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A Market Design for Swarm Grids

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ABSTRACT

In this paper, we are proposing a policy innovation for both a more sustainable and a more inclusive electrification strategy, particularly for improved energy access in the Global South: combining the extension of national grids whilst taking advantage of existing decentralized renewable energy infrastructure allowing their collective feed-in to the national grid. We are introducing community power purchase agreements as a regulatory instrument for compensating and incentivizing the actors active at the intersection of the two infrastructures (prosumer, grid operator, state utility). We use both a mixed complementarity and a linear model for analyzing the concept in a case study of Pirgacha village, Bangladesh, in which a cluster of solar home system prosumers are interconnected into a renewable energy swarm grid. We determine the energy infrastructure cost components and their split among the actors. The results demonstrate a series of co-benefits: (a) the prosumer is monetarily rewarded for the utilization of her assets and for electricity trading with no additional infrastructure investment; (b) if the state utility takes over the investment costs with the interconnection infrastructure and outsources the integrated grid operations and maintenance to the private sector, the otherwise high grid expansion costs can be saved and repurposed in other infrastructure investments; (c) the operations of the decentralized renewable energy company are no longer threatened by the grid expansion and it can become an Integrated Grid Operator.

1. Introduction

Between 2010 and 2019, the population without access to electricity decreased from 1.2 billion to 759 million (IEA et al., 2021). Electricity access can be provided in two ways: either through top-down, centralized electrification via national grid extension or bottom-up through decentralized renewable energy solutions (DREs), that is, standalone solar systems, mini grids, and swarm grids[1].

The IEA (2020) estimates that the number of people connected bottom-up to DREs between 2010 and 2019 more than doubled, reaching 11 million people. GOGLA et al. (2020) calculate that by 2019, 105 million people had access to off-grid solar systems (lanterns and solar home systems (SHSs)). To achieve the United Nation's Sustainable Development Goal (SDG) 7[2], Tilleard et al. (2018) estimate that in Africa alone, by 2030, more than 290 million people could be connected to mini grids (this translates to more than 4,000 mini grids). These represent the most economically viable option for servicing the part of the population that is too remote or for which the national grid extension is too expensive.

Following a top-down approach to electricity access, countries of the Global South, with support of international aid and development funding, are accelerating their national grid expansion. As the national grid reaches their customers, the private sector (DRE companies) is put at danger of having to either relocate their assets or abandon them (Asian Development Bank, 2020). At the same time, the DRE end-user, reached by the national grid, faces several challenges due to being exposed to a double infrastructure. These challenges can be of technical and financial nature and are caused by the assets becoming abundant or needing additional equipment to be suitable for national grid and DREs.

This paper investigates a technically and economically viable solution for the co-existence of the national grid—a centralized infrastructure—with the decentralized, renewable energy infrastructure in Global South countries. At the intersection of these two electrification pathways the question arises if the two approaches can be integrated to the benefit of society by maintaining existing assets. For this paper we assume the technical link to be a bidirectional inverter and a battery representing the point of common coupling (PCC) between national grid and currently off-grid systems. We then suggest to apply a cost recovery approach to calculate the economic value of a community power purchase agreement (C-PPA) that allows the community to enter into a trade agreement with the national grid to export at a specified rate. To verify and assess the feasibility we run an optimization model to simulate allocation of revenues and track trade activity for a case study. In this analysis, we find that the C-PPA would bring economic benefits to end-users (consumers and prosumers) by decreasing network charges and increasing

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[1]Swarm grids are built bottom-up, through the interconnection of decentralized renewable energy assets such as solar home systems. Mini grids can be defined as a set of centralized electricity generators (e.g. solar, diesel, hydro, wind) and possibly energy storage systems, connected to a distribution network that supplies electricity to a localized group of customers.

[2]Access to affordable, reliable, sustainable, and modern energy for all by 2030.

revenue from additional sales of electricity. Based on the indication of this being beneficial we suggest a framework where the private sector and national utilities work in a collaborative effort through a public-private partnership.

The remainder of the paper is structured as follows: Section 2 reviews the status quo of DREs. We suggest and investigate an integrated and coordinated approach between DREs and national grids, and describe the technical and economic implementation in Section 3. To verify the approach and test for its economic feasibility, Section 4 describes a case study using data from Bangladesh. Drawing on the general insights and the case specific results, Section 5 discusses the novel C-PPA approach. Section 6 concludes by presenting policy implications and gives an outlook on further research.

2. Background

The progress in electrification has been unequal across geographic regions, and urban and rural population. In Sub-Saharan Africa, by 2017, more than 570 million people still did not have any access to electricity. At the same time, Latin America, the Caribbean, and South and South-East Asia managed to provide 98% of their population with access to electricity (IEA et al., 2021). Across the urban vs. rural divide, in the last decade, the access rate in rural areas improved faster than in urban settings. This was particularly due to the deployment of DREs enabled through international funding, private sector innovations, and supportive national policies. Nevertheless, rural areas still account for the largest proportion of unelectrified population, with more than 759 million people underserved (IEA et al., 2021). The front runners of the previous decade in national electrification were Bangladesh, Kenya, and Uganda, with an average increase in coverage of three percentage points per year since 2010.

Each of these three countries has employed different electrification strategies. Through its micro-financed solar home system program between 2010 and 2016, Bangladesh managed to install more than 4.5 million solar home systems in a bottom-up approach (Cabraal et al., 2021). During 2016 to 2019, Bangladesh also heavily focused on a rapid expansion of the national grid (top-down), which now reaches 92% of its population (IEA et al., 2021). With VAT exemptions on DREs and other solar components, a high penetration of mobile money, and supportive national and international financing mechanisms, Kenya and Uganda are two of the countries in which DREs have the widest reach.

