasons.” (Smale et al., 2017: 133) Hence, it is necessary to make a few basic assumptions concerning the households in the model communities.

Figure 1: Comparison of SLP (H0) and LPG load profiles, weekday and weekend (illustrative)

In this regard, the LPG helps by providing a set of predefined households (“modular households”). Each modular household contains one or more inhabitants with individual activities (e.g., go to work, wash the dishes). The names of the modular households convey a first impression of their behavior (e.g., “CHR30 Single, Retired Man”). To have load diversity, the model uses three categories of modular households: families (at least one parent and one child), employees (singles or couples without children), and retirees (retired single or couple). Table 2 gives an overview of all modular households that match these categories. Note that only six modular retiree households exist. This could lead to artificial load spikes when aggregating the load of several retiree households, if they showed the exact same behavior. Among other things, Section 5 also addresses this issue.

Table 2: Overview of the modular households by household category

<table>
<thead>
<tr>
<th>LPG name of the modular households</th>
<th>Family</th>
<th>Employee</th>
<th>Retiree</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHR05, CHR18, CHR20</td>
<td>CHR01, CHR02,</td>
<td>CHR30, CHR31,</td>
<td></td>
</tr>
<tr>
<td>CHS04</td>
<td>CHR04</td>
<td></td>
<td>CHR51</td>
</tr>
<tr>
<td>CHR27, CHR43, CHR44</td>
<td>CHR07, CHR09,</td>
<td>CHR54, CHR58,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CHR10, CHR21,</td>
<td></td>
<td>CHS04</td>
</tr>
<tr>
<td></td>
<td>CHR29, CHR33</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CHR34, CHR35,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CHR37</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CHR39, CHR55</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Since the “community composition differs a lot […] between urban and rural areas” (Koirala et al., 2016: 728), the model employs different community compositions. Table 3 reports the total number of households by category, setting, and building type. Despite of poor data availability, the model aims to create representative living situations. It assumes that the share of retirees is higher in rural areas and that employees prefer to live in the suburb setting, while families prefer the village setting (see Table 3). Among other issues, Section 5 assesses the representativeness of these community compositions.

Table 3: Community composition of the three settings

<table>
<thead>
<tr>
<th></th>
<th>Countryside</th>
<th>Village</th>
<th>Suburb</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Households living in</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>detached houses</strong></td>
<td>1x Family</td>
<td>2x Family</td>
<td>3x Family</td>
</tr>
<tr>
<td></td>
<td>1x Employee</td>
<td>2x Employee</td>
<td>3x Employee</td>
</tr>
<tr>
<td></td>
<td>4x Retiree</td>
<td>4x Retiree</td>
<td>3x Retiree</td>
</tr>
<tr>
<td><strong>Households living in</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>apartment buildings</strong></td>
<td>-</td>
<td>8x Family</td>
<td>9x Family</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>8x Employee</td>
<td>36x Employee</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>16x Retiree</td>
<td>27x Retiree</td>
</tr>
<tr>
<td><strong>Total share of the</strong></td>
<td>Family: 16.7</td>
<td>Family: 25.0</td>
<td>Family: 14.8</td>
</tr>
<tr>
<td>household categories</td>
<td>Employee: 16.7</td>
<td>Employee: 25.0</td>
<td>Employee: 48.1</td>
</tr>
<tr>
<td>[ % ]</td>
<td>Retiree: 66.7</td>
<td>Retiree: 50.0</td>
<td>Retiree: 37.0</td>
</tr>
</tbody>
</table>

4.4 Existing small-scale PV systems

The last step in establishing the reference networks is to consider existing RES. Here, the focus lies on estimating the number of existing, small-scale, roof-mounted PV systems. First, the model estimates how many roof-mounted PV systems exist in each state. Secondly, it uses the state population to calculate the penetration rate of roof-mounted PV generators. Thirdly, it considers the community size in the reference networks and multiplies it with the penetration rate.

Estimating the total number of roof-mounted PV systems requires knowledge of the total and average capacity of roof-mounted PV systems. The German Renewable Energies Agency provides the total capacity of roof-mounted PV systems for each state (AEE, January 6, 2020; see first row of
Table 4). Using the Marktstammdatenregister\(^3\) (MaStR), it is possible to estimate the average capacity of roof-mounted PV systems for each state (see second row of Table 4). Combining the total and average capacity and using the state population (Statista, January 6, 2020) subsequently allows to estimate the total number of roof-mounted PV systems and the penetration rate for each state.

### Table 4: Estimation of the penetration rate of small-scale roof-mounted PV systems in Germany

<table>
<thead>
<tr>
<th>[Unit]</th>
<th>BW(^4)</th>
<th>BY</th>
<th>B</th>
<th>BB</th>
<th>HB</th>
<th>HH</th>
<th>HE</th>
<th>MWP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capacity [MW]</td>
<td>4,936</td>
<td>9,371</td>
<td>91</td>
<td>1,023</td>
<td>41</td>
<td>38</td>
<td>1,642</td>
<td>664</td>
</tr>
<tr>
<td>Avg. capacity [kW]</td>
<td>16.89</td>
<td>17.60</td>
<td>14.58</td>
<td>71.60</td>
<td>22.01</td>
<td>17.23</td>
<td>15.86</td>
<td>88.68</td>
</tr>
<tr>
<td>Estimated no. [-]</td>
<td>292,244</td>
<td>532,443</td>
<td>6,262</td>
<td>14,284</td>
<td>1,863</td>
<td>2,223</td>
<td>103,512</td>
<td>7,491</td>
</tr>
<tr>
<td>Inhabitants [m]</td>
<td>11.07</td>
<td>13.08</td>
<td>3.65</td>
<td>2.51</td>
<td>0.68</td>
<td>1.84</td>
<td>6.27</td>
<td>1.61</td>
</tr>
<tr>
<td>Penetration rate [no./1,000 citizens]</td>
<td>26.40</td>
<td>40.72</td>
<td>1.72</td>
<td>5.69</td>
<td>2.73</td>
<td>1.21</td>
<td>16.52</td>
<td>4.65</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>NI</th>
<th>NRW</th>
<th>RLP</th>
<th>SL</th>
<th>SN</th>
<th>ST</th>
<th>SH</th>
<th>TH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capacity [MW]</td>
<td>3,171</td>
<td>4,365</td>
<td>1,621</td>
<td>324</td>
<td>910</td>
<td>954</td>
<td>1,135</td>
<td>714</td>
</tr>
<tr>
<td>Avg. capacity [kW]</td>
<td>22.34</td>
<td>18.86</td>
<td>16.60</td>
<td>15.83</td>
<td>22.63</td>
<td>33.86</td>
<td>23.99</td>
<td>43.96</td>
</tr>
<tr>
<td>Estimated no. [-]</td>
<td>141,956</td>
<td>231,453</td>
<td>97,639</td>
<td>20,461</td>
<td>40,203</td>
<td>28,163</td>
<td>47,307</td>
<td>16,240</td>
</tr>
<tr>
<td>Inhabitants [m]</td>
<td>7.98</td>
<td>17.93</td>
<td>4.09</td>
<td>0.99</td>
<td>4.08</td>
<td>2.21</td>
<td>2.90</td>
<td>2.14</td>
</tr>
<tr>
<td>Penetration rate [no./1,000 citizens]</td>
<td>17.78</td>
<td>12.91</td>
<td>23.90</td>
<td>20.65</td>
<td>9.86</td>
<td>12.75</td>
<td>16.33</td>
<td>7.58</td>
</tr>
</tbody>
</table>

The pronounced differences in the penetration rates suggest that the number of existing small-scale, roof-mounted PV generators strongly depends on the location. It is important to verify that the penetration rates are realistic because they determine the number of existing PV systems in the reference networks. According to KfW (2019), 7% of all German households own a PV system. By comparison, the paper estimates the national average to be 19.08 roof-mounted PV systems per 1,000 households, which translates into only 3.8%, using an average household size of 1.99 (Destatis, 2019). It is likely that the existence of large roof-mounted PV systems in the MaStR data sample yields relatively high average capacities, which decreases the estimated total number of roof-mounted PV systems. Still, the model employs the state-specific penetration rates so that it can

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\(^3\) Accessible via [https://www.marktstammdatenregister.de/](https://www.marktstammdatenregister.de/). The MaStR is a ledger for master data of electricity and gas generators in Germany.

account for regional differences. Moreover, the model follows Zepter et al. (2019), who argue that households with a higher demand may be more likely to own a PV system. Also, the model assumes that existing PV systems do not have a battery and utilizes the same state-dependent penetration rate for all settings.

