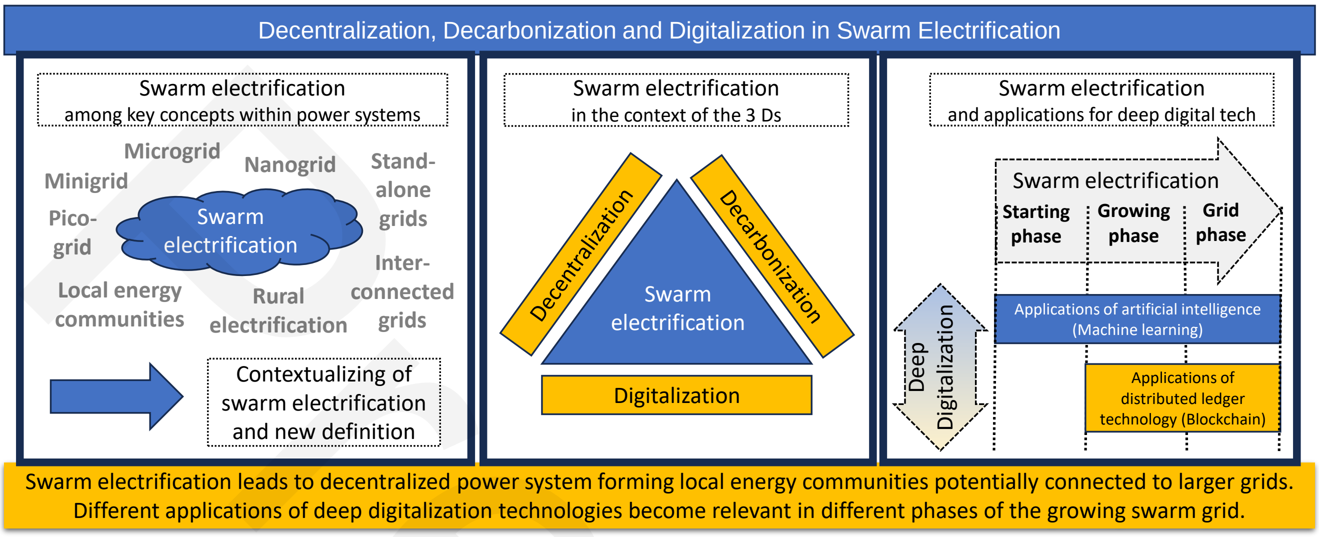
Graphical Abstract

Decentralization, Decarbonization and Digitalization in Swarm Electrification

Ida Fuchs, Jayaprakash Rajasekharan, Ümit Cali



Highlights

Decentralization, Decarbonization and Digitalization in Swarm Electrification

Ida Fuchs, Jayaprakash Rajasekharan, Ümit Cali

- Defined Swarm Electrification (SE) within power system's terminology.
- Linked SE to 3Ds: Decentralization, Decarbonization, Digitalization.
- Power system's decentralization and SE both unify into local energy communities.
- Analyzed digital tech enabling swarm electrification.
- Explored main digital tech applications in swarm electrification.

Decentralization, Decarbonization and Digitalization in Swarm Electrification

Ida Fuchs[a], Jayaprakash Rajasekharan[a], Ümit Cali[a]

[a]*Department of Electric Energy, Norwegian University of Science and Technology, Trondheim, Norway*

Abstract

Meeting the targets of Sustainable Development Goal (SDG) 7, which focuses on ensuring access to affordable, reliable, sustainable, and modern energy for all, poses significant challenges. Overcoming these hurdles requires innovative solutions that can bridge the gap between current capabilities and future needs. Swarm electrification emerges as a promising concept that could accelerate progress towards achieving SDG 7 goals by leveraging the collective power of decentralized energy resources. This review delves into the concept of swarm electrification, placing it within the context of the prevailing trends in the power system sector: decentralization, decarbonization, and digitalization. It examines the role of digital technologies in enhancing swarm electrification and categorizes application areas according to the phases of swarm electrification. Particular attention is given to the technologies underpinning Deep Digitalization, such as distributed ledger technology, notably blockchain, and artificial intelligence, with a focus on machine learning. These technologies play pivotal roles in advancing swarm electrification. The review demonstrates how deep digitalization can facilitate the improvement of swarm electrification and ultimately support the integration of bottom-up initiatives with top-down grid expansion efforts over time.

Keywords: Rural electrification, energy access, swarm electrification, solar, blockchain, machine learning

1. Introduction

The UN's tracking report on Sustainable Development Goal (SDG) 7, according to the International Energy Agency IEA (2022), indicates that the 2030 target for SDG 7 is off-track with the current progress pace, leaving 733 million people without electricity in 2022. The 20 countries with the least electricity access account for 76% of the global population, highlighting the urgent need to accelerate energy access to meet the 2030 SDG 7 goal. Ensuring access through clean, low-emission solutions requires innovative knowledge, tools, and methods.

A promising concept for energy access of the last-mile is Swarm Electrification (SE) first suggested by Groh et al. 2014b. The main idea behind SE is a bottom-up grown microgrid consisting of several individual solar home systems (SHS). It is build via individual connections via controllers and expanded over time. It enables SHS owners to sell surplus energy, earning income and expanding electricity access for additional users — a win-win driven by financial benefits, including cost reduction and lowered entry barriers by mitigating the initial investment challenge, crucial for last-mile energy access.

A recent review by Sheridan et al. 2023 on SE finds the following main aspects that are focus of the current literature: Drivers/barriers and financial, architecture and stability, control systems, peer-to-peer (P2P) markets and communications, and finally optimization. The review recommends further research in the areas of optimization, stability and reliability with a view to scaling up the swarmgrids and introducing productive use appliances to support small businesses. Information and communication technology (ICT) plays a pivotal role to meet these goals. The digitalization in modern power systems is enabling enhanced grid management, reliability, and efficiency through real-time monitoring, smart grid technologies, and advanced data analytics, thus facilitating the transition towards more sustainable and resilient energy infrastructures. In our review we relate SE to the recent technological changes, trends and evolution of the power system and show how SE is part of a larger development of our future grids. Specifically, we review digital technologies that can enable and improve SE facing the necessary challenges to succeed. The main contributions of our paper are:

- Situate and elucidate the concept of swarm electrification within the power system sector, delineating its relation to other key terms and concepts.
- Contextualize swarm electrification within the framework of the three Ds: Decentralization, Decarbonization, and Digitalization, highlighting its integral role.
- Illustrate how swarm electrification constitutes a critical component of the evolving landscape towards the future power system.
- Conduct a comprehensive review and analysis of the digital technologies that enable swarm electrification, underscoring their significance.
- Identify and dissect the primary application domains of digital technologies in swarm electrification, evaluating their impact and utility.

The paper is structured as follows: Section 2 outlines the data collection methodology. Section 3 explores SE, introducing the concept, terminology, a new definition, previous works, opportunities, and challenges. Section 4 examines SE in the context of digitalization, decentralization, and decarbonization (the 3Ds). Section 5 reviews enabling technologies for deep digitalization in SE. The findings are synthesized in Section 6, and the paper concludes in Section 7.

2. Data collection

Throughout this study, data and information were gathered from both research papers and field visits to relevant case studies. The foundation of this paper is built on a total of 88 literature references. The majority of the literature reviewed spans from 2018 to 2023, with the inclusion of some earlier works owing to their importance. Figure 1 displays the yearly distribution of the literature reviewed from 2018 to 2024. The review was completed by February 2024. We primarily concentrated on journal papers, which constituted 80% of the total literature reviewed. Conference papers accounted for 20%, and other sources made up the remaining 10%.