Countries of the Global South in general and Bangladesh in particular are yet to achieve their potential for renewable energy for electricity generation. Currently, the Global South's energy sector faces five main challenges:

- meeting growing energy demand (both retail and industrial) while transitioning to a cleaner energy mix,
- improving the governance and transparency of the energy sector institutions,
- increasing affordability and access particularly for rural consumers,
- addressing environmental degradation and climate change, and
- achieving power sector financial viability.

To address these challenges, many countries could take advantage of the great outreach DREs have even to the most remote areas. The national grid is needed for power generation and transmission to large urban and industrial loads. But to reach the large number of dispersed rural customers, the energy infrastructure needs to stay simple and low-cost, both for the national utility and the consumer. For example, Ferrall et al. (2020) suggest the integration of DREs into the national grid infrastructure to allow for one system to serve peak load to the other in order to reduce load shedding. Additionally, transmission losses could be reduced by avoiding the long distances to rural areas. In a scenario analysis conducted by Tilleard et al. (2018) for Sub-Saharan Africa, the national grid extension was deemed to be the least costly option for the urban and peri-urban population. Mini grids were considered the least-cost option for the remote but densely enough populated areas to support the CAPEX of the mini grid infrastructure. Standalone SHSs were the optimal solution for remote and sparsely populated areas, where the mini grid infrastructure becomes too expensive.

Innovative technical and operational solutions that try to integrate the two types of infrastructures—centralized and decentralized—are also currently being tested in Uganda. Umeme Ltd., the centralized power utility company, together with several partners, are piloting Utilities 2.0 Twaake[3] through a public-private partnership. With the average cost of grid extension connection at USD 1,400, if grid extension is the sole method of service provision, the required investment to electrify the entire population of Uganda would likely be in the range of USD 7 billion. Utilities 2.0 Twaake aims at halving these costs by integrating DREs (specifically mini grids) into the national grid infrastructure for the rural communities, whilst also providing asset financing for appliances. Among the DREs that help address energy access and energy poverty challenges are the peer-to-peer (P2P) energy exchange grids.[4] In the case of Bangladesh, the P2P grids function on the principles of swarm electrification (Groh et al., 2015b). Hence, also their designation "swarm grids", in which direct current (DC) standalone solar generation and storage assets (in this case, SHSs) can be interconnected into a smart decentralized grid, which allows for sharing of surplus electricity among the members of the grid. In the case of Bangladesh, the SHSs owned by households in rural areas currently generate surplus electricity that exceeds own demand. The surplus electricity often stems from oversized SHSs compared to the household's energy demand, or if the SHS is charged during the day, when the inhabitants of the households are not around and unable to consume electricity. By trading (selling and buying) the surplus electricity generated by their SHS, the households step up from their passive role of consumers to prosumers who are able to generate income from their solar asset.

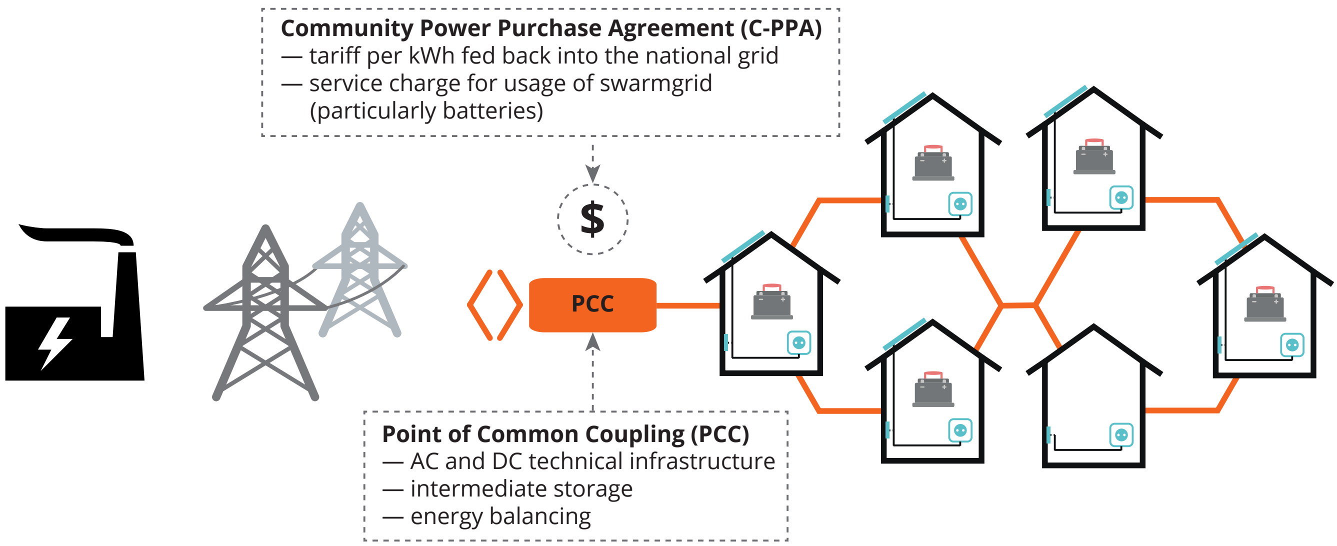
However, with the aggressively subsidized expansion of national grids to rural and more remote population already covered by DRE solutions, prosumers face two outcomes. Due to the highly subsidized grid connections and energy prices, DREs

[3] See Power For All (`https://sun-connect-ea.org/utilities-2-0-twaake-pilot-universal-electrification-for-half-the-cost-as-grid-only/`).