4.5 Grid-friendliness

Communities can act grid-friendly in several ways. In detail, the paper assesses their grid-friendliness using two parameter types: autarky and the volatility of the net community load.

From a grid perspective, increasing a community’s degree of autarky is positive since it can reduce the must-run capacity of conventional power plants (Gährs et al., 2016). Also, the local consumption of electricity generated by distributed small-scale generators can reduce the need for grid enhancement (Quaschning et al., 2015). To achieve a higher degree of autarky, communities can either reduce their demand, increase local generation, or consume a higher share of the locally generated electricity.

However, any of those measures also changes the shape of the net community load (NCL; i.e., gross community load less local consumption). In this regard, it is instructive to examine how implementing an autarky-increasing measure affects the maximum absolute NCL gradient and its 99%-quantile. The NCL gradient describes by how much power the NCL changes between two time steps. In centralized electricity systems with conventional power plants, a community is considered to be grid-friendlier if the NCL varies as little as possible. A “constant power demand profile might […] [even] be the preferred feature of grid-friendly users.” (Wang, 2016: 629) Following this rationale, grid-friendly communities exhibit low NCL gradients. Conversely, high gradients imply that the grid has to react more quickly and to withstand higher stress (increased resilience). Hence, if a measure reduces the maximum absolute NCL gradient, this is positive from a grid perspective. Yet, it is insightful to also examine how the 99%-quantile changes. This allows to verify whether high NCL gradients are an exception or occur regularly. Table 5 summarizes the parameters considered in this paper and explains how they indicate a grid-friendly community behavior.

Table 5: Overview of the parameters used to indicate grid-friendly behavior

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Grid-friendly behavior</th>
<th>Indicator of</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree of autarky</td>
<td>[%]</td>
<td>Higher degree = grid friendlier</td>
<td>Grid independence</td>
</tr>
<tr>
<td>Maximum absolute NCL gradient</td>
<td>[kW]</td>
<td>Lower gradient = grid friendlier</td>
<td>Load volatility</td>
</tr>
<tr>
<td>99%-quantile of the absolute NCL gradient</td>
<td>[kW]</td>
<td>Lower quantile = grid friendlier</td>
<td>Load volatility</td>
</tr>
</tbody>
</table>
5. Measures

A main goal of the paper is to examine how the inception of different CEC types and implementation of the following measures influences the communities’ grid-friendliness.

5.1 Energy efficiency

Compared to 2007, the EU aims to become 32.5% more energy efficient by 2030 (European Commission, January 6, 2020). This is referred to as the “energy efficiency first” principle. The idea is simple: reducing the overall energy demand reduces the need for new RES and the losses in the transmission and distribution grids. Simply put, efficiency can be a cost-effective approach to reducing the EU’s carbon footprint. In fact, in 2018, a growing energy efficiency was the most important factor in slowing down the increase of CO₂ emissions (BMWi, 2018b). However, households often lack information and contact partners for efficiency measures in Germany (BMWi, 2019). Here, CECs can play a vital role, using their communication channels to inform members “about rational energy use [and] energy-efficient technologies” (Bauwens and Eyre, 2017: 10). In this regard, CECs profit from their trustworthiness, an important prerequisite for citizen participation in energy efficiency projects (Laskey and Syler, 2013). In the model, only centralized and decentralized CECs can implement efficiency measures.

The paper models the implementation as follows. In the load simulation, the LPG allows the user to set the household’s energy intensity to “Random devices,” “Energy saving,” or “Energy intensive.” By default, the “Random devices” option is selected. If a household participates in the energy efficiency measure, the “Energy saving” option is selected, translating into a 30% lower electricity consumption.

Judging from the documentation, the LPG does not model behavioral changes when switching between two energy intensities. Yet, there is extensive proof that switching to energy-efficient devices or performing environmentally friendly actions can induce a moral licensing or rebound effect (Tiefenbeck et al., 2013; Harding and Rapson, 2019).

5.2 Bulk purchases

In the model, centralized and decentralized CECs can also organize bulk purchases. Instead of buying individually, community members pool their orders and purchase collectively, achieving a higher bargaining power (Koirala et al., 2016). While the paper considers only the bulk purchase of small-scale PV systems, other applications are conceivable. Based on their annual consumption, community members choose between four PV system sizes (see Table 6). The available capacities are close to
the average capacity of small-scale roof-mounted PV systems. We assume that all building types can accommodate all PV systems.

Table 6: Specifications of the small-scale PV systems

<table>
<thead>
<tr>
<th>Unit</th>
<th>Model S</th>
<th>Model M</th>
<th>Model L</th>
<th>Model XL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity [kWp]</td>
<td>3.25</td>
<td>5.2</td>
<td>7.8</td>
<td>9.75</td>
</tr>
<tr>
<td>Required area [m²]</td>
<td>17</td>
<td>27</td>
<td>41</td>
<td>51</td>
</tr>
<tr>
<td>Retail price [€]</td>
<td>6,900</td>
<td>9,500</td>
<td>12,500</td>
<td>14,900</td>
</tr>
<tr>
<td>Recommended annual consumption [kWh]</td>
<td>&lt; 2,500</td>
<td>&lt; 4,000</td>
<td>&lt; 5,500</td>
<td>≥ 5,500</td>
</tr>
</tbody>
</table>

In Germany, there is a trend towards also purchasing a battery when buying a PV system. In 2018, every second new PV system under 30 kWp came with a battery (AEE, January 6, 2020). Using the battery, households can store excess electricity for later use. In a recent survey, 83% of German battery owners stated that (energy) cost reduction was a main purchase motivation (KfW, 2019). The model reflects this development by assigning a battery to every second new PV system, starting with the largest PV system. The corresponding batteries are 5.1 kWh, 6.4 kWh, 7.7 kWh, and 9.0 kWh in size and have a C-rate of 1. These storage capacities are close to the average capacity of batteries put into operation in 2018, which is 8.40 kWh (BNetzA, 2019d).

Analogous to Zepter et al. (2019), the model does not consider any form of performance degradation for the batteries. This assumption is also extended to the PV systems. Following Broering and Madlener (2017), the model assumes that all PV systems face South and are tilted 35 degrees. The South-facing orientation is usually the optimum for PV systems in the northern hemisphere (Sarbu and Sebarchievici, 2017). In the present model, the charging strategy is to maximize self-consumption.

5.3 Community-scale RES

In the model, centralized and decentralized CECs can also install community-scale RES. Through member cooperation, “more energy options become feasible at a community level due to economies of scale” (Koirala et al., 2016: 729). The output power of such RES is typically quite large. As such, they may be connected to the medium-voltage level if they have a rated power between 200 kWp and

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5 The MaStr reports that roof-mounted PV systems under 30 kWp that went into operation between Sep. 2017 and Sep. 2019 had an average net rated power of 8.60 kWp.