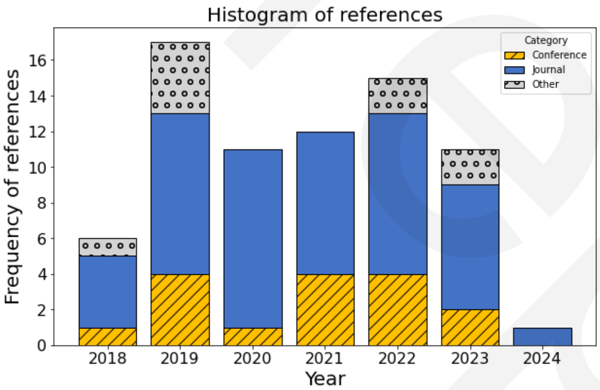


Figure 1: Histogram of literature occurrences between 2018-2024

To elucidate and define SE, we reviewed 31 papers that cover SE and related concepts within power systems. This effort aimed to accurately define and distinguish SE from other concepts. Further, we present a total of 21 references covering research related to 7 companies that have implemented technology or services to enable SE. Next, we examined 8 papers to contextualize SE within the framework of ongoing megatrends. This review primarily concentrate on exploring how digitalization can enhance SE. A specific emphasis of this paper is on deep digitalization, highlighting blockchain and machine learning as pivotal technologies enabling the future power system. The objective was to identify compelling test cases and examples where these technologies have been investigated, while simultaneously examining their features and potential for SE. Consequently, literature featuring case studies received priority. We analyzed 10 papers on information and communication technology and general digitalization realted to SE, 19 papers on distributed ledger technology and blockchain, and 16 papers on artificial intelligence and machine learning.

Additionally, we enhanced the substance of this review paper by incorporating experience from participating in relevant case studies. The first case study focused on the Eco Moyo Education Centre[1], a primary school in rural Kenya. The school was visited during three field trips from 2022 to 2024. During these visits, the school implemented a new solar battery off-grid system and repurposed an older system for additional uses. The second case study delves into interconnected nanogrids in rural Madagascar, undertaken as part of the Horizon 2020 project ENERGICA[2]. This research included a field trip to Madagascar, where several villages with installed nanogrids were explored. The third case study that provided insights for this paper involves the deployment of solar home systems in Raqaypampa, a rural village in Bolivia. This project was executed by the Centro Universitario de Investigaciones en Energías[3], part of Universidad Mayor de San Simon (UMSS) in Cochabamba, and financed by Académie de recherche et d'enseignement supérieur (ARES), the federation of French-speaking higher education establishments in Belgium. A research exchange was conducted at UMSS, allowing for discussions with project partners.

3. Swarm electrification

3.1. The concept

Introduced in 2014 by Groh et al. (2014b), the SE concept starts with individual SHS units linking to form a swarmgrid. The system expands by integrating new members or technologies, progressing through electrification levels, as depicted in the multi-tier framework by Bhatia et al. (2014). The multi-tier approach captures several dimensions of energy access, showing that access to electricity cannot exclusively be measured in binary terms, but rater gradually. At tier 1 the access is defined as "very low power" for 4-8 hours during a day, but inadequate capacity for primary cooking solution. At tier 5 the access is defined as "high power" for above 22 hours of a day and including adequate capacity for primary cooking solutions. Groh et al. (2015) demonstrates SE's superiority over centralized minigrid planning, particularly in managing demand growth and avoiding oversized or undersized systems, as discussed in Koepke et al. (2016). The methodology in SE is analogous to the principle of swarm intelligence, wherein each separate node contributes autonomous input, culminating in a collective output that surpasses the aggregate value of the individual components. Kirchhoff et al. (2016) develop mutual success factors for 100 % renewable energy communities in Germany and energy communities in off-grid areas for energy access in the Global South. The authors show that these success factors can also be found in SE. The three categories that were analyzed are: 1) ownership and participation, 2) technology and system design and 3) policy and financing. Both in the 100 % renewable energy communities in Germany as well as for the energy communities in the Global South, strong initiatives from users indicate a key role for bottom-up approaches. However, top-down mechanisms regarding technology design and standards have their

[1] https://www.ecomoyo.com/
[2] http://energica-h2020.eu/
[3] http://cuie.umss.edu.bo/

place in both settings. The long-term success of SE is based on evolutionary growth of a power system, where both bottom-up and top-down approaches merge.

The process of SE is divided in four phases, starting from the installation of off-grid SHS, the interconnection of off-grid SHS and connection of households without a system forming a microgrid. Further, it evolves to the interconnection of several households into a local minigrid and finally connecting the minigrid with the national grid as presented byGroh et al. (2014b) and Dumitrescu et al. (2020):

- Phase 1 - Stand-alone SHS
- Phase 2 - Interconnected households
- Phase 3 - Interconnected SHS and local grids
- Phase 4 - Local grids connected to national grids

The first phase is the initial starting point of SE with individual SHS implemented in some households in a village. The second phase of SE is where the first lateral connections are made between households giving some households a new income and other households additional access to electricity as presented by Fuchs et al. 2023. The third phase of SE starts when several households are connected to a local microgrid that is growing into a local minigrid, requiring more coordination of the community than the previous phases. Some common owned assets might be needed and operated at this stage. The fourth and last phase is when the local minigrid is interconnected with the national or regional grid. Naturally, this phase requires cooperation with the distribution system operator (DSO) and the transmission system operator (TSO).

3.2. Terminology

When defining such steps in SE, a categorization of the terms nano-, micro-, and mini-grid is necessary. Such was proposed through the International Renewable Energy Agency (IRENA) by Kempener et al. (2015) and is shown in table 1. The terms nano-, micro- and minigrid have also been used to describe phase 2, phase 3 and phase 4 in SE, respectively, by Richard et al. (2022b). Figure 2 visualizes the four phases and shows the different names and terms found in literature for the phases.

The different phases in SE represent already known energy system concepts. Microgrids is a widely used term, as are integrated community energy systems, renewable energy communities, citizen energy communities or local energy communities. In Koirala et al. (2016) the authors investigate the terms and concepts of community microgrids, virtual power plants, energy hubs, prosumer community groups, community energy systems, and integrated community energy systems. Subsequently, the authors introduced a comprehensive concept for integrated community energy systems. The terms renewable energy communities and citizen energy communities with official definition have been issued by the European Union The European Commission 2018, The European Commission 2019.

Table 1: Proposed grid categories by IRENA

Picogrid	0-1 kW	Single controller	Single voltage
Nanogrid	0-5 kW	Several controllers	Single voltage bus
Microgrid	5-100 kW	Several controllers	Several voltages and buses
Minigrid	0-100000 kW	Several controllers	Several voltages up to 11kV

Hernandez-Matheus et al. (2022) offer an extensive literature review on local energy communities (LEC) and machine learning techniques, initially outlining the concept of LECs through a novel definition of five distinct criteria:

1. Locality
2. Energy sustainability
3. Community engagement
4. ICT
5. Transactions

These criteria are used to identify if a phase of SE constitutes a LEC using the definitions stated in Hernandez-Matheus et al. 2022. The result is presented in Table 2. The first and second phase of SE does not fulfill all the five criteria for LEC. In the first phase the community members do not cooperate on providing energy, therefore no transactions are present. In the second phase, ICT solutions for energy sharing and transactions enabled by Pay-As-You-Go (PAYG) can be present. Yet, this does not suffice to classify phase two as a LEC, due to the absence of broad community engagement. Clearly, phases three and four qualify as LECs, with phase three being an off-grid LEC and phase four being an on-grid LEC.