[4] P2P energy exchange describes trading of electricity among actors in close vicinity that are connected with each other by the same grid (Soto et al., 2021).

could become economically infeasible for the private sector, since households would consume electricity from the national grid at lower tariffs. The DREs would either become stranded assets or—in the best case—continue to operate as redundant infrastructure for cases of national grid failures and power outages. This would come at higher financial and operational risks for the infrastructure owners and operators, though. Alternatively, DREs could be integrated into the national grid system in a co-operative manner: the existing decentralized grid infrastructure built through the interconnection of the DREs would act as bidirectional DC distribution system, allowing households to consume electricity from the local grid and prosumers to feed their surplus electricity into the national grid. This way, the existing DC appliances could still be used without the need for replacement or investment in additional converters at the household grid connection point.

Figure 1: PCC and C-PPA layout. *Source: own depiction derived from insights of Hannes Kirchhoff.*



The main technical and economic challenge with integrated electrification pathways is in linking the centralized electrification infrastructure (the national grid operating on alternating current (AC)) with the decentralized electrification infrastructure (direct current (DC) DREs). One technical solution is the installation of the point of common coupling (PCC)—a single access point for interconnecting a DRE community to the national grid consisting of a converter, inverter, and batteries. In the case of Bangladesh, the PCC is the integration of the country's two major electrification efforts: grid extension and SHS dissemination (see Figure 1). The national grid connects to the one side of the PCC. On the other side stands a decentralized renewable energy grid, which in our example is a swarm grid where SHSs are interconnected with each other. The swarm grid can sustain itself through individual SHS generation and storage, and peer-to-peer energy trading. But it can also provide last mile national grid infrastructure: renewable energy feed-in, load balancing, reduced load shedding, and increased service stability. For the Bangladesh case, the existing infrastructure of 4.5 million+ SHSs (representing approximately 250 MAh of storage capacity and approximately 200 MW of generation) can be leveraged to address the national grid's resilience and reliability by:

- Smartening the grid: Enabling advanced metering at the customer level allows for automatic outage detection and service restoration.
- Distributing generation: Swarm grids can integrate into the national grid and be part of its operational and resource mix. They can also "island" if need be to keep running during grid outages, particularly relevant for extreme weather conditions and damages to distribution lines. The interconnected battery systems would out-perform any existing generators in the market as first respondents to the national grid, providing short-duration emergency power to arrest a frequency decline, allowing larger generators to ramp up and do the heavy lifting.

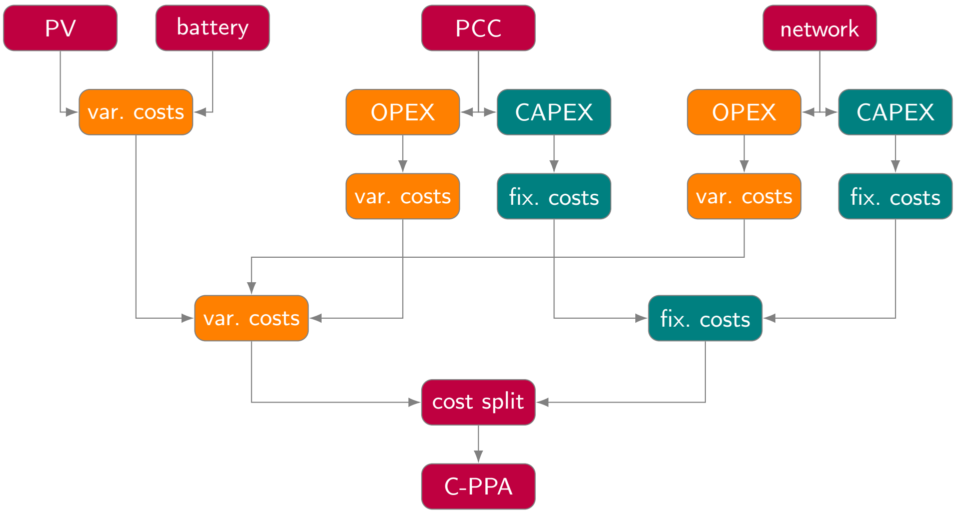
While it makes little sense that a small SHS feeds into the national grid (the expense of connecting each SHS is not economically justifiable for a national utility), a multitude of interconnected SHSs could help Bangladesh achieve its Nationally Determined Contributions (NDCs) goals. In our proposed solution swarm grids would be interconnected to the national grid, both technically—through a point of common coupling—and contractually—through a community tariff (see Figure 1).

The following section describes our core suggestion for a contractual framework when interconnecting swarm grids with the national grid. We present a so-called community power purchase agreement (C-PPA) as the regulatory instrument enabling the interaction between private and public actors.

3. Community Power Purchase Agreements

A PPA is usually a performance-based long-term contract to buy the electricity generated by a (renewable) energy installation. The contract is arranged between the owner or operator of the installation as the seller and an electricity utility (merchant PPA) or

Figure 2: C-PPA calculation scheme. *Source: own depiction.*



an end-user company (corporate PPA) as the buyer. PPAs are based on the levelized costs of electricity (LCOE) of the renewable installation (that is, the total capital costs and O&M costs of the installation broken down to the amount of electricity produced), amended by return and risk adjustments as well as additional conditions on the minimum and maximum amount of electricity to be delivered (Miller et al., 2017). Bruck et al. (2018) extend the LCOE approach for PPAs by developing new cost models. Mendicino et al. (2019) develop frameworks and business models for PPAs in the corporate context while Mirzania et al. (2020) assess innovative financing models for PV projects by introducing a community-owned energy storage with a time-of-use PPA and balancing services to the national grid.

We are proposing a regulatory instrument called community power purchase agreement (C-PPA) as a special manifestation of a PPA. Under a C-PPA, the interconnected SHS end-users in a swarm grid are rewarded for stepping up from their roles as passive power suppliers during daylight hours to battery-enabled energy service providers to the national grid, available at any hour. Under such a scheme a 'poor' household can be a net importer of electricity while still being a net-earner given a fair evaluation of her timed renewable power contribution at the edge of the grid and improving her payback time for the battery installation (as part of the SHS). This section 3 presents a methodology to determine the price level of such a C-PPA.