6 Data retrieved from [https://www.eigensonne.de/preise/](https://www.eigensonne.de/preise/). The PV systems consist of Heckert NeMo 60M 325 Wp modules with $\eta_{Module,STC}=19.4\%$ and $C_{P,Temperature}=-0.40\%/°C$. 
20 MW<sub>p</sub> (Konstantin, 2017). Hence, community-scale RES are considered not as part of the community’s low-voltage grid but as part of a different voltage level within close proximity.

In Germany “there has been a notable shift towards wind projects” (Kahla et al., 2017: 15, own translation). Thus, the model only provides the option to install a community-scale WEC, neglecting other technologies. Although constructing new energy infrastructure often causes controversies, citizen involvement and co-determination can provide relief (IZES, 2015). For wind farms in Germany, Liebe et al. (2016) find that the possibility to own the wind park has a positive effect on the local acceptance of wind power. Also, *active* citizen approval is necessary for distributed RES because citizens have to be willing “to provide space for the installation of these technologies, capital investment and behavioral changes.” (Bauwens, 2013: 11) In some cases it may be that “only by connecting the locally-based citizens, certain areas are rendered available for wind energy projects.” (IZES, 2015: 44, own translation) Also, the literature finds wind power to be “less viable in urban settings” (Walker, 2008: 4405). In part, this is due to the density of constructions and thus lower wind speeds (UBA, 2013). Hence, the model provides the option to install a community-scale WEC only in the countryside and village settings.

To calculate the WEC output, the model uses the characteristic power curve of an ENERCON E-70 (see Figure A.). This WEC model has a rated power of 2.3 MW<sub>p</sub>. This is a bit lower than the average output power of WECs installed in Germany in 2018, which was 3.3 MW<sub>p</sub> (AEE, January 6, 2020).

### 5.4 P2P trading

Finally, distributed and decentralized CECs can introduce a P2P trading scheme. In this context, Zepter et al. (2019) argue that the price for *locally* traded electricity (i.e., between two actors within the same low-voltage network) should not include transmission network charges. However, the EU Renewable Energy Directive states that “community members should not be exempt from relevant costs, charges, levies and taxes that would be borne by final consumers who are not community members, producers in a similar situation, or where public grid infrastructure is used for those transfers.” (RED, Remark 71)

If P2P consumers are not willing to pay more than the standard electricity retail price, this would mean that the producer receives 7.06 €-ct/kWh (Strom-Report, January 6, 2020). Yet, this is less than 9.87 €-ct/kWh, the FiT for RES generators commissioned in January 2020 with a rated power of less than 10 kW<sub>p</sub>. It is questionable whether producers would sell their electricity for 7.06 €-ct/kWh, particularly because older PV systems have even higher FiTs. Still, FiTs will likely decrease in the near future and may fall below the aforementioned 7.06 €-ct/kWh. Between January 2019 and January 2020, the FiT for PV systems under 10 kW<sub>p</sub> fell by 1.60 €-ct/kWh.

In reality some households might pay a price premium for locally generated electricity. In fact, as much as 10% of the German population may be willing to pay price premiums for electricity
generated by RES, regardless of its location (Mattes and Wittenberg, 2012). Nonetheless, the model assumes a P2P price of 7.06 €-ct/kWh. Also, note that the model only covers intra-community P2P trading between different buildings, located in the same low-voltage grid. Table 7 summarizes the measures that the CEC types can implement.

Table 7: Overview of possible measures

<table>
<thead>
<tr>
<th></th>
<th>Centralized</th>
<th>Distributed</th>
<th>Decentralized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy efficiency</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Bulk purchases</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>P2P trading</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Community scale RES</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

6. Analysis and evaluation

6.1 Scenarios

We consider three scenarios: “Business as usual,” “Conservative,” and “Maximum.” While scenarios do not constitute a forecast, they constitute a justifiable possible future (UBA, 2013), allowing to assess the potential effects of CECs on a community’s grid-friendliness.

In the Business as Usual (BaU) scenario, no CEC exists and thus no measures are implemented. It serves to compare how measures conducted in the other two scenarios change the status quo. In particular, it allows to determine whether implementing a measure leads to grid-friendlier community behavior.

In the Conservative scenario (CON), the model uses moderate assumptions. Regarding energy efficiency, KfW (2019) found that 49.9% of the German population want to save more energy. Yet, cost motivations and split-incentive barriers likely reduce the number of households that actually participate in energy efficiency measures. Taking into account these limiting factors, the model assumes that 20% of all households participate in the efficiency measure in the CON scenarios. In the model, the households with the highest annual electricity consumption are the first to participate in this measure.

The households can also participate in the bulk purchase. While in Germany 35.9% of the population want to generate more energy, only 2.2% of all households without a PV system plan to purchase one within the next 12 months (KfW, 2019). Since CECs can buy PV systems at lower prices, the CON scenario assumes that CECs can increase the share of households who purchase a PV system within the next 12 months by 50% (i.e., 3.3% of all households participate). Here, buildings with the highest gross load that do not own a PV system yet are the first to receive a new one.
Regarding the community-scale WEC, Gancheva et al. (2018) point out that some energy cooperatives may install RES only at a later stage, once they are more stable from a financial point of view. Following this rationale, the model assumes that CECs do not install a community-scale WEC in the CON scenario.

Lastly, CECs can introduce a P2P trading scheme. Note that the model considers buildings as the actors, not individual households. Since P2P trading “is viable only when there are at least a certain number of participants” (Park and Yong, 2017: 4), the CON scenario assumes that one in five prosumer buildings locally sells its excess electricity. On the demand side, two in five consumer buildings participate. The buildings with the most fed-in kWh or the highest net building load are the first to participate. To guarantee a minimum number of participants, at least always one prosumer building and two consumer buildings participate. Table 8 (center column) summarizes the CON scenario.

Table 8: Summary of the CON and MAX scenarios

<table>
<thead>
<tr>
<th>Participation/Implementation</th>
<th>CON</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy efficiency</td>
<td>20% of all households</td>
<td>49.9% of all households</td>
</tr>
<tr>
<td>Bulk purchases</td>
<td>3.3% of all households who do not own a PV system yet</td>
<td>Such that 52% of all buildings own a PV system</td>
</tr>
<tr>
<td>P2P trading</td>
<td>20% of prosumer buildings (min. = one) 40% of consumer buildings (min. = two)</td>
<td>100% of prosumer buildings 100% of consumer buildings</td>
</tr>
<tr>
<td>Community-scale RES</td>
<td>No</td>
<td>Yes (countryside and village)</td>
</tr>
</tbody>
</table>

By contrast, the maximum scenario (MAX) uses more extreme values. In this scenario, CECs can be interpreted as sworn-in, environmentally-friendly communities highly dedicated to increasing the community’s degree of autarky. In a way, the MAX scenario investigates what would happen if communities took their efforts to the next level.

Starting with energy efficiency, the model assumes that all households who want to save more energy can do so (i.e., 49.9% of the households participate). Also, the bulk purchase adds small-scale PV systems until 52% of the buildings are equipped. This is equal to the aggregated percentages of homeowners who either already own a system, plan to purchase one, or can generally imagine buying one (KfW, 2019). Moreover, all prosumer and consumer buildings participate in the local P2P trade and the community may install a community-scale WEC. Table 8 (right column) summarizes the MAX scenario.