Table 2: Swarm electrification and local energy communities

SE phase	Locality	Energy Sust.	Com. Engage.	ICT	Transactions
1 Stand-alone SHS	✓	✓	x	✓	x
2 Interconnected households	✓	✓	x	✓	✓
3 Interconnected SHS and local grids	✓	✓	✓	✓	✓
4 Local grids connected to national grids	✓	✓	✓	✓	✓

Placing SE into perspective of these power system terms, it is obvious that SE defines a process of electrification, while most of the existing terms describe a certain state or type of the power system. When first introduced by Groh et al. 2014b SE was defined as: "Individual stand-alone energy systems are linked together to form a microgrid that can expand towards and eventually interconnect with national or regional grids." Groh et al. 2015 presented the four phases of SE for the first time. In another publication Groh et al. 2014a formulates: "SE is based on nodes in a swarm intelligence network where information and electricity flows are shared among neighbors to achieve a compounding network effect, in that they are linked together to form a microgrid – to achieve a networked grid effect." In a recent comprehensive literature review on SE by Sheridan et al. 2023 the concept is described as follows: "SE is a relatively new concept, gaining considerable attention as a tool to provide last-mile electrification. A swarmgrid is like a micro-grid, but rather than a planned network, it is assembled in an ad-hoc manner, connecting available equipment and growing organically as

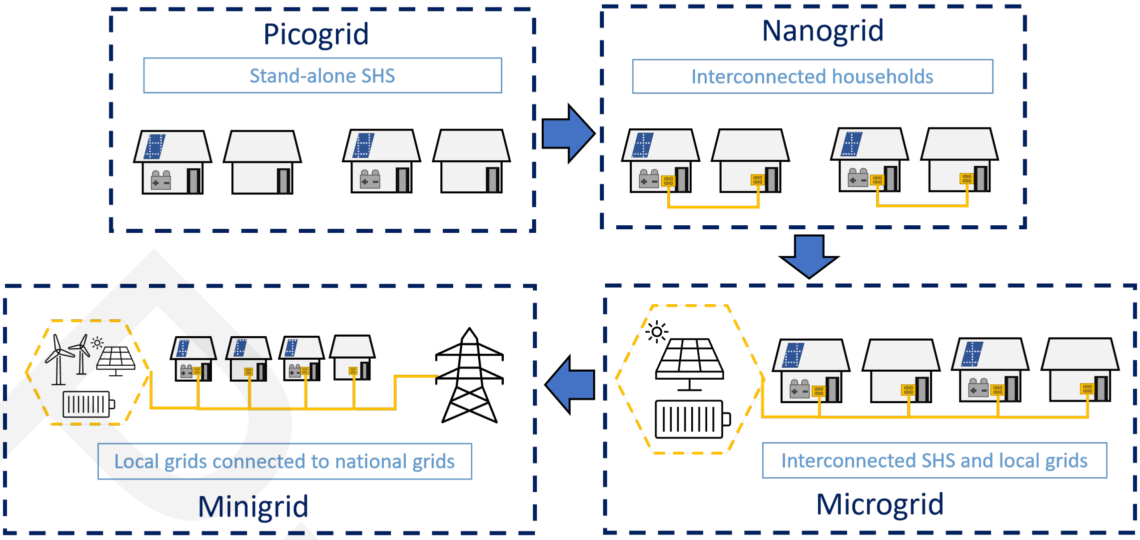


Figure 2: Swarm electrification with four phases and different names used in literature.

more resources become available mitigating the capital expenditure required for a community grid." Although these formulations capture parts of the capabilities of SE, none of these formulations pinpoint the essence of the concept. Therefore we suggest a new definition of SE as follows:

> **Swarm electrification** is the process of incrementally creating a power network from the bottom up. It begins with individual solar home systems that connect to form a decentralized microgrid, which can then expand and potentially link with larger regional or national grids. The approach is characterized by its modularity, scalability, and focus on prosumers - users who both produce and consume energy. The strength of swarm electrification lies in energy sharing among participants, embodying the principles of swarm intelligence where the collective capabilities exceed those of individual components. Although primarily associated with rural electrification in developing countries, the concept is applicable beyond these settings.

3.3. Companies

Seven companies have started to develop and implement technology that enables SE for energy access. Table 3 lists the companies found by the authors of this paper. It is noticeable that four out of seven companies started in 2014/2015, which are Solshare, PowerBlox, Okra Solar and Meshpower. While Solshare, Okra Solar and Meshower focused on the energy sharing technology, PowerBlox is providing a combined solution of energy sharing and storage. In 2017 Nanoé and Wattero started. Wattero delivered an energy sharing solution based on blockchain, but only excecuted a couple of pilot projects before the company resigned. Nanoé not only developed a smart energy sharing controller, but also developed a whole business model for SE or as they call it "lateral electrification". The business model involves a franchise set-up with local entrepreneurs that operate and run the nanogrids. Finally, BBOXX recently developed their own enrgy sharing unit for SE, however their main business has been PAYG solutions for a long time.

Table 3: Swarm electrification companies

Company	Year	Countries	References
Solshare	2014	Bangladesh	Groh et al. (2014a), Groh et al. (2014b), Groh (2015), Groh et al. (2015), Magnasco et al. (2016) Kirchhoff et al. (2016), Koepke et al. (2016), Dumitrescu et al. (2020), Groh et al. (2022),
Meshpower	2014	Rwanda	Soltowski et al. 2019, Beath et al. 2023
PowerBlox	2015	Africa, Indonesia	Nzalé 2020
Okra Solar	2015	Haiti, Cambodia, Nigeria, Philippines	Prevedello et al. 2021 Zyl 2022
Nanoé	2017	Madagascar	Richard et al. (2022a), Richard et al. (2022b) Bertram et al. 2023
Wattero*	2017	Ivory Coast	Norwegian SEC (2019)
BBOXX	2019	Rwanda	Soltowski et al. (2018), Soltowski et al. (2019) Soltowski et al. (2022),

* Not operating anymore

3.4. Challenges

Groh et al. (2014a) outlines the escalating challenges in (SE) across its four phases, with complexities arising from increased participant and asset diversity, potential topologies, control options, and conflicting interests. This complexity poses significant challenges for planners, ranging from technology providers, or Distributed Energy Service Companies (DESCO) to governments and none-governmental organizations, in terms of system dimensioning, growth prediction, and effective engagement. The heterogeneous goals of participants and unknown variables further complicate planning, making simulation and optimization of SE difficult. Fuchs et al. 2023 highlights decisions individuals face regarding system size, connectivity, and electricity trading.

Operationally, SE relies on integrated automated and decentralized controls, with planners contending with demand variability and renewable energy's unpredictability. Accurate projections and data are crucial to avoid unnecessary investments, while understanding flexible resources and demand is key in managing the dynamic nature of the system. Technical hurdles identified by Sheridan et al. (2022) include overloading risks, system complexity, appliance limitations, DC networks, and the need for communication layers. These challenges emphasize the need for interoperability in decentralized energy systems, ensuring secure and efficient data exchange across diverse components for specific objectives.

3.5. Opportunities

SE stands out by offering more than just electricity access. Faster electrification is enabled by individual SHS as highlighted by Norwegian SEC (2019). SE allows for cost savings through shared access and efficient system use, and is recognized for its reliability and service level improvements by Hoffmann et al. (2019) and Narayan et al. (2019). Its scalable design accommodates demand growth, avoiding oversizing and reducing initial costs, thus lowering entry barriers and investment risks.

Especially in regions with unstable grids, SE enhances electricity reliability and supports local economies, as shown by Babajide et al. (2020), with a focus on renewable energy that aligns with SDG7. Sheridan et al. (2022) summarizes its benefits: energy trading opportunities, income generation for asset owners, deployment flexibility, utilization of existing infrastructure to avoid stranded investments, capital expenditure reduction, lower energy costs, and increased system resilience through redundancy and decentralization.