In general, a C-PPA determines a framework for trade between swarm grid prosumers and national utilities. The trade is technically enabled through the installation of a PCC allowing for the exchange of electricity between the national grid and the swarm grid. As the regulatory instrument for interconnecting the national grid and the swarm grid, the C-PPA will govern the price at which the national grid buys electricity from the prosumers, that is, the swarm grid. In the following, we describe an approach to derive a C-PPA in general. The levelized price will need to cover a range of costs that occur in the supply chain until the electricity is fed into the national grid. Costs arise from production of electricity, use of swarm grid infrastructure, and the introduction of the technical infrastructure around a PCC. These clusters of costs can be grouped into variable cost and fixed cost as depicted in Figure 2. The PCC's fixed costs and the network reinforcement or extension costs are split over the quantity of energy available to be traded through the interconnection. Fixed cost for the PV and battery system (components of the SHS) owned by the prosumers are in this approach already transferred into the marginal cost of one unit produced and thus only reflected in variable costs, that is, the price per Watt hour (Wh) at which a prosumer would sell her production. Generally, marginal production costs arise per Wh produced and possibly stored, while network components, including the PCC, are fixed costs that are a one-time investment, with an average lifetime of five years[5].

Depending on the given situation where an introduction of a C-PPA is considered, different cost components may be excluded. As the setups for a PCC and the regulatory structure can vary, we suggest a range of possible combinations to calculate the network component of a C-PPA. Table 1 lists the different approaches to define the network component either as split of costs included in the C-PPA or a fixed one-time investment negotiated. This refers to the furthest right box in Figure 2. We list different variations on how to distribute network infrastructure costs among the actors and thereby vary the amount transferred into the C-PPA. While in all cases we suggest to split costs for the swarm grid infrastructure over all local trading activity including exchange with the grid, we vary the way we split cost for the additional trade enabling technology of the PCC. The option indicated by the black triangle suggests to split the costs only over trade activity, thus making the infrastructure fully supported by the C-PPA, while the options with a white square partially make swarm grid activity cross-subsidize the grid link. In the options I-IIa where PCC infrastructure is not financed over the quantity traded, we consider the investment to be subsidized or supported by other one-time funding.

Overall, the C-PPA would thus include variable cost for distributed generation, variable operational costs, and fixed costs split over the final or estimated amount traded. Besides the characteristics of each cost component, the calculation of the C-PPA is also highly influenced by the given infrastructure, regulatory framework, and consumer characteristics.

[5] On Bangladesh's market, lead acid batteries come with a five years warranty. They are expected to last longer, yet based on the number of charging cycles five years are used as an assumption here.

Table 1
Network component of C-PPA.

	PCC		Swarm Grid		Description
	CAPEX	OPEX	CAPEX	OPEX	
I			◊	◊	split of swarm grid cost over all swarm grid activity
II		◊	◊	◊	**I** including PCC operations split over all swarm grid activity
IIa		▲	◊	◊	**I** including PCC operations split over exchanged electricity
III	◊	◊	◊	◊	**II** including PCC investment split over all swarm grid activity
IIIa	▲	◊	◊	◊	**II** including PCC investment split over exchange

◊ – split over swarm grid activity ▲ – split over exchange

The PCC, as the technical solution, together with the C-PPA as the regulatory instrument, create a setup in which renewable energy can be used more efficiently and at a higher rate. As part of this setup, new organizational roles emerge for the participating actors: the private sector operator of a swarm grid becomes an Independent Grid Operator (IGO) who operates an integrated distribution grid connected to a higher level grid, manages customer relations, and is the contracting seller of the C-PPA in the form of an aggregator. The national grid continues its role as network operator, but transfers parts of its responsibilities to the IGO. In addition, the national utility is the buyer and contracting party of the C-PPA, and gets access to renewable electricity and battery flexibility from the swarm grids, as well as access to a larger range of customers who are already part of the swarm grid.

4. A Case Study from Bangladesh

With a population of approximately 164 million, ranking it as the world's 8th largest country by population (UN Department of Economic and Social Affairs, 2019) and a GDP per capita of USD 1,970 in 2020 (CEIC Data, 2020), Bangladesh is a developing country that has emerged as one of the fastest growing economies in the world.

Annual per capita electricity consumption in Bangladesh is relatively low at 320 kWh[6]. While the peak demand occurs during the evening hours due to lighting load, there is a significant use (500-2,500 MW) of expensive liquid fuel-run generation during daytime, which can be cost-effectively replaced by renewable energy. Currently, 57.4% of supplied energy is generated from natural gas, followed by diesel and oil (32.39%). Imported power contributes at 6.12%, whereas coal (2.76%) and renewables including hydro and solar (less than 2%) are used least (Asian Development Bank, 2020).

Since 2010, Bangladesh has been one of the countries making the most progress with reducing the electricity access deficit, at an annual rate of over 3% (IEA et al., 2021), through decentralized and centralized electrification infrastructures, which are crucial in the fight against the energy poverty penalty (Pachauri et al., 2004; Groh, 2014). On-grid electrification has now reached about 92% of the population according to official numbers (IEA et al., 2021). Off-grid penetration reached about 14% of its population or approximately 20 million people in rural communities, with SHSs as the main electrification pathway, making Bangladesh one of the most successful off-grid energy access implementer in the world (Cabraal et al., 2021).[7]

Bangladesh's energy infrastructure is now at a crossroad between the integration of centralized and decentralized energy systems and the consumer level redundancy created by overlapping infrastructures. On the one hand, Bangladesh has proven to be an innovator in the off-grid sector (Chowdhury et al., 2015; Groh et al., 2015b; Alam Hossain Mondal et al., 2010; Palit and Chaurey, 2011): it is the world's first country in which SHSs are interconnected into P2P networks or swarm grids (Groh et al., 2015a), allowing for the sharing of surplus electricity among peers (transforming consumer households into prosumers), enabling a circular economy based on prosumerism and local value creation. This modular infrastructural approach allows consumption to grow dynamically while the asset ownership is distributed.