6.2 Data validation
This section analyzes and validates the load and generation data. Since both differ throughout the year (e.g., due to seasonal influences), it is advisable to examine at least an entire calendar year. This allows to determine the maximum stress which the grid experiences (Wiest et al., 2014). Hence, our study examines the calendar year of 2018.

To simulate the residential load, the model uses two building types in the LPG: “HT20 Single Family House (1-2)” and “HT22 Big Multifamily House (10-200).” Subsequently, a settlement is created in the LPG, consisting of detached houses (i.e., HT20) and apartment buildings (i.e., HT22). Based on the community composition (see Table 3), the LPG randomly chooses modular households from the three household categories (i.e., family, employee, and retiree) and performs the load simulation. In total, it simulates 82 unique households with both the “Energy saving” and “Random devices” setting.\(^7\)

In the LPG settings, the user can determine a seed to initialize the simulation. While performing the simulation twice with the same seed should yield identical results, this was not true for the simulations carried out by the authors. The silver lining of this is that every simulated load profile is truly unique.

Knowing the exact household sizes of the chosen modular households, it is now possible to determine the average household size in the three settings. On average, 2.33, 2.08, and 1.95 citizens live in a countryside, village, and suburb household, respectively. This is close to the German average of 1.99 inhabitants per household (Destatis, 2019).

Furthermore, it is necessary to validate the households’ annual electricity consumption. In 2018, the average annual electricity consumption of a household living in a multi-family building in Germany was 2,801 kWh (BDEW, 6 January 2020). In comparison, with 4,212 kWh for a two-person household (“Random devices”), the average annual consumption of the model households is significantly higher. There are two possible explanations for this. First, households in detached houses consume more electricity than households in apartment buildings. Yet, with an annual consumption of 4,268 kWh, model households in detached houses are only slightly above the overall average. Secondly, the employment rate influences the residential electricity consumption. People who spend more time at home tend to consume more electricity, especially during the day. In the three settings, the employment rate amounts to 28.6%, 27.7%, and 43.0% (countryside, village, and suburb, respectively). In reality, 54.5% of the German population are employed (Statista, November 5, 2019). Hence, in all three settings, the employment rate is well below the German average.

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\(^7\) Simulation input: Geographic location = Hamburg (Germany); Temperature profile = Hamburg 2018; External time resolution = 00:10:00 (10 min); Random seed = -1; Period under review = January 1, 2018 until December 31, 2018. All LPG results are given in local wintertime.
The relatively high load has important implications. As Gährs et al. (2015) point out, a higher electricity demand also means that more locally generated electricity is consumed on site. However, this concerns a comparison between two or more households with the same PV system size but a different annual electricity consumption. According to Gährs et al. (2015), a household consumes around 25% of the electricity generated by a South-facing PV system. In comparison, the model yields 24.3% for detached houses. Hence the chosen PV systems seem appropriate. Interestingly enough, the average degree of autarky for detached houses in the model is 38.2% whereas Gährs et al. (2015) report typical values of around 24%. Although the degree of self-supply suggests that the PV systems in the model have a reasonable size, the degree of autarky suggests that they may be oversized.

One of the main inputs of the model is meteorological data. The German Meteorological Service (Deutscher Wetterdienst, DWD) provides open access to its solar and wind data. These are available in a 10-min resolution and for many years. Regarding solar data, DWD provides the 10-min sums of the diffuse and the global irradiation on a horizontal plane (DWD, 2019a). For the calculations, data from a weather station located in Augsburg, Bavaria, are used. Due to the high penetration rate in Bavaria (see Table 4), the reference networks should already contain some PV systems.

In the DWD data set, not all entries are valid. In detail, the 2018 solar data of Augsburg contains 52,527 out of 52,560 valid time-steps (99.9%). Also, one or both irradiation components is sometimes temporarily zero between sunrise and sunset. Moreover, the irradiation is sometimes zero although it is greater than zero at the same time on both neighboring days. It is assumed that these time steps also do not contain valid data. Thus, in total 52,148 out of 52,560 time-steps (99.2%) appear valid. Invalid entries are ignored and not replaced.

With the valid solar data, it is possible to validate the PV system output. In the model, PV systems achieve 1,277 kWh/kWp or 1,277 full load hours (FLH). In comparison, an average PV system in Bavaria (building- or ground-mounted) achieved 1,052 FLH in 2018 (AEE, January 6, 2020). Consequently, the calculated PV generation seems to be significantly above average. In part, this may be due to the employed diffuse irradiance model, which is prone to overestimation (Demain et al., 2013). To create a more plausible PV output, the model scales the PV generation such that the PV systems achieve 1,052 FLH per year.

With regard to wind data (DWD, 2019b), the model uses wind speed and wind direction data. The wind data comes from the same weather station as the solar data. For 2018, the DWD marked

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8 Average of six detached houses in a suburb setting, all with a 9.75 kWp PV system. The corresponding households have an annual electricity consumption between 5,896 kWh and 7,033 kWh.

9 Access via https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/10_minutes/.

10 DWD ID 00232, located at 48.4254 °N 10.9420 °E.
52,383/52,560 time-steps (99.7%) as valid. Similar to the solar data, the model excludes further wind data entries. This includes entries with no wind direction since during the nighttime, the model calculates the hourly standard deviation of the wind direction (using the “Modified Sigma Theta” method). If the wind direction is missing in one time-step, all time steps of that hour are marked as missing. During the daytime, the model employs the “Solar Radiation/Delta T” method. Since this method uses global irradiation data, the stability class cannot be calculated in time steps with missing irradiation data. Hence, in total 51,398/52,560 time-steps (or 97.8%) are considered valid.

Using the valid wind data allows to validate the annual WEC output. While the model yields 1,226 FLH for the ENERCON E-70, WECs in Bavaria yield an average of 1,779 FLH per year (AEE, January 6, 2020). Thus, the results suggest that either the model miscalculates the wind speed or the location of the weather station is not suitable for the chosen WEC model.

To exclude the former, it is necessary to verify that the calculations of the atmospheric stability class are correct. According to EPA (2000), the atmospheric stability should be either Class 1 or Class 2 in the mid-afternoon if the sky is clear. For an arbitrarily chosen day with high irradiation (July 31, 2018, the 212th day of the year), this holds true between 3:10 p.m. and 7:30 p.m. and thus also in the mid-afternoon. Moreover, the stability Classes 5 and 6 should occur during the last hours before sunrise. For the same day, this is true between 3:20 a.m. and 6:10 a.m. (on that day, the sun rose at 6:30 a.m.). Hence, at a first glance, the stability class estimation appears valid. However, it could also be that the model miscalculates the Hellmann exponent, which is required to estimate the wind speed at hub height.

In this regard, Figure 2 shows the average calculated Hellmann exponent for each stability class (“Model average”) and the values provided by EPA (2000). The latter are indicated as “EPA (rural)” and “EPA (urban).” The weather station is located on airport property, rather resembling a rural area. It appears that the model overestimates the Hellmann exponent for all stability classes, leading to higher wind speed estimates and thus higher WEC electricity generation. Still, the cut-off speed of the ENERCON E-70 is not exceeded once and thus the chosen WEC model may not be suitable for the location.