4. The 3Ds

SE is a concept that highly relies on the latest technological and policy changes, which led to an evolution of the existing electricity systems during last decades. This evolution can be summarized via the 5Ds described by Cali et al. (2021): Deregulation, Decentralization, Decarbonization, Digitalization, Democratization. Moghaddam et al. (2022) delve into the impact of theses global trends, examine the challenges currently confronting existing power infrastructures and underscore the opportunities arising from the emergence of these trends within the power system landscape.

Deregulation and the advances in distributed renewable energy technologies lead to a more decentralized power system. The integration of renewable energy into the power system results in a slowly but steadily necessary decarbonization process. But a new challenge arises: The variability of renewables, requiring more advanced balancing and stability technologies for power systems. This need provoked the digitalization of power systems by introduction of sensors and automized grids, the use of internet of things (IoT) , artificial intelligence (AI) for data analysis and optimizing and distributed ledger technology (DLT) for decentralized operation, interaction, trade and finance. Step by step all these transformation stages lead to a more democratized power system, where consumers become active participants as prosumers and power asset owners.

4.1. Decentralization

"Can developing countries leapfrog the centralized electrification paradigm?" This question was asked by Levin et al. 2016 in a extensive cost study comparison of rural electrification with SHS compared to national grids. They look at 3 different regions in sub-Saharan Africa. Their findings indicate that SHS could significantly contribute to the universal provision of basic energy services. The impact of SHS on achieving this goal is influenced by three main factors: the costs of SHS, the expenses associated with grid expansion, and the costs of centralized generation. Moner-Girona et al. 2019 demonstrate in their study how decentralized rural electrification in Kenya could speed up universal energy access. The national rural electrification master plan in Kenya estimates the expenses associated with expanding the current power infrastructure. It predicts an average connection cost of 620 EUR, based on an assumed annual average electricity consumption of 350 kWh. According to the authors the investment required for a 50 Wp SHS in Kenya, capable of meeting the 350 kWh/year demand, varies between 150 EUR and 200 EUR. These concrete economic benefits highlight the potential of decentralized methods in achieving affordable solutions in rural electrification.

Decentralization in developed countries has been driven by deregulation and technological advances. The situation is different i none-electrified areas in developing countries where specific rules regarding regulation of the power systems do not yet exist. However, the extraordinary development and growth of renewable energies, especially photovoltaic (PV) systems in combination with battery storage gave the none-electrified areas in the world a chance to get easy and fast access to small amounts of electricity demonstrated by Norwegian SEC (2019). SHS started on a incredible rise and helped to reach the last-mile energy access where all other technologies failed. This led to a large adoption of SHS during the last years with a continuing increase each year IEA (2022). This purely decentralized energy access is the starting point for SE. To reach higher degrees of energy access at a still low cost, the most efficient and cost beneficial way is to interconnect the existing SHS and

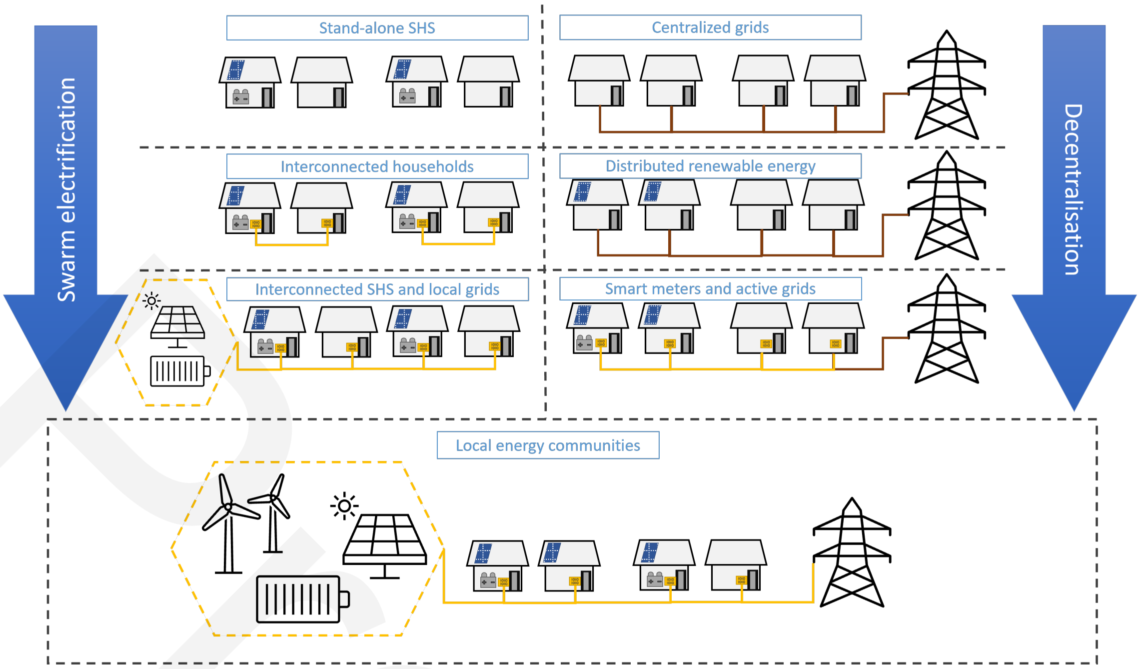


Figure 3: Swarm electrification and decentralization of power systems in several steps side by side. Both processes can potentially end with the same results: Local energy communities (LEC).

share surplus energy according to Narayan et al. (2019). The process of SE reaches the same final stage as the decentralization process of power system in developed countries. Figure 3 sets both these processes side by side and demonstrates how the power system decentralization in developed countries and the decentralized rural electrification method of SE end in the same equilibrium, namely grid-connected LEC.

4.2. *Decarbonization*

While centralized power system generation often is related to fossil power generation, the decentralized solutions are mainly related to renewable energy generation, strongly relating decentralization to decarbonization.

According to Dagnachew et al. (2020) close to 900 million individuals in Sub-Saharan Africa depend on conventional cooking techniques. The authors argue that reliance on traditional biomass exerts considerable pressure on both local and global ecosystems, causing deforestation, forest degradation, soil erosion, and soil degradation. The burning of biomass, such as firewood and coal, also contributes to climate change through emissions of black carbon gas. Transitioning to clean cooking methods would, therefore, yield social, environmental, and health benefits, supporting the objectives of SDG 7.