On the other hand, Bangladesh is among the world's ten most vulnerable countries to climate change (Eckstein et al., 2018). Every year, Bangladesh experiences frequent flooding and salinity problems, displacing a growing number of people from rural areas and forcing them to move to urban areas. While this could benefit energy distribution planning by focusing the grid extensions to consolidated urban regions, that trend also hinders the country's economic growth by limiting large-scale economic activity from growing beyond the major urban areas. The national grid has a very low reliability and resilience[8]. Bangladesh has enough generation capacity at approximately 22,000 MW against a demand of 9,000 MW (Hossain, 2020). Yet brown- and blackouts continue to occur, with power cuts longer than one hour and frequent voltage fluctuations (Fairley, 2020), due to age-old infrastructure incapable of carrying the load needed, overloading of transformers to a point of non-functionality or burning, and hampering with the distribution lines. In addition, extreme climatic events impact the already vulnerable grid. As outlined in Section 2, in the presence of a developed off-grid sector, national grids can benefit from interconnecting with the

[6]See World Bank (`https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC?locations=BD`).

[7]The rural electrification program started in 2003, and has been implemented through the governmental agency IDCOL (`https://idcol.org/home/solar`), with financial support from World Bank, JICA, KfW, ADB, IDB and USAID.

[8]Grid resilience is the ability to avoid or withstand grid stress events without suffering operational compromise or to adapt to and compensate for the resultant strains so as to minimize compromise via graceful degradation (Taft, 2018).

Table 2
Network component of C-PPA for case study, Bangladesh.

	PCC		Swarm Grid	
	CAPEX	OPEX	CAPEX	OPEX
I			482.39 ¢/kWh	
II		208.73 ¢/kWh		
IIa		235.80 ¢/kWh		
III	376.06 ¢/kWh *			
IIIa	449.32 ¢/kWh *			

* – not considered in the model calculations

existing decentralized infrastructure (Ferrall et al., 2020) to improve resilience and reliability for larger parts of the grid. While electricity from the national grid can be bought at low rates (0.082 USD/kWh), prosumers may not want to give away their achieved security of supply from owning their own assets and being in a cooperative environment with their peers. Therefore, the suggested integration by using a C-PPA can be a good fit for the case of Bangladesh.

In the following sections this paper gives sample calculations for a possible C-PPA derived from the schemes developed in Section 3 and presents a simulation based on data from an existing swarm grid in Bangladesh (see Section 4.1).

4.1. Data and Simulation

We use the village of Pirgacha in the Rangpur district of Bangladesh as case study. 25 interconnected households (thereof eleven consumers and 14 prosumers; 21 households operate micro enterprises) and ten micro utilities[9] form one of the 100 swarm grids operated by ME SOLshare Ltd.[10] The data set for the swarm grid contains information on the type of appliance (i.e. LED bulbs, table fans, fridges, TVs, laptops, printers, sewing machines, hotguns, and soldering irons), size of PV panel (between 20 and 300 Wp) and battery storage (between 20 and 130 Ah), and detailed trading data for the local electricity exchange, that is, P2P trade on SOLbazaar[11]. We use the given data set to estimate household demand applying a self-developed load generator[12]. The load time series generator uses information about households' appliances and their general usage pattern from customer surveys, simulating randomized usage of appliances and consolidating them to hourly load time series for every simulated household. Variable cost for PV and battery use are derived from investment and operations and maintenance cost using the concept of levelized cost of electricity (LCOE). The data and description on PV and battery technology is listed the Appendix. For PV generation data we use simulations from renewables.ninja (Pfenninger and Staffell, 2016) applying tilt variations as described in Mamun et al. (2017).

Combining all this data, we obtain a data set with time series for household consumption, PV generation, and storage information, which is then used to simulate demand-supply-matching in the village. The calculation of the specific C-PPA for Pirgacha, Bangladesh is based on SOLshare's information on costs from contractors, suppliers, and collaborators, as well as common market players selling appliances and SHS components in Bangladesh. Given the investment cost for network, PV and battery technology, as well as the PCC (see the Appendix for an overview of the cost input), we compute annual fixed cost to be split over the electricity quantity traded using the swarm grid. The specific values for this case following the different options presented in Section 3 are shown in Table 2. For the variable cost component of the C-PPA, we account for the cost of generation (determined as LCOE) by PV and add 20% of the batteries marginal production cost where the 20% equal the share of exports to the grid that originate from batteries. This adds up to 13.61 ¢/kWh. The transmission limits on the swarm grid lines have been neglected. It is assumed (and confirmed by swarm grid operators) that they are sufficient given the number of connected households and would grow with an increasing participation rate in the village. Used connection costs already reflect this issue.

To assess the impact of a C-PPA on SHS owners, micro utilities, and consumers in a swarm grid, we use both, a mixed complementarity and a linear model for evaluation. These models were developed by Lüth et al. (2018) and Lüth et al. (2020) and are used with minor modifications. For the mathematical formulation please see the Appendix. The mixed complementarity model allows for the determination of a local market price for trade within the swarm grid based on supply-demand matching and enabled trade. When this local trading price is obtained, the trade behavior and the available feed to the national grid through the PCC are simulated in the linear model to observe the allocation of quantities over time and be able to conclude on additional revenue streams.