With the Nordex N117 (2.4 MW), a second WEC is added to the model\textsuperscript{11}. The Nordex N117 has a lower rated speed than the ENERCON E-70 (11 m/s vs. 16 m/s) and a lower cut-out speed (20 m/s vs. 26 m/s). Hence it reaches its rated power at lower wind speeds and does not support very high wind speeds. Using the Nordex N117, the model yields 3,090 FLH for a hub height of 141 m. While

\textsuperscript{11} The characteristic power curve was calculated using data from www.windenergie-im-binnenland.de. Its fifth degree polynomial approximation for the WEC power in kW is \( P_{WEC} = 0.1057 \times v_{Wind,at\ hub}^5 - 5.5719 \times v_{Wind,at\ hub}^4 + 92.098 \times v_{Wind,at\ hub}^3 - 619.31 \times v_{Wind,at\ hub}^2 + 1970.6 \times v_{Wind,at\ hub} - 2385.2 \).
the manufacturer advertises the WEC as being capable of reaching up to 3,504 FLH (Nordex, 2019),
the results again suggest that the model overestimates the Hellmann exponent. Subsequently, the
“EPA (rural)” values are employed instead.

![Figure 2: Validation of the Hellmann exponent](image)

6.3 Results

The following three sections present the results for each CEC type. Before delving into the results, it
is advisable to consider two preliminary thoughts. First, the more households live in a community,
the smaller their individual influence is on the aggregated community behavior. Hence, the potential
for more extreme results is higher in smaller communities. Secondly, when assessing grid-
friendliness, the model neglects the time at which the communities feed electricity to the wider grid
(ideally, they would do so at times of high demand in the wider grid).

Table 9 reports the main parameters that characterize the BaU scenario. The data show a positive
correlation between community size, gross community load, and maximum absolute NCL gradient.
Furthermore, the village and suburb communities consume more electricity locally (99.18% and
99.24%, respectively) than the countryside community (83.74%). This is due to the fact that the “PV
systems to citizens” ratio is higher there than in the countryside setting.12

<table>
<thead>
<tr>
<th>Unit</th>
<th>Countryside</th>
<th>Village</th>
<th>Suburb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>0.10</td>
<td>0.11</td>
<td>0.13</td>
</tr>
<tr>
<td>Class 2</td>
<td>0.15</td>
<td>0.15</td>
<td>0.19</td>
</tr>
<tr>
<td>Class 3</td>
<td>0.15</td>
<td>0.20</td>
<td>0.25</td>
</tr>
<tr>
<td>Class 4</td>
<td>0.19</td>
<td>0.25</td>
<td>0.43</td>
</tr>
<tr>
<td>Class 5</td>
<td>0.30</td>
<td>0.30</td>
<td>0.35</td>
</tr>
<tr>
<td>Class 6</td>
<td>0.55</td>
<td>0.55</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Table 9: Results of the BaU scenario

12 Using the penetration rate and community size, the model estimates that 0.6, 3.4, and 6.4 PV systems already exist in the countryside, village, and suburb setting, respectively. Rounding to the nearest integer results in a higher “PV systems to citizens” ratio on the countryside.
<table>
<thead>
<tr>
<th>Gross community load [kWh]</th>
<th>35,849</th>
<th>165,304</th>
<th>325,985</th>
</tr>
</thead>
<tbody>
<tr>
<td>Already existing PV systems [-]</td>
<td>1</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Local PV generation [kWh]</td>
<td>10,029</td>
<td>30,086</td>
<td>60,172</td>
</tr>
<tr>
<td>Local PV consumption [kWh]</td>
<td>8,398</td>
<td>29,840</td>
<td>59,712</td>
</tr>
<tr>
<td>Degree of autarky [%]</td>
<td>23.43</td>
<td>18.05</td>
<td>18.32</td>
</tr>
<tr>
<td>Maximum absolute NCL gradient [kW]</td>
<td>11.76</td>
<td>27.78</td>
<td>43.21</td>
</tr>
<tr>
<td>99%-quantile of absolute NCL gradient [kW]</td>
<td>6.03</td>
<td>12.19</td>
<td>19.34</td>
</tr>
</tbody>
</table>

Next, we analyze how implementing measures influences the community’s grid-friendliness in the different settings. The figures presented follow a specific color code. The BaU scenario is always presented in black, results of the CON scenario have a lighter color, and results of the MAX scenario have a darker color. The figures use the following abbreviations: “Eff” (efficiency measure), “Bulk” (bulk purchase), and “Wind” (community-scale WEC).

The model assumes that communities try to maximize their degree of autarky, which is a core preference of energy communities (Koirala et al., 2016; Gancheva et al., 2018). For communities, a higher degree of autarky is desirable because it reduces the expenses for electricity drawn from the wider grid. Since the proposed measures can require one-off and recurring payments, they differ in their financial attractiveness. For the purpose of this analysis, however, these payments are neglected. Note that all measures increase the community’s degree of autarky.

### 6.3.1 Centralized

Beginning with the countryside community, Figure 3(a) depicts the maximum absolute NCL gradient and the degree of autarky for each measure, while Figure 3(b) depicts the 99%-quantile of the maximum absolute NCL gradient. It is clearly visible that the BaU exhibits the lowest degree of autarky. This is intuitive since all measures either reduce the community load or increase the local electricity generation.

In the CON scenario, the efficiency measure is the only available measure since the combination of community size and participation rate is not big enough to motivate the purchase of a single PV system. Therefore, Figure 3(a) and Figure 3(b) do not include data points for bulk purchases in the CON scenario.
In the MAX scenario, the efficiency measure and the bulk purchase reduce the 99%-quantile whereas installing a WEC significantly increases it. If communities can choose only one measure and maximize their degree of autarky, they choose the energy efficiency measure (CON) and the WEC (MAX). In the CON scenario, this has positive effects on the 99%-quantile (-0.05 kW) and negative effects on the maximum absolute NCL gradient (+1.09 kW). Also, it increases the degree of autarky (+0.74%). In the MAX scenario, installing a community-scale WEC increases the degree of autarky markedly (+57.93%). Yet, it also makes the NCL more volatile: The maximum absolute NCL and its 99%-quantile increase by 7.97 kW and 1.02 kW, respectively. Thus, for the chosen measures in the countryside setting, there is a grid-friendliness trade-off in both scenarios.
Moving on to the village setting, it will be interesting to see whether a different community size and composition will have an influence on the community’s choice. To this end, Figure 4(a) shows the maximum absolute NCL gradient for the village community. Here, only the community-scale WEC increases the maximum absolute NCL gradient. In contrast to the countryside setting, the efficiency measure and bulk purchase do not increase the maximum absolute NCL gradient, but reduce it. Moreover, they also decrease the 99%-quantile (see Figure 4(b)). Sticking with the autarky-maximizing strategy, the community will pick the bulk purchase (CON) and the WEC (MAX). In the CON scenario, pursuing the bulk purchase is grid-friendly in all three dimensions. More specifically, the bulk purchase comprises one PV system and one PV battery in the CON scenario (five PV systems and three batteries in the MAX scenario). Moreover, installing a community-scale WEC in the MAX scenario has the same effects in the village setting as in the countryside setting: Although it significantly increases the degree of autarky, it also increases the NCL volatility. Hence, based on its decision, the centralized CEC in the village setting acts grid-friendlier in the CON scenario while a tradeoff exists in the MAX scenario.