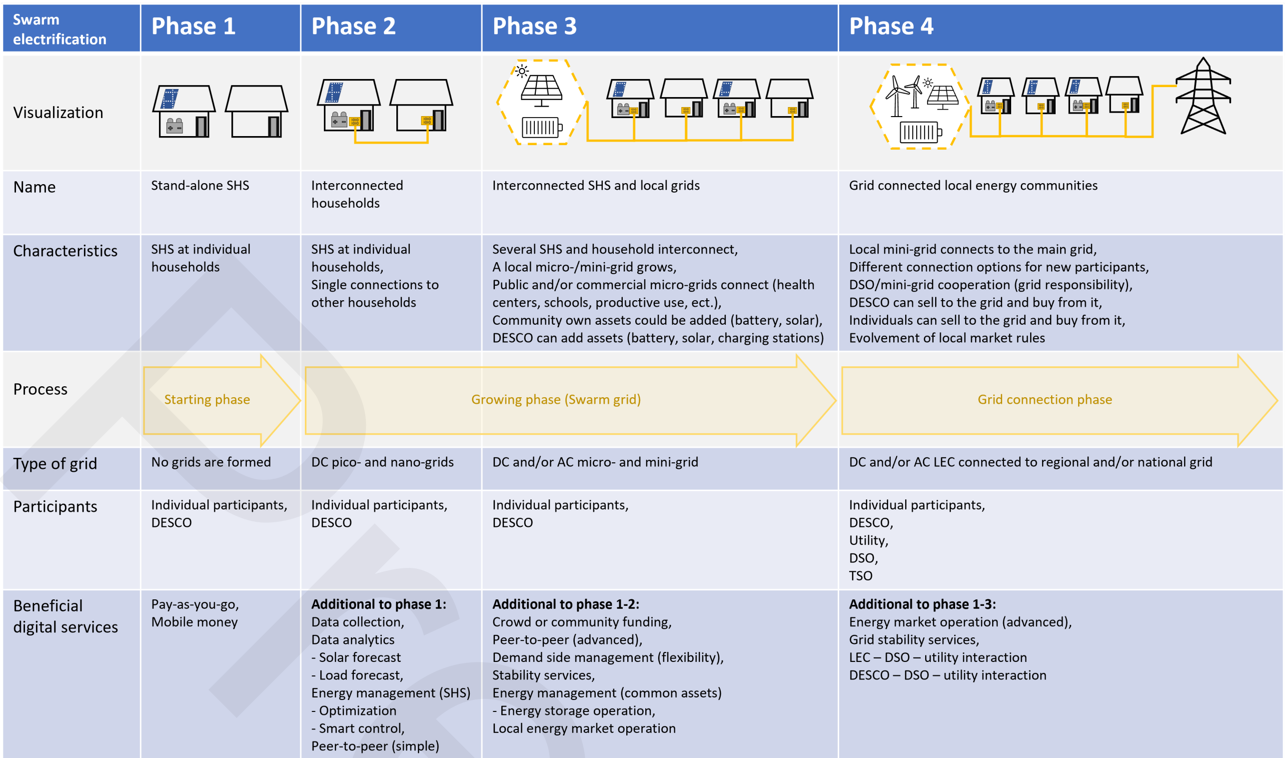
Maji (2019) investigate the effects of renewable energy and inclusive development on CO2 emissions. Data from 42 sub-Saharan countries reveals that renewable energy significantly indirectly influences CO2 emissions, suggesting that an increase in the use of renewable energy will lead to a reduction in CO2 emissions within the region.

Moner-Girona et al. 2019 show the Rural Electrification Master Plan in Kenya suggesting that 78% of the anticipated capacity in remote off-grid areas will rely on diesel-based minigrids. There renewables will play a minor role, with wind energy constituting 17% and solar PV less than 5%. The author's model's analysis of additional decentralized renewable energy alternatives indicates the potential for substantial annual CO2 eq emissions savings—up to 620,000 tonnes, when compared to the use of diesel generators.

Antonanzas-Torres et al. (2021) analyzed the environmental impact of SHS in Sub-Saharan Africa. Emission factors for greenhouse gases (GHG) from SHS were compared to those from different electrification methods, including national grids, entirely PV, and hybrid PV-diesel off-grid mini grids, as well as off-grid diesel generators. In most cases, SHS showed GHG emission factors on par with those from PV-based mini grids and significantly lower than those from Sub-Saharan Africa national grids and diesel generators.

4.3. *Digitalization*

The digitalization of the power system offers increased opportunities for the energy access problem and rural electrification. It can improve the access to clean and reliable electricity in remote areas with no grid or an unreliable grid connection demonstrated by Pittalis et al. 2023. Mantellassi et al. (2019) presents case studies from emerging countries where different digital technologies were used for energy access, micro- and mini-grids in rural areas. Among the digital technologies were IoT and connected smart objects, smart meters, mobile and 5G, wireless connections, big data analysis and AI and finally DLT/blockchain. In the case studies they use digital technologies for example for smart control of micro- and mini-grids, demand forecasting and demand side management, operation



Swarm electrification	Phase 1	Phase 2	Phase 3	Phase 4
Visualization				
Name	Stand-alone SHS	Interconnected households	Interconnected SHS and local grids	Grid connected local energy communities
Characteristics	SHS at individual households	SHS at individual households, Single connections to other households	Several SHS and household interconnect, A local micro-/mini-grid grows, Public and/or commercial micro-grids connect (health centers, schools, productive use, ect.), Community own assets could be added (battery, solar), DESCO can add assets (battery, solar, charging stations)	Local mini-grid connects to the main grid, Different connection options for new participants, DSO/mini-grid cooperation (grid responsibility), DESCO can sell to the grid and buy from it, Individuals can sell to the grid and buy from it, Evolvement of local market rules
Process	Starting phase	Growing phase (Swarm grid)		Grid connection phase
Type of grid	No grids are formed	DC pico- and nano-grids	DC and/or AC micro- and mini-grid	DC and/or AC LEC connected to regional and/or national grid
Participants	Individual participants, DESCO	Individual participants, DESCO	Individual participants, DESCO	Individual participants, DESCO, Utility, DSO, TSO
Beneficial digital services	Pay-as-you-go, Mobile money	**Additional to phase 1:** Data collection, Data analytics - Solar forecast - Load forecast, Energy management (SHS) - Optimization - Smart control, Peer-to-peer (simple)	**Additional to phase 1-2:** Crowd or community funding, Peer-to-peer (advanced), Demand side management (flexibility), Stability services, Energy management (common assets) - Energy storage operation, Local energy market operation	**Additional to phase 1-3:** Energy market operation (advanced), Grid stability services, LEC – DSO – utility interaction DESCO – DSO – utility interaction

Figure 4: Characterization of swarm electrification and beneficial digital services.

and maintenance tasks, PAYG solutions, improved asset performance, energy forecasting, and energy procurement. Figure 4 characterizes the different phases of SE and summarizes its required digital services that enable the growth of a swarmgrid. While phase 1 represents the starting phase, and phase 4 is final stage that is similar to integrated local energy communities, we can find the growth of the actual swarmgrid in the combined phase 2 and 3.

5. Digital technologies

Digitalization in power systems is unfolding before our eyes. It all kicked off with ICT, bringing computers, telecommunication, sensors, and data collection to the forefront. This initial stage, often tagged as smart grid technologies in the power sector, has been thoroughly explored in literature and practice, as highlighted by IRENA 2019. We're now stepping into the next phase, dubbed Deep Digitalization by Cali et al. (2021). This stage puts a spotlight on digital technologies like DLT, including blockchain, and AI, notably ML, as key drivers toward achieving a secure, cost-effective, and eco-friendly energy system.

5.1. ICT/IoT in energy access

The traditional digital technologies can offer several opportunities for electrification of emerging countries with solar energy as presented by Mantellassi et al. (2019), thus also viable for SE. One of the first game changer in energy access was mobile money enabled PAYG solutions, eliminating the high up-front cost through a cellular enabled micro-inverter demonstrated by Unger et al. (2011). IEA (2022) shows that it contributed to an increased deployment of SHS systems in developing countries worldwide. Adwek et al. (2020) and Yadav et al. (2019) present recent reviews of SHS in both Kenya and India and show that it still is the best financial option for SHS deployment. Thus, the digital technology solution PAYG is main enabler for phase one of SE.

Dumitrescu et al. (2020) explore the role of smart metering, ICT, and IoT within SE systems, highlighting a transition from off-grid SHS to interconnected SHS, and ultimately to national grid connectivity. They emphasize the ongoing benefits of SE's decentralized approach in rural electrification, aiding both ”close-to-the-grid” and ”weak-on-grid” populations, thus bridging bottom-up and top-down electrification initiatives.

Pittalis et al. 2023 investigates the emerging trends, benefits, and obstacles of remote monitoring for minigrids, highlighting its crucial role in boosting minigrid operational efficiency. Their study draws on firsthand data from seven minigrid developers, covering 49 PV hybrid rural minigrids across seven sub-Saharan African countries. They present a classification to highlight the advantages of remote monitoring over conventional methods and provide a cost-benefit analysis demonstrating potential operational cost savings up to 17% and an investment payback period of as little as one year.

Marahatta et al. (2021) address the challenges of deploying digital technologies in rural areas, notably the absence of reliable, affordable communication systems. They show the feasibility of using a Low Power Wide Area Network for smart metering, presenting star and meshed network topologies. However, limitations such as varying terrain and external noise were not accounted for in their simulation.