4.2. Results

The results of the simulation show that for the chosen village of Pirgacha, Bangladesh, the costs for electricity of the households would not increase when introducing a C-PPA, but end at a lower level for all participants: consumers profit from decreased network charges, prosumers can earn additional money from sales through the C-PPA, and the micro utilities can profit most from trades under the C-PPA. The IGO in this context can cover all expenses while facing a higher usage of the grid. The costs are compared between groups of participants and across the different cases, that is, today's swarm grid, C-PPA under calculation scheme II, and C-PPA scheme IIa; see Figure 3.

[9] Micro utilities are additional SHSs installed by the swarm grid operator to increase the amount of electricity produced and stored in the swarm grid.
[10] See SOLshare's website for more information (`https://me-solshare.com/`).
[11] SOLbazaar is SOLshare's proprietary IoT-driven trading platform.
[12] The load time series generating tool SGDemTool is available on GitHub (`https://github.com/weibezahn/SGDemTool`).

Figure 3: Cost savings and profit increase for swarm grid participants, relative to base case.

The used input data gives clear indication that the decreased network charges occurring due to the split among more traded electricity will lead to lower electricity costs. Nonetheless, a set of sensitivities has to be considered looking at the given setup. The size of the community is decisive for the amount of electricity consumed and produced. The chosen data set comprises a small number of electrified households with a limited set of appliances, a few micro enterprises, and some micro utilities. The current development shows that more and more households are eager to invest in a SHS increasing the aggregated capacity in a swarm grid and leading to extensions. The higher the number of participants in a swarm grid, the larger the capacity that can be made available under a C-PPA. In addition, easier access to electricity enabled by a connection to the national grid may lead to increased demand. Due to a lack of indicators whether demand will increase and to what extent, the connection between swarm grid and national grid is only represented as a one-directional connection. In real applications, the implementation of a PCC would lead to bidirectional electricity flows, and may thus impact trading and consumption behavior.

Overall, although absolute numbers of available overproduction in the community are small due to a small data set, the community faces empowerment on different levels: On the one hand, the existing investments, infrastructure, and achieved progress can be utilized to create synergies with the state to accelerate electrification while maintaining profitable agreements between rural communities and top-down major state players. On the other hand, utilization of SHS increases the share of clean and sustainable energy sources in the setting of this case study where coal-fired power plants fuel the national utility.

5. Discussion

Integrating two distinct electricity infrastructures (one centralized–the national grid, the other decentralized–the swarm grid) and two electricity markets (one centralized–encompassing consumers, the other decentralized–renewable energy prosumers) can be done technically, through the PCC, and regulatory and economically synergetic through the C-PPA. The results presented in Section 4.2 show that for each of the stakeholders active in the new energy infrastructure, several benefits, limitations, and risk mitigation strategies can be derived.

Prosumers benefit on several levels. Rural households generate revenue from the sale of the surplus electricity through the swarm grid into the national grid (13.61 ¢/kWh as explained in Section 4.1) and are compensated by the national grid for the utilization of their generation (PV panel) and storage (battery) assets. Through the unfettered access to electricity, bigger loads (productive use appliances) can be used, thus diversifying the economic activities within the community. And through the integration of the two electricity infrastructures, the households are no longer required to invest in new appliances (to account for the AC/DC connections). Also some risks are mitigated: as the PCC enables the bidirectional transfer of electricity between the national grid and the swarm grid, households have 24/7 access to a source of electricity, eliminating the need of complementary generation sources (hence avoiding an investment in a fossil-fuel based technology, such as diesel generators). In case of national grid failures, the swarm grid can continue to function in "island" mode, hence the households' access to electricity is uninterrupted. These benefits might be limited by a possibly low community social buy-in due to unclear ownership roles for generation and storage assets (Kirchhoff and Strunz, 2019) within the swarm grid, and by extension, the C-PPA compensation for the prosumer.

The private **swarm grid operator** also benefits from the PCC/C-PPA setting. Through access to the national grid as a source of additional electricity, investment in additional micro utilities is avoided and the payback time of the existing micro utilities is reduced. As the swarm grid interconnection to the national grid becomes more complex, in the future, new ancillary grid services could be provided, diversifying the operator's business and operational model. On the risk mitigation side, the swarm operator is no longer in the position of having to abandon or relocate the decentralized grid, as the C-PPA contractual framework allows them to continue the business operations as an IGO. However, the easiness with which the contractual C-PPA can be set up highly depends on the public sector institutional setup. For the case of Bangladesh, several governmental institutions[13] need to provide their approval. Yet, the private operator needs to constantly monitor the performance of the swarm grid and of the nodes (SHSs) to assure that the optimal provision of ancillary grid services can be provided–otherwise, they risk being penalized (as in any PPA). In addition, the cost of the PCC should be taken over by the national utility as the implementation primarily benefits the national grid (for the increase of reliability and resilience in specific parts of the grid).

At the grid level, the **national utility** profits through the reduction of high costs for the interconnection of rural households, as a one time PCC interconnection (investment cost approximately USD 4,000) is cheaper than an individual household connection (expert assessments estimate the individual connection cost at USD 4,000 in Sub-Saharan Africa, and at around USD 5,000 in South-East Asia). A one time PCC interconnection can reach a cluster of households (minimum 15), while through normal national grid expansion, distribution lines, transformers, and household meters need to be installed in order to reach each household. Technical failures in the grid (voltage spikes, frequency irregularities) can be serviced through the utilization of the newly integrated decentralized storage units (the batteries of the SHSs as part of the swarm grid) and through the integration of the more than 4.5 million SHSs, the national utility is able to diversify its energy generation sources with renewables, instead of relying on traditional energy sources, contributing to the country's NDCs. According to our estimates, if the swarm operator's current energy infrastructure (100 swarm grids) would be interconnected to the national grid through the PCC, this can lead to annual saved emissions of approximately 120 t CO_2.[14] Additionally, there is a high potential of increasing the environmental impact, by sustainably interconnecting another 4.5 million SHS users not part of a swarm grid or not feeding into the national grid. The risk of losses due to failures to collect consumer payments are reduced or eliminated, as the activity is now outsourced to the IGO. The approach is limited, though, by the need for the national grid to be "smart" so that it can activate and utilize the full range of offered trade quantity and in the future potentially ancillary services provided by the swarm grid. Additionally, such services need to be quantifiable and monitored, so that they can be priced in the C-PPA.