Lastly, examining the suburb setting may show what happens when the number of buildings increases only slightly (from 16 buildings in the village setting to 18 buildings in the suburb setting) while the number of citizens increases considerably (almost doubling from 83 to 158 citizens). Note that the community composition again changes and that the share of working people increases significantly (from 27.7% in the village setting to 43.0% in the suburb setting). For the suburb setting, Figure 5(a) and Figure 5(b) depict the maximum absolute NCL gradient and its 99%-quantile, respectively. Since the model does not allow the suburb community to install a community-scale WEC, it is not able to achieve a degree of autarky comparable to the countryside or village community.
In the suburb setting, centralized CECs choose to conduct bulk purchases in both scenarios. In the CON scenario, this adds two PV systems and one battery, slightly increasing both the maximum absolute NCL gradient (+2.58 kW) and its 99%-quantile (+0.62 kW). In the MAX scenario, the bulk purchase leads to the installation of three new PV systems and two batteries, also increasing the maximum absolute NCL gradient (+3.87 kW) and its 99%-quantile (+0.72 kW). Interestingly, in the MAX scenario, the degree of autarky increases much less in the suburb setting when conducting a bulk purchase. Whereas in the village setting, a bulk purchase increases the degree of autarky from 18.05% to 37.37% (MAX), the suburb community can only increase it from 18.32% to 25.85% (MAX). Here, the higher number of citizens and thus a higher load, as well as the limitation of equipping only 52% of all buildings with PV systems, lead to a smaller increase. To conclude, a grid-friendliness tradeoff exists in both scenarios.
Table 10 summarizes the decisions of the centralized CECs. A green background color indicates a grid-friendlier behavior while a cream-colored background indicates a less grid-friendly behavior. In the CON scenario, only the village community increases its grid-friendliness in all three regards, by conducting the bulk purchase. While conducting the bulk purchase in the suburb setting also maximizes the degree of autarky, it increases the maximum absolute NCL gradient and its 99%-quantile. This suggests that the effects of the bulk purchase depend on the number of buildings and the community composition.

While in the MAX scenario the chosen measures maximize the degree of autarky, they also increase the maximum absolute NCL gradient and its 99%-quantile in all settings. Consequently, a clear trade-off exists between energy independence and NCL volatility.
Table 10: Summary of the results for centralized CECs

<table>
<thead>
<tr>
<th></th>
<th>Countryside</th>
<th>Village</th>
<th>Suburb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chosen measure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autarky [%]</td>
<td>23.43</td>
<td>24.17</td>
<td>81.36</td>
</tr>
<tr>
<td>Max. abs. NCL grad.</td>
<td>11.76</td>
<td>12.85</td>
<td>19.73</td>
</tr>
<tr>
<td>99% quant. abs. NCL grad. [kW]</td>
<td>6.03</td>
<td>5.98</td>
<td>7.05</td>
</tr>
</tbody>
</table>

6.3.2 Distributed

This section analyzes how much electricity is traded locally if the community uses a P2P trading scheme. Subsequently, “prosumer buildings” refers to buildings that own a PV system, while “consumer buildings” refers to buildings without PV systems.

Since the analysis builds on the status quo, no batteries exist in the reference networks. If the PV generation exceeds the aggregated load of a prosumer building, it can offer electricity to other buildings. These buildings either consume all the electricity (i.e., local demand exceeds supply) or the prosumer building exports some PV electricity to the wider grid (i.e., supply exceeds local demand). Since the model only compares excess generation and consumer demand, it does not change the community’s degree of autarky. Currently, the challenge in low-voltage grids is to “[match] renewable energy supply to domestic energy demand, locally if possible.” (Smale et al., 2017: 133)

In this regard, it will be insightful to examine to which extent the communities automatically consume local excess generation.

In the P2P trading scheme, the only difference to the status quo is that consumer buildings directly pay prosumer buildings for the locally generated electricity they consume, instead of paying electricity retailers. With the given constellation, however, consumer buildings may (by default) consume local surplus PV electricity, regardless of whom they pay (i.e., introducing P2P trading causes only a change in the cash flow, while the electricity flow stays the same). Also, the model does not consider a change in the load pattern although consumers could try to shift their demand to times of high PV generation to increase the consumption of locally generated electricity.

For all settings, Figure 6 shows the electricity volume that participating prosumer buildings feed into the grid (“P2P feed-in”) and the electricity volume that participating consumer buildings purchase (“P2P consumption”). Since in the MAX scenario all buildings participate, the “P2P consumption” there is equal to the total community consumption of local PV electricity and the “P2P feed-in” is equal to the total PV feed-in. Thus, the difference between “P2P feed-in” and “P2P consumption” in the MAX scenario describes the electricity export to the wider grid.

In the countryside, the total PV feed-in is 7.09 MWh, of which the community consumes 5.46 MWh in total. Consequently, it exports 1.63 MWh (or 23% of the total feed-in) to the wider grid.
In the CON scenario, the P2P consumption volume is 3.59 MWh, inducing a cash flow of €253.35. The results in Figure 6 also imply that 1.87 MWh of electricity are delivered to non-participating consumer buildings, who instead pay their electricity retailers.

In the MAX scenario, the P2P feed-in remains the same, since the countryside setting has only one PV system and thus no additional prosumer buildings can join the trading scheme. Still, the P2P consumption increases to 5.46 MWh, inducing an intra-community cash flow of €385.61.

![Figure 6: P2P consumption vs. P2P feed-in (distributed)](image)

By comparison, the export of surplus PV electricity is significantly lower in the village and suburb settings. In the village setting, the community exports 1.10% of the surplus PV electricity. While in the CON scenario the purchase volume is 7.32 MWh (€517.01), it almost triples to 21.44 MWh (€1514.00) in the MAX scenario. Also, 14.12 MWh are consumed locally in the CON scenario, but the revenues flow to the electricity retailer.

In the suburb setting, the community exports 0.96% of the surplus generation. Here, the P2P purchase volumes amount to 8.02 MWh (CON) and 45.07 MWh (MAX). This induces intra-community cash flows of €566.01 (CON) and €3182.06 (MAX).

To conclude, the induced intra-community cash flow is higher in the MAX scenario than in the CON scenario in all settings. Moreover, it correlates positively with the number of PV systems and the number of consumer buildings. Should a community decide to install more PV systems, one can expect that the prosumer buildings will have to export more electricity to the wider grid. Note that

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13 This assumes that consumer buildings pay 7.06 €-ct/kWh to the prosumer buildings, while they still pay the standard taxes and levies to the electricity retailer. In total, they continue to pay 30.43 €-ct/kWh for the electricity they consume (i.e., the average electricity retail price in Germany, in 2019). Since existing PV systems may receive FiTs that are higher than the proposed P2P trading price, this section can be considered a thought experiment.
the P2P trading results likely differ when considering batteries since the feed-in of surplus electricity would occur only once the batteries are full. Consequently, the P2P purchase volume would depend on how much electricity participating consumer buildings consume once the prosumer batteries are full.

6.3.3 Decentralized

Finally, this section examines how communities can completely self-supply themselves. As the previous sections illustrate, conducting only one measure cannot provide 100% autarky. In contrast to centralized CECs, decentralized CECs can subsequently pursue more than one measure. This also allows to examine the interplay between different measures.