Demidov et al. (2020) introduce a novel solution to address connectivity issues by integrating electricity and connectivity into a single system. Their concept platform, tested in a lab and through a case study in Namibia, combines electricity provision with digital services, including a wireless internet connection via a 4G LTE Base Transceiver Station.

Effective communication between assets and stakeholders, alongside data collection and analysis, is essential for long-term planning and engagement with electricity network planners, power providers, and government entities. As an example, Groh et al. (2022) demonstrate phase 4 of SE, where intelligently interconnected groups of SHS and national grid infrastructure work together based on a new designed tariff, the Bangabandhu Tariff.

Although communication between the participants in the swarmgrid has advantages for the energy sharing, it is not necessary to enable it. Several examples in the literature suggest a communication-free control algorithm for nanogrids for example Richard et al. (2022a), Richard et al. (2022b), Nasir et al. (2019) and Kirchhoff et al. (2022). Energy sharing without the implementation of a marketplace or local energy market is handled based on the power flow in the swarmgrid and boundary conditions for voltage at the sharing bus and state-of-charge of the battery for the individual systems. Stability for the overall swarmgrid can be handled as Richard et al. (2022b) and Kirchhoff et al. (2022) show for real-world examples. However, the consumer or SHS owner that has little influence on the sharing conditions. The system shares energy between the units to benefit the overall swarmgrid, which could mean that some individual SHSs get a worse outcome with energy sharing, meaning a lower self-sufficiency ratio presented by Fuchs et al. (2022).

SE as a concept is not dependant on digitalization however it can benefit from it. Smart metering, ICT and IoT infrastructure for rural areas are the foundation of implementing the deep digitalization technologies DLT and AI. DLT and AI can improve the swarmgrid and help the concept to scale.

5.2. Deep digitalization with DLT/Blockchain

A distributed ledger is a consensus of replicated, shared, and synchronized digital data that is decentralized in various nodes. Blockchain is a type of DLT where transactions are recorded with an unchangeable cryptographic signature. This technology enables decentralisation and, therefore, democratisation of the power system. SE is a decentralized bottom-up approach of building a power system, which makes DLT an interesting technology to consider. Teufel et al. (2019) gives an overview of the areas and use cases related to the energy sector where blockchain can be used. Different technologies are quantified (which platform, which consensus, etc.). The advantages and disadvantages of using blockchain in energy systems are listed. Cali et al. 2022 presents a study to prioritise such cases of energy use for DLT according to specified criteria. In both studies the most interesting use cases for DLT in energy are:

- P2P Energy Trading
- Sustainability and Green Energy Certification
- EV Charging and E-Mobility
- Grid Management and Transactions
- E-Metering and Payment Settlement
- Energy Finance

Kuzlu et al. (2020) sketches the cyber-physical power system including DLT and lists companies that are already using such a platform. The paper provides a classification for what DLT can be used divided into the classical areas of power systems: generation, transmission, distribution, retail, prosumer/consumer. It highlights that P2P trade is the most suited application for DLT. For SE, where the individual households connect themselves to a local swarmgrid, P2P trade or any form of local transactions or a local energy market (LEM) for the members of the swarmgrid is a crucial part.

Zia et al. (2020) present a review on recent developments of DLT applications for LEM highlighting P2P and Community LEM as main types. Bjarghov et al. (2021) present an overview on developments in LEM, and conclude with specific research gaps in the fields of distribution of generation, integration of demand response, decentralization of markets, legal framework and social issues. The authors found that real life demonstrations of LEM show strong inclination towards centralized and hybrid topologies over fully decentralized. Although there is a strong foundation of theoretic literature on fully decentralized markets, there is a research gap in applying such in practical settings.

Esmat et al. (2021) propose a two-layer system for P2P trade consisting of the market layer and the blockchain layer. For the market clearing process, they use a decentralized Ant-Colony Optimization, including inter-temporal dependency related to storage use. For the blockchain layer they use a permissioned blockchain based on Hyperledger. Although the authors show that the system simulation was successful, they show several limitations that still need to be addressed, for example the uncertainty of the prosumers commitment to the market results, the intermittency of renewable energy resources and therewith the handling of forecasting failures, but also the physical limitations of power flow constraints.

Noor et al. (2018) propose a cyber-physical system with demand side management (DSM) based on game theory and DLT based on a Zig-ledger blockchain which is tested on a hypothetical system of 15 households of 3 categories. By trading and DSM, they can smoother the demand curve by reducing the peak-to-average ratio and the dips during outages.

Siano et al. (2019) present a review of existing solutions for the energy trade of prosumers and active consumers based on DLT. The authors propose a three-layer transactive management infrastructure to be implemented in LEM. In this setting the paper provides a proposal for the consensus protocol in DLT, and it suggests a Proof-of-Energy as a new concept for P2P trade. The advantage is that it is not energy demanding as other consensus protocols. It is based on proof-of-stake, and it requires a permissioned chain.

Christidis et al. (2021) describes a performance analysis of a blockchain in a real case. Different configurations of a permissioned blockchain based on Hyperledger with a Byzantine Fault Tolerance as consensus is tested on 63 houses with solar generation that participate in the trade. The configurations where data slicing is done per transaction, perform significantly better than the one where it was done per slot. The blockchain is not a black-box but described, performance tested and even open-sourced.

Yang et al. 2022 proposes a hierarchical blockchain system set up based on Ethereum platform using a Proof-of-Authority method. The study demonstrates the effectiveness of blockchain technology in safeguarding distributed control systems from false data injection attacks. It conducts a test on a microgrid consisting of four prosumers. The authors present that blockchain calculations require up to $30W$ which seemed insignificant to their study, but for SE with first energy access it is important to consider.

Dong et al. 2022 introduce a strategy for trading energy within a blockchain framework. A Stackelberg game is applied to create a dual-layer model for the purpose of price determination. The authors introduce a fast Practical Byzantine Fault Tolerance (f-PBFT) algorithm achieving efficient consensus in P2P energy trading by assuming the majority of user nodes in the consortium chain are trustworthy. The authors test their method with 10 prosumer households.

Hardjono et al. (2020) examines the critical role of interoperability in decentralized energy systems, proposing a framework for blockchain networks to enhance system resilience and control. Coll-Mayor et al. (2023) further explores the challenge of achieving interoperability with DLT-enabled devices in the energy sector, categorizing DLT-energy use cases and advocating for a universal reference architecture to ensure seamless integration.

Kulkarni et al. (2020) outline various electrification challenges in rural Indian areas from a consumer perspective, including affordability, billing irregularities, high connection costs, unreliable power supply, and low electricity demand due to minimal appliance use. They suggest a blockchain-based smart grid for energy trading and smart metering, although this proposal lacks practical testing.

Ledwaba et al. (2021) examine the viability of a blockchain enabled energy market in a South African microgrid. Their experiments on a Raspberry Pi 3 reveal that while blockchain processes don't interfere with basic operations, they are unsuitable for real-time applications and could increase costs and affect scalability. These findings highlight the need for further research on DLT in rural swarmgrids.

Baig et al. 2022 details a cost-effective, open-source P2P energy trading system designed for a geographically isolated community in Pakistan. The system uses a local Ethereum blockchain and IoT devices on a Raspberry Pi 4 Model B for managing energy resources. Essential functions such as energy transfer, data monitoring, and blockchain ledger maintenance are efficiently performed, with the entire system demonstrating significant energy efficiency: the central and IoT servers, along with the communication channels, consume a fraction of the energy compared to similar systems, specifically one third of the $30W$ usage reported by Yang et al. 2022.