Despite outlining many benefits, there are shortcomings in both the model and the setup of the C-PPA as a regulatory instrument. The outcome of the used simulation model is limited to the quality of the data set and its ability to reflect a valid setting. We observe missing data points and limitations in availability of consumer demand and trading patterns to benchmark our tool against. For the calculation of the C-PPA, the value is indicative, as information on components costs may vary depending on contracts with suppliers. The introduction and functionality of a C-PPA is bound to a transparent and cooperative institutional setup, public sector willingness to finance the support of decentralized infrastructure, and the political consensus on engaging with the private sector on electrification topics. Due to lack of or conflicting information on value of subsidies to national utilities, and cost parameters on grid enhancement and improvements, we are not able to calculate revenues and profits for any other actors than the prosumers and the micro utilities, under the assumption that the status quo will simply extend by trade options. The integration of the two systems may only be achieved if the current financial support of the energy system can be re-balanced, allowing the C-PPA to become an instrument supporting clean energy supply. Currently, the model only considers the feed-in of electricity; theoretically, ancillary services could also be provided to the national grid, yet, as of today there is no framework for pricing these services. Generally, the case study indicates a direction of where this can lead to and supports the benefits of this. The full appreciation of values remains slightly uncertain as they will only be visible in an agreed setup which this paper can help to develop based on indications and arguments.

6. Policy Implications and Outlook

The pilot projects in Uganda, and the case analysis in Bangladesh display modalities through which state utilities can leverage distributed private-sector business models to extend the grid to rural or remote areas and by doing so, make critical upgrades to their infrastructure. In this context, our analysis shows that through the introduction of a C-PPA, multiple co-benefits can be achieved for the actors situated at the intersection of the two electrification pathways, while fighting climate change. Nevertheless, to assure the uptake of the C-PPA, a clear institutional setup and policy framework need to be in place. This implies several recommendations for each of the actors.

State utilities need to define the grid interconnection requirements (i.e. delivery voltage, special requirements and conditions, point of supply, interconnection arrangement) so that the C-PPA can be accurately calculated. The private sector needs to be informed about the range of services it can provide to the national grid and the discussion to differentiate between a feed-in tariff and the C-PPA tariff need to be taken up. Finally, due to its better access to financing, the state utility should take over the cost of the DRE interconnection–in our case analysis, the cost of the PCC. Our estimations show that the cost of the PCC is lower than that of the grid extension and that its CAPEX can be recovered faster if the risk is taken over by the national utility. As the scenario analysis shows (see Section 4.2) the OPEX of the newly interconnected infrastructure can be priced in the C-PPA. As the C-PPA is a derivation of a standard PPA, **energy regulators** (such as energy ministries or renewable energy agencies) need to ensure that the contractual framework is defined and standardized[15]. Moreover, regulators could also consider setting up utility concessions that can allow the IGOs to obtain the rights to provide services under the C-PPA, under public

[13]Ministry of Power, Energy and Mineral Resources, Power Division, Bangladesh Power Development Board, the Sustainable and Renewable Energy Development Authority, the Bangladesh Rural Electrification Board.

[14]Based on Bangladesh's energy CO_2 intensity (Climate Analytics, 2019) and estimated avoided grid electricity usage through C-PPAs.

[15]E.g. operation, metering, delivery and acceptance of buyer's entitlement, relationship of partners, liability limitations, penalties, dispute resolution, force majeure, term and termination.

sector oversight or public-private partnership (PPP). These PPPs are a means to leverage private capital and must have a clear legal structure balancing between ensuring adequate financial returns and meeting the public objectives of the governing agency, particularly given that the fundamental economics of grid-based rural electrification remain difficult (Attia and Shirley, 2018). Finally, tracking and making public the costs incurred with the national grid extension and individual consumer interconnection could enable researchers, international development organizations, and policymakers in further investigating the cost-benefit analysis of centralized vs. decentralized electrification, in quantifying the investment required to reach the remaining unelectrified population, and in supporting more targeted policy recommendations.

Further research is needed for the concrete organizational and institutional structure of a C-PPA as well as the risk-sharing agreements between the national grid and the IGO. A more in-depth technical and economic analysis on the type of ancillary grid services (given also the availability and accuracy of data reporting) needs to be conducted in order to fully price the C-PPA. Depending also on the tracking of DREs at national level and their contribution to driving down carbon emissions, NDCs could be revised, in light of the opportunity of interconnecting DREs to the national grid (hence, increasing the share of renewable energy in the country's energy mix). Lastly, the importance of digitalization for each of the actors could be investigated—for example, utilization of blockchain for tracking prosumer contribution, asset financing, or other smart (IoT) technologies for monitoring grid service and performance.

In our paper, we have developed and assessed an economically feasible solution for integrating two electrification pathways in the Global South. The community power purchase agreement and its scenario analysis show that a combination of cost-sharing agreements, decentralization of operations, asset financing, and a well-designed tariff regime can transform un- or under-electrified households into prosumers—consumers and producers of renewable electricity in a decarbonized integrated energy infrastructure.

A. Appendix

A.1. Data

The case study for a swarm grid in Pirgacha, Bangladesh, uses the following data to calculate annual cost of technology. While the cost for production and storage make use of the concept of LCOE (Tegen et al., 2012; Brown et al., 2015) and calculate values split over annual production, we specify annuities for the investment costs, which are then turned over to the grid operator.