For the countryside setting, Figure 7(a) shows the maximum absolute NCL gradient and Figure 7(b) shows the corresponding 99%-quantiles. Here, square data points indicate that the community conducts several measures. The figures indicate that no combination can provide 100% autarky. Even in the MAX scenario, combining energy efficiency, bulk purchase, and WEC is not enough. Thus, the community would still have to change its behavior and/or install more generators or batteries. The literature finds that community energy storage “facilitates energy sharing and local self-supply of locally generated renewables.” (Koirala et al., 2018a: 573) So what if the community used its batteries collectively to store not only the electricity of the corresponding PV system but also from other generators? In other words, what would happen if it was possible to charge the batteries from “outside?” Subsequently, this thought experiment is referred to as a “virtual community battery” (VCB). A VCB would allow the community to stock up on electricity in times of excess PV and wind generation and to use that electricity in times of underproduction. As Wiest et al. (2014) point out, PV systems usually feed in a significant amount of electricity even if they are set up to maximize self-supply. Using a VCB, excess generation of PV systems without batteries could be retained in the community, at least to some extent. If available, the community-scale WEC can also charge the VCB so that, especially at nighttime, the VCB and the WEC can satisfy the community load together.
Figure 7: Countryside setting (decentralized)

Figure 7(a) and Figure 7(b) depict combinations including a VCB by using a triangle shape (the VCB is only available in the MAX scenario). Still, even using a VCB is not enough to reach 100% autarky. Adding a VCB can increase the degree of autarky only to 98.80% (“Eff + Bulk + Wind + VCB”), inducing an additional €238.74 in intra-community cash flows.\(^\text{14}\) Hence, the countryside community is physically not capable of reaching 100% autarky in any scenario. That said, the figures provide some additional insights for the MAX scenario. First, when installing a community-scale WEC, also conducting the efficiency and bulk purchase measures results in an overall grid-friendlier behavior. Secondly, conducting the efficiency and bulk purchase measures is grid-friendlier than only conducting the efficiency measure. For the CON scenario, it is not possible to make similar inferences since in that scenario no PV systems are bought in the course of the bulk purchase measure.

In the village setting, the community is also not able to reach 100% autarky. Here, combining energy efficiency, bulk buying, and community-scale WEC yield an 86.97% degree of autarky (Fig. 8(a)). Thus, the degree is very close to the one in the countryside community but below 100%.

In the CON scenario, conducting not only the efficiency measure or bulk purchase but both yields a higher degree of autarky (25.84%), a lower maximum absolute NCL gradient (24.24 kW), and a lower 99%-quantile (11.31 kW). The same is true for the MAX scenario. While using a VCB increases the degree of autarky, it also adds volatility. Note that using a VCB in the “Eff + Bulk +

\(^\text{14}\) This figure is based on how much less energy the community needs to draw from the wider grid when activating the VCB option, also taking into account the battery round-trip efficiency.
Wind” combination increases the degree of autarky by a lot more than in the “Eff + Bulk” combination. This is partly due to the fact that the WEC generates electricity throughout the entire day and can thus charge the VCB also after sunset. This increases the average state of charge during the night and hence the VCB can better help to satisfy the community load. When conducting the efficiency measure and bulk purchase, adding the VCB induces an additional €157.35 in intra-community cash flows. If the community also adds the community-scale WEC, this increases to €1,037.21 (Fig. 8(b)).

Lastly, Figure 9(a) and Figure 9(b) show the results for the suburb setting. In contrast to the previous settings, the suburb is a lot further away from reaching 100% autarky. In part, this is due to the fact that the suburb community cannot install a community-scale WEC. Also, for the bulk purchase, equipping 52% of the buildings with PV systems results in a smaller “PV systems to household” ratio since the population density is higher (MAX).

In the CON scenario, the suburb community can at most reach 25.7% (“Eff + Bulk”). While this decreases the 99%-quantile, it increases the maximum absolute NCL gradient. Here, a tradeoff also exists for adding the efficiency measure to the bulk purchase measure, which increases both the degree of autarky and the maximum absolute NCL gradient while reducing the 99%-quantile (compared to only conducting the bulk purchase).

(a) Autarky vs. max. absolute NCL gradient
In the MAX scenario, the community can reach a 30.9% degree of autarky (“Eff + Bulk”). Using a VCB would improve this to 31.95% while increasing the grid-friendliness and inducing an additional €207.96 in intra-community cash flows. Moreover, conducting not only the bulk purchase but also the efficiency measure improves the community’s grid-friendliness in all three regards.
6.4 Sensitivity analysis

The sensitivity focuses on the MAX scenario and whether a community can achieve 100% autarky in any setting by tweaking the electricity generation parameters. For PV systems, changing the orientation and inclination angles results in a different generation curve. For three PV systems facing South, Figure 10(a) depicts how varying the inclination angle $\beta_{PV}$ changes the generation curve on a clear summer day. It shows that reducing $\beta_{PV}$ to 0° increases the electricity generation in the early morning and the late afternoon. While this can result in an overall lower annual PV generation, it could help communities reach 100% autarky since it influences the interplay between PV and WEC electricity generation.

Consequently, the sensitivity analysis examines whether varying the orientation and inclination angles of the PV systems can enable 100% autarky. To this end, Figure 10(b) displays the maximum degree of autarky when conducting all measures and using the VCB (MAX). Still, even under these circumstances no community is able to reach 100% autarky in any of the three settings. This suggests the existence of a brief period with insufficient generation. Another reason may lie in the fact that in the model all PV systems have the same angles and thus electricity generation curve. Positioning them at different angles could result in generation curves that better complement each other and enable 100% autarky. Figure 10(b) shows that modifying the angles of all PV systems can enable over 99% autarky.

Moving on to WECs, limiting the maximum hub height can change the degree of autarky. While the chosen hub height is very high in the original results (141 m), in Bavaria, WEC operators have to actively involve municipalities in the process of installing a WEC if the distance between the nearest
residential building and the WEC is less than ten times the hub height. Thus, choosing a lower hub height might be necessary to avoid conflicts in anti-wind power areas. To this end, Figure 10(c) depicts the degree of autarky for a WEC with a hub height of less than 100 m. In the **countryside**, the autarky decreases by 0.60% (with VCB) and 2.62% (without VCB). In the **village**, the decreases amount to 1.32% and 2.70%, respectively. Thus, by using the VCB, the lower WEC electricity generation can be partially absorbed. While the communities would still choose the Nordex N117 in both settings, they would have to choose a hub height of 91 m. This reduces the FLH from 3,090 to 1,818 FLH.

Lastly, three additional cities are examined using the original setup to examine the location-dependence of the results: Hamburg (North), Berlin (East), and Cologne (West). Since the cities are located far from each other, their weather data may vary significantly. Still, none of them reaches 100% autarky, regardless of the setting. Moreover, the results indicate that the model overestimates the PV electricity generation also at the other locations. Apart from the employed diffuse irradiance model, this could also be due to the employed temperature-dependent efficiency model. Yet, using the Ross thermal model (Olukan and Emzi, 2014) and the model proposed by Tamizhmani et al. (2003) leads to a similar overestimation.\(^{15}\)

\(^{15}\) Note that the WEC results for Hamburg, Berlin, and Cologne confirm the hypothesis that using the original method to determine the Hellmann exponent overestimates the WEC electricity generation. Even using the lower EPA values, a Nordex N117 located in Hamburg would achieve 3,819 FLH (with a hub height of 141 m). Hence, using the EPA exponents cannot prevent an overestimation of the WEC output.
Summary and conclusions

As the paper has shown, modeling CECs is a complex task. This is reflected in the challenges that arose during the simulation of the electricity generation. In particular, the model overestimates the generation of PV and WECs, calling for more accurate models. It is necessary to improve the approximation of the wind speed at hub height, which may be viable using light detection and ranging devices in the near future. With this in mind, we can now return to the two main research questions.

The first research question of this paper is to determine how the emergence and actions of different types of CECs influence a community’s grid-friendliness. As the results of the centralized CECs show, conducting only one measure almost always leads to a grid-friendliness trade-off. While the proposed measures decrease the grid-dependence, they often increase NCL volatility in both scenarios. Here, the bulk purchase in the village community (CON) constitutes the only exception, improving all three parameters. Also, the results of the decentralized CECs suggest that combining measures can increase the communities’ grid-friendliness. Nearly in all cases, adding the efficiency
measure and/or bulk purchase to the already chosen measure improves the grid-friendliness. Only in the suburb, adding the efficiency measure to the bulk purchase increases the maximum absolute NCL gradient (CON).