Demidov et al. 2023 presents a study from Namibia on managing energy in community-based off-grid microgrid systems. Their system combines energy estimation for different times of day, a P2P energy market, and blockchain for secure transactions. The evaluation used a model with real power data and historical weather conditions from a Namibian microgrid project. Developed with Python, the Energy Management System integrates smoothly for field testing. Its blockchain setup, essential for transparency and security in remote areas, consists of six local nodes, including five users and an energy provider.

Condon et al. 2023 focus on creating a P2P energy trading platform, leveraging IoT and blockchain technology. Utilizing Chainlink oracles and a private Ethereum blockchain, it enables energy trading through smart contracts and an open auction mechanism. Tested in Valparaiso, Chile using real household energy data and AWS cloud storage, the study confirms the platform's effectiveness in supporting local energy trading.

Shibu et al. 2024 introduces a strategy for power recovery after outages centered around microgrids, utilizing blockchain smart contracts and optimization methods for P2P energy. The study presents an incentive system to encourage prosumers to participate in restoration efforts during power disruptions. This method aims to lessen the adverse effects of power disruptions by offering dependable and community-focused power recovery options. They authors validate their model by actual data from a 13-node distribution grid test bed at their university in India. This method is extremely relevant for SE in phase 4 when the swarmgrid connects to the main grid, where the swarmgrid can utilize the recovery during outages of the main grid.

Summarizing the DLT review, it is apparent that numerous studies propose DLT, particularly blockchain, as a viable solution for transactions and, more specifically, for P2P energy trading within power systems. However, there is a noticeable scarcity of research exploring various blockchain architectures and evaluating their performance in real life cases. This need is especially critical in the context of rural electrification, where the challenges of limited communication infrastructures and energy resources make the performance of such technologies even more pivotal. An evaluation of the prospects and hurdles for deploying DLT technology in Sub-Saharan Africa by Andriarisoa et al. 2023 indicates that its development is still in the nascent stages within the region. Opportunities are identified in the form of decreasing costs for stand-alone solar technology and growing investments in the minigrid sector. Conversely, significant challenges include limited private sector involvement in the minigrid area, the complexities of regulatory procedures and licensing prerequisites, complications with the tariff system, and the regulatory uncertainty concerning future grid integration. Table 4 summarizes the relevant use case examples in literature demonstrating the potential and maturity of DLT as technology.

For SE P2P energy sharing is the backbone of the whole concept and becomes crucial in phase 3 when a decentralized swarmgrid is established and growing. Additionally, decentralized billing is a valuable technology for the concept. Table 5 presents our evaluation of the importance of the use cases for

DLT found in literature and combined with field experience for the SE phases.

Table 4: DLT/Blockchain for swarm electrification - phase 3 - swarmgrid

Ref.	Year	Application	Technology	Attributes	Key content and case study
Noor et al. (2018)	2018	P2P platform	Zig-Ledger	Permissioned	Simulation of trading between 15 households
Siano et al. (2019)	2019	P2P platform	Any chain	Permissioned	Proposing Proof-of-Energy as consensus protocol
Esmat et al. (2021)	2021	P2P platform	Hyperledger	Permissioned	Simulation of trading between 17 nodes
Christidis et al. (2021)	2021	P2P platform	Hyperledger	Permissioned	Simulated performance analysis with 63 households
Ledwaba et al. (2021)	2021	P2P platform	Ethereum	Permissionless	Test of blockchain performance on Raspberry Pi
Yang et al. (2022)	2022	P2P platform	Ethereum	Permissioned	Test of blockchain in real-time simulator with 4 prosumers
Baig et al. (2022)	2022	P2P platform	Ethereum	Permissioned	Test of blockchain on real-life case with 10 households
Dong et al. (2022)	2022	P2P platform	Ethereum	Permissioned	Test of blockchain with simulation of 10 prosumer households
Demidov et al. (2023)	2023	P2P platform	Ethereum	Permissioned	Test of blockchain with simulation of 5 households with real data
Condon et al. (2023)	2023	P2P platform	Ethereum	Permissioned	Test of blockchain with simulation of 1 households with real data
Shibu et al. (2024)	2024	P2P platform	Hyperledger	Permissioned	Test of blockchain for outage recovery with real case of 13 nodes

Table 5: Degree of value of blockchain application areas in SE phases

DLT application	SE Phase 1	SE Phase 2	SE Phase 3	SE Phase 4
P2P energy trading	low	medium	high	high
Sustainability and Green Energy Cert.	low	low	low	medium
EV charging and E-Mobility	low	low	medium	medium
Grid management and Transactions	low	low	medium	high
E-Metering and Payment Settlement	low	medium	high	high
Energy Finance	low	low	medium	medium

5.3. Deep digitalization with AI/ML

AI is the ability of a computer-controlled machine to do advanced tasks that require intelligence. ML is a subcategory of AI that defines the self-learning of a machine from given data and the application of that learning without further human intervention. It is specifically useful to make decisions based on large amount of data, so called big data. It can be used for many different applications. ML is based on the development of computer systems and their ability to learn from data without following explicit instructions. Through algorithms and statistical models, the computer can analyze data, find patterns, and draw conclusions.

In section 3 it was shown that SE phase 3-4 are equivalent to LEC according to the five criteria established in Hernandez-Matheus et al. (2022). The same authors present a comprehensive review of ML techniques improving LEC, subsequently also apply for SE. The ML techniques are clustered, described and allocated to suitable application areas in LECs:

- Forecasting of generation, demand, flexibility, and price
- Storage Optimization
- Demand response
- Energy management system
- Power quality, security, and stability
- Energy Transactions

In SE the timing of relevance of these applications varies. During the first phases the most relevant applications are those matching demand and supply, which means demand and generation forecasting combined with DSM. The value of the listed ML applications may vary based on the main functionalities and complexity level of each SE phase.

Ahmad et al. (2020) present a review of different algorithms for short-, medium- and long-term forecasting. They explore different ML algorithms, ensemble-based approaches, and artificial neural networks. The paper focuses on methods for forecasting renewable energy and load demand for a planning point of view. Allee et al. (2021) predict the initial electricity demand for off-grid rural communities in Tanzania using both customer survey data and ML methods. Huang et al. (2019) shift focus to short-term operational forecasting by introducing a deep convolutional neural network model for predicting PV power, outperforming traditional forecasting methods. Markovics et al. (2022) compare 24 different ML techniques for PV short-term forecasting tested in 16 PV systems in Hungary. The results show that the most accurate predictions come from the methods kernel ridge regression and multilayer perceptron.

Peña et al. 2023 propose a monitoring system with power forecasting capability to enhance the safety and reliability of microgrid operations. Forecasting of both load and generation can improve the optimization of a decentralized system, when using communication between the individual units. This is demonstrated by Gorla et al. 2023 in their recent study of decentralized renewable resource redistribution and optimization for beyond 5G Small Cell Base Stations. The study integrated a learning-based algorithmic framework to utilize decentralized energy flow control units for the preemptive optimization and redistribution of resources based on anticipated future demands.

Antonopoulos et al. (2020) review AI used for DSM. The authors do not only review scientific publications but also companies and industry projects. They show which methods are used for which applications in DSM. An example of a successful application of AI in active DSM is shown by Di Santo et al. (2018). The decision-making system is a validated neural network, trained with optimization data. Claessens et al. (2018) use convolutional neural networks for the dynamic control of residential loads. It successfully reduces the electricity bill of the modelled household. A peer-to-peer energy trading platform with the integration of ML for energy trading strategies is presented by Jamil et al. (2021). The trading strategies are based on deep learning approaches. The platform is tested in 16 years of real world data. Chen et al. (2019) presents trading strategies with deep reinforcement learning to overcome the challenges of dealing with uncertain variables such as renewable generation and load demand.