The concept of LCOE uses Eq. 1 and Eq. 2 where investments I_0 are discounted using the annuity factor ANF. Operations and maintenance costs OM are considered at a level of approximately 10% of the investment cost for equipment in the Global South and annual production M is individual to each producer. The interest rate i is set to 5%. Table 3 presents the final cost input with specific investment costs, lifetime, and a link to the data origin.

$$LCOE_h = \frac{I_0 \cdot ANF + OM}{M} \tag{1}$$

$$ANF = \frac{i \cdot (1+i)^T}{(1+i)^T - 1} \tag{2}$$

A.2. Simulation

We apply two models to assess the value of a C-PPA in a case study for Bangladesh. First, the mixed complementarity model by Lüth et al. (2020) is used to determine the market price in a peer-to-peer grid setting. The model and its description can be found in Lüth et al. (2020).[16] Only the prosumer's problem is applied in the context of the case study using Eq. (1)-(8) without the possibility of grid procurement $G_{n,t}$ and feed $F_{n,t}$.

Second, the calculated C-PPA and the estimated market price for the local market are set as input to simulate the electricity trading and sales into the national grid. The linear program described in a basic version in Lüth et al. (2018) in Eq. (1) - (10) calculates costs for electricity for each participant in the village and determines the impact of introducing a C-PPA. The reason for using a linear model in this step is to avoid the C-PPA influencing the local balancing price. The basic model is slightly adjusted to the following set of equations using the nomenclature in Table 4. Each member of the swarm grid aims at minimizing costs of electricity according to Eq. 3 while still maintaining the specific supply and demand balance in Eq. 4 that allows for trade and sales to the national grid. Local trade happens according to Eq. 5 and in order to avoid loop trading, the aggregated amount is limited through Eq. 6. In addition, the prosumers' storage levels, Eq. 7, are constrained by the physical characteristics of the individual batteries that are reflected in the bounds, Eq. 8, charging rate, Eq. 9, and discharging rate, Eq. 10.

$$\begin{aligned}\min_{R_{n,t},X_{n,t},I_{n,t},S^C_{n,t},S^D_{n,t},S_{n,t},F_{n,t}} \quad & \sum_t \Big[R_{n,t} \cdot p_n^{mc} + I_{n,t} \cdot \left(p_t^{lem} + p^I\right) \\ & + S^D_{n,t} \cdot p^D_n - X_{n,t} \cdot p_t^{lem} - p_{CPPA} \cdot F_{n,t} \Big]\end{aligned} \tag{3}$$

[16] The modeling framework code is available on GitHub (https://github.com/weibezahn/NRGdingo).

Table 3
Cost input for Bangladesh case study

	Unit	Cost	Lifetime (years)	Source
PV	\$/Wp	0.67	25	Rahimafrooz Solar
Battery	\$/Ah	1.5	5	Rahimafrooz Batteries Ltd.
Grid Node	\$/node	305	5	ME SOLshare Ltd.
PCC	\$/unit	4132	5	ME SOLshare Ltd.

Table 4
Designated sets, parameters, and variables of the mathematical model.

Sets	
$n \in \mathcal{N}$	prosumer n in community $\mathcal{N}$
$t \in \mathcal{T}$	hour t in time horizon $\mathcal{T}$
Scalars	
p^I	local balancing mechanism consumption tariff per kWh
p^{CPPA}	community power purchase agreement per kWh
ψ	losses on power lines
η	battery round trip efficiency
Parameters	
$dem_{n,t}$	demand of player n in time step t
p^D_n	discharge penalty per kWh for player n
p^{mc}_n	marginal cost per kWh for player n
p^{lem}_t	local market price in t
$res_{n,t}$	renewable energy production of player a in time step t
$\overline{s}_n$	upper bound of storage level in battery for player n
$\underline{s}_n$	lower bound of storage level in battery for player n
s^{init}_n	initial storage level in battery for player n
α_n/β_n	maximum charge/discharge rate of battery for player n
Primal Variables	
$F_{n,t} \in \mathbb{R}^+$	feed into the grid for player n in time step t
$I_{n,t} \in \mathbb{R}^+$	consumption from swarm grid for player a in time step t
$R_{n,t} \in \mathbb{R}^+$	consumption of renewable energy for player n in time step t
$S_{n,t} \in \mathbb{R}^+$	battery storage level for player n in time step t
$S^C_{n,t} \in \mathbb{R}^+$	battery storage charging for player n in time step t
$S^D_{n,t} \in \mathbb{R}^+$	battery storage discharging for player n in time step t
$X_{n,t} \in \mathbb{R}^+$	export to swarm grid of player n in time step t

$$dem_{n,t} + X_{n,t} + S^C_{n,t} + F_{n,t} = R_{n,t} + I_{n,t} + S^D_{n,t} \qquad \forall\, t, n \tag{4}$$

$$\psi \sum_n I_{n,t} = \sum_n X_{n,t} \qquad \forall\, t \tag{5}$$

$$\sum_{n,t} dem_{n,t} + \sum_{n,t} \leq \sum_{n,t} R_{n,t} \tag{6}$$

$$S_{n,t-1} + \eta \cdot S^C_{n,t} - S^D_{n,t} = S_{n,t} \qquad \forall\, t, n \tag{7}$$

$$\underline{s}_n \leq S_{n,t} \leq \overline{s}_n \qquad \forall\, t, n \tag{8}$$

$$S^C_{n,t} - \alpha_n \leq 0 \qquad \forall\, t, n \tag{9}$$

$$S^D_{n,t} - \beta_n \leq 0 \qquad \forall\, t, n \tag{10}$$

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