To conclude, the results suggest that the different measures can complement each other quite well, increasing the community’s grid-friendliness in most cases. This suggests that policy makers should continue to promote efficiency measures and the installation of small-scale PV systems, particularly in communities where a WEC is present.

The second research question is to quantify the extent of the induced intra-community cash flows. For distributed CECs, the CON scenario estimates annual induced cash flows of €253.35 (countryside), €517.01 (village), and €566.01 (suburb). Paired with the community size, these figures allow to estimate the potential of local P2P trading in Germany. At the same time, it is questionable whether these cash flows alone can justify the purchase of P2P-enabling infrastructure (e.g., smart meters). Also, the MAX scenario likely indicates the maximum cash flow potential. Here, local P2P trading induces intra-community cash flows of up to €386, €1,514, and €3,182, respectively (with VCB).

Furthermore, it is conceivable that some consumers are willing to pay more than the proposed P2P price. Future research could examine the willingness-to-pay for “local” electricity generated by energy communities. Additionally, future research could extend the scope of the model to a regional level. This would allow to assess how and when neighboring communities can help each other to act grid-friendlier.

It is important to point out that real-world communities likely differ from the reference communities. For example, they may prefer certain technologies or face particular challenges. Hence, it is crucial to consider the local context.

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**Appendix: Renewable energy technologies considered**

Employing RES constitutes a key characteristic for CECs. Generally speaking, RES technologies include PV, wind, solar thermal, geothermal, hydro, and biomass power, among others. While PV, wind, and solar thermal are less location-dependent, geothermal, hydro, and biomass are highly location-dependent. This confirms the decision to focus on PV and wind which should help to create a model that is applicable at many locations in Germany. Also, PV systems and WECs have benefitted from significant price decreases in the past years (BMWi, 2018b) and will likely continue carrying the German energy transition. It is estimated that the current portfolio of building-mounted PV systems in Germany utilizes only ten percent of the total potential (BMWi, 2019). Hence, Germany can still exploit a considerable potential.

Installing generators always involves a landscape change which citizens perceive differently, depending on the technology. For example, Koirala et al. (2018b) find that the sight of WECs is more disturbing than the sight of PV systems. They also find evidence that “the noise of wind turbines is the most disturbing [factor]” (Koirala et al., 2018b: 36). Moreover, Süsser (2016) reports a lower perceived deterioration of nature by PV systems than by WECs. While it is generally advisable to consider landscape perception and change, the present paper neglects this for reasons of simplicity.

16 We do not consider solar thermal because it neglects heat demand and focuses on electricity demand and generation only.
To correctly assess the results, it is necessary to understand how the paper models the electricity generation via PV systems and WECs.

A.1 Photovoltaic systems

In the model, irradiance data is the main input for calculating the output power of PV systems. As the original data is measured on a horizontal plane, it is necessary to convert the data such that it can be used for inclined and oriented systems. This conversion yields the global irradiance reaching a PV system, subsequently referred to as $E_{Global, PV} \ [W/m^2]$. In general, PV systems are either building-mounted or ground-mounted. They consist of several PV modules and use their total surface area $A_{PV, Total} \ [m^2]$ to convert electromagnetic irradiance (i.e., the sunlight) into electricity using the photoelectric effect. $\eta_{PV, System}$, the system efficiency of the PV generator, dictates how much of the irradiance is converted into electricity. Equation (A.1) describes the output power of a PV system, $P_{PV} \ [W]$:

$$P_{PV} = E_{Global, PV} \times A_{PV, Total} \times \eta_{PV, System} \quad (A.1)$$

$P_{PV}$ can either be consumed directly, used to charge a battery, or be fed into the grid. The overall system efficiency consists of several components. The paper approximates $\eta_{PV, System}$ using the module efficiency under standard test conditions ($\eta_{Module, STC}$), the temperature-dependence of the module efficiency ($\eta_{Temperature}$), and the inverter efficiency ($\eta_{Inverter}$):

$$\eta_{PV, System} \approx \eta_{Module, STC} \times \eta_{Temp} \times \eta_{Inverter} \quad (A.2)$$

All manufacturers of PV systems test their modules under standard test conditions (STC). Typically, they include $\eta_{Module, STC}$ in the data sheet of the PV module. While the STC assume a cell temperature of $T_{Cell, STC} = 25 ^\circ C$, the actual cell temperature $T_{Cell, Actual}$ often differs from 25 °C. To this end, Eq. (A.2) describes the temperature-dependence of the module efficiency:

$$\eta_{Temp} = 100\% + C_{P, Temp} \times (T_{Cell, Actual} - T_{Cell, STC}) \quad (A.3)$$

Here, $C_{P, Temp}$ denotes the temperature-dependent performance coefficient of the PV module. For most silicone-based modules, one can assume that $C_{P, Temp} \approx -0.40\%/^\circ C$ (Wirth, 2014). Thus, for every degree Celsius that $T_{Cell, Actual}$ is higher (lower) than $T_{Cell, STC}$, the module efficiency decreases (increases) by 0.40%. To approximate $T_{Cell, Actual}$, the paper relies on the formula by Blank (2006), where $T_{Ambient}$ describes the ambient temperature:

$$T_{Cell, Actual} \approx T_{Ambient} + (0.0325 \ ^\circ C \times \frac{m^2}{W} \times E_{Global, PV}) \quad (A.4)$$

Lastly, $\eta_{Inverter}$, the third factor, is usually included in the inverter data sheet.
A.2 Wind energy converters

Similar to the PV systems, it is necessary to convert the wind input data in order to calculate the WEC output power. To this end, it is necessary to extrapolate the wind speed between two heights, allowing the model to simulate the wind speed at hub height. As Eq. (A.4) illustrates, the kinetic power of an air flux $P_{\text{Air}}$ depends on the cubic wind speed at hub height (Manwell et al., 2010):

$$P_{\text{Air}} = \frac{1}{2} \times \rho_{\text{Air}} \times A_{\text{Rotor}} \times v_{\text{Wind, at hub}}^3$$

(A.5)

Here, $\rho_{\text{Air}}$ and $A_{\text{Rotor}}$ denote the air density and the rotor disc area, respectively. Using the WEC’s characteristic power curve it is possible to approximate the WEC output power $P_{\text{WEC}}$ as a function of $P_{\text{Air}}$ (UBA, 2013). This allows “to predict the energy production of a wind turbine without considering the technical details of its various components.” (Manwell et al., 2010: 7) To exemplify this, Figure A. shows the characteristic power curve of a 2.3 MW ENERCON E-70.

Three wind speeds characterize the power curve: the cut-in speed (here: 3 m/s), the rated speed (16 m/s), and the cut-out speed (26 m/s). The cut-in speed is the minimum wind speed necessary for the rotor to overcome its inertia. With higher wind speeds, the WEC starts to generate more energy. Once the rated speed is reached, the WEC delivers its rated output power. It continues to deliver its rated power even at greater wind speeds, up to the cut-out speed. Once the cut-out speed is reached, the WEC is shut down for safety reasons.

Figure A.1: Characteristic power curve of an ENERCON E-70, based on data in Crespo Del Granado et al. (2016)\textsuperscript{17}

\textsuperscript{17} Between the cut-in and rated speed, Crespo Del Granado et al. (2016) approximate as follows: $P_{\text{WEC}}[\text{kW}] = 0.0498 \times v_{\text{Wind, at hub}}^5 - 2.5155 \times v_{\text{Wind, at hub}}^4 + 44.91 \times v_{\text{Wind, at hub}}^3 - 336.68 \times v_{\text{Wind, at hub}}^2 + 1165.9 \times v_{\text{Wind, at hub}} - 1480.5$. 

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