Looking more into literature that present AI and ML in a rural electrification setting, it can be found that ML is mainly applied for forecasting of demand and therewith improving DSM. Mbuya et al. (2019) propose an approach for short-term day-ahead load forecast in rural hybrid microgrids in emerging countries. They focus on testing different feature selection methods for forecasting, and they conclude that a combination of several methods gives the best results for their cases. Moradzadeh et al. (2020) explores short-term load forecasting in rural microgrids using a hybrid model, combining Support Vector Regression (SVR) and Long Short-Term Memory (LSTM) networks. Focusing on a rural African microgrid, the model accounts for various residential and commercial loads. The combined model outperforms standalone SVR and LSTM models.

Wang et al. (2021) introduce a ML algorithm for anomaly detection in demand to enhance supply reliability in a Tanzanian microgrid, supporting effective DSM and local energy utilization. Halden et al. (2023) reviews common power system anomalies, offering a detailed classification and analysis of identification methods, emphasizing consumer to producer levels and the use of AI for detection in power systems and markets. Mehra et al. (2016) delve into demand analysis with activity-based load forecasts using classification and clustering algorithms to identify appliance use without additional sensors, improving load forecasting through insights into consumption patterns.

As a conclusion of the section on ML one can say that the ML methods needed for SE are widely covered in literature and Table 6 summarizes relevant examples. However, the full po-

Table 6: AI/ML for swarm electrification

Ref.	Year	Application	Technology	Attributes	Key showcase
Mehra et al. (2016)	2016	Forecasting demand	Activity-based	Classification	3 rural households
Di Santo et al. (2018)	2018	DSM	Neural network	Validated	Two productive load profiles
Claessens et al. (2018)	2018	DSM	Neural network	Convolutional	400 Thermostatically Controlled Loads
Chen et al. (2019)	2019	Energy transactions	Deep learning	deep Q-network	Tested on 100 household data for hourly one year data
Huang et al. (2019)	2019	Forecasting PV	Neural network	Convolutional	24-h forecasting of PV power output
Mbuya et al. (2019)	2019	Forecasting demand	Feature selection	short-term	load for 10kW hybrid micro-grid
Moradzadeh et al. (2020)	2020	Forecasting demand	Support vector	short-term	50-100 households load profiles
Jamil et al. (2021)	2021	Energy transactions	Deep learning	Long-Short-Term	116189 energy consumption data points for 16 years
Allee et al. (2021)	2021	Forecasting demand	Several	long-term	Data from 1378 mini-grid customers
Wang et al. (2021)	2021	Anomaly detection	Support vector	None-intrusive	40 household microgrid in rural Tanzania
Markovics et al. (2022)	2022	Forecasting PV	24 methods		Tested on 16 PV systems with 2 year 15 min data
Peña et al. (2023)	2023	Forecasting PV	Neural network	Multi perceptron	Tested for ten days at the laboratory.
Gorla et al. (2023)	2023	Forecasting PV/demand	Neural network		A 3 nodes system is tested

Table 7: Degree of value of ML application areas in SE phases

ML application	SE Phase 1	SE Phase 2	SE Phase 3	SE Phase 4
Forecasting	medium	medium	high	high
Storage Optimization	low	medium	high	high
Demand response	medium	medium	high	high
Energy management system	low	low	medium	high
Power quality, security, and stability	low	low	medium	high
Energy Transactions	low	medium	high	high

tential of AI and ML on SE and swarmgrids is not demonstrated in neither literature nor practical examples. Table 7 summarizes our evaluation of the value of the ML applications for the different phase in SE.

6. Discussion and perspective

Digitalization plays a pivotal role in achieving optimal operation, control, and efficiency within an increasingly decentralized power system landscape and SE epitomizes this shift. Despite the clear application potential, the literature reflects a scarcity of studies on practical implementation of DLT and AI in rural contexts.

Even in the first phase of SE involving simple SHS or larger solar and battery off-grid setups, the utility of (ML) for forecasting is evident. Such forecasting facilitates DSM to efficiently allocate scarce resources, thereby minimizing unmet loads avoiding over-dimensioned systems. This was observed during a field trip to Eco Moyo Education Centre in Kenya, which required an off-grid system for daily operations. The absence of smart control and DSM based on forecasts led to a system designed to meet peak demands at all times. This resulted in a system that was frequently underutilized, with actual loads often amounting to only 2% of the system's capacity. The incorporation of ML-based forecasts for generation and load, coupled with ML-enhanced DSM, could have circumvented such over-dimensioning, by facilitating flexibility in the system as demonstrated by Dihle et al. 2023.

As SE matures, the relevance of ML-based forecasting for both generation and demand persists, with an added emphasis on battery optimization. Optimized energy storage management gains importance with the potential increase in battery cycles due to energy sharing. DLT can facilitate P2P energy trading within a local market and proves instrumental for energy metering and payment settlement. Companies such as Solshare and Wattero have integrated such technologies, while PowerBlox and Nanoé have focused on energy sharing based on technical parameters like voltage, frequency control, and battery state of charge. Nanoé is exploring the feasibility of establishing a P2P market for nanogrid operators highlighted by Bertram et al. 2023. Implementing such a market could incentivize participation in the swarmgrid's expansion and offer financial benefits to participants. In cases where a market is not established, the benefits of energy sharing tend to accrue to the technology provider, manifesting either as enhanced system efficiency which could translate into lower energy prices for end-users, or as increased financial returns for the provider.

SE witnesses varying impacts of deep digitalization technologies across different stages as summarized in Figure 5. In the Starting Phase optimal DSM based on precise forecasting of generation and demand emerges as a key benefit for individual participants. Here, an overall planner - be it a technology provider, a none-governmental organization or a utility - can leverage demand data and growth forecasts to strategize grid integration and expansion plans. Such a benefit is experience in the case study of Raqaypampa in Bolivia, that we have followed during this research. Dataloggers included in the SHS provide valuable information in demand and can help to plan the growth of a swarmgrid in the area.

As SE transitions into the Growth Phase, participants begin to interconnect, facilitating electricity trade potentially through blockchain technology, leading to the expansion of local minigrids and the integration of existing microgrids. Moreover, the intermediate phase sees the emergence of local energy planners as service providers, offering additional storage capabilities which, depending on the proximity to the grid, serve varying functions. ML is instrumental in optimizing storage management regardless of the grid's state. Blockchain technology enhances e-metering and payment processes, streamlining financial transactions in a manner that complements the widespread use of mobile money in developing regions - a synergy exemplified by Solshare's numerous projects.

As the system complexity escalates, cybersecurity, along with power quality, stability, and reliability, gains prominence, underscoring the critical role of ML in the advancement of SE.

7. Conclusions

This review delves into Swarm Electrification (SE) and its pivotal role in energizing rural areas, aligning with modern power system trends. Analyzing 88 sources and three case studies has deepened our insight. We discuss SE within the evolving landscape of power systems, highlighting its relevance to decentralization, decarbonization, and digitalization, and provide the following key insights:

- A refined definition that unequivocally differentiates swarm electrification from analogous concepts in the power systems domain, emphasizing its unique nature as a process.
- Both general power system decentralization and swarm electrification processes culminate in a unified outcome: the formation of local energy communities interconnected with larger grids.

Our spotlight on Distributed Ledger Technology (DLT), especially blockchain, and Artificial Intelligence (AI) with a focus on Machine Learning (ML), was essential in uncovering how these advanced technologies can play a game-changing role in SE. Characterized by its decentralized nature SE presents an ideal scenario for blockchain application, primarily facilitating Peer-to-Peer (P2P) transactions within the swarmgrid. Moreover, ML's capability in forecasting generation and demand significantly aids in Demand-Side Management (DSM) and optimizes storage utilization, showcasing the diverse benefits of digital technologies for both individual grid participants and overall planners. We conclude the following key aspects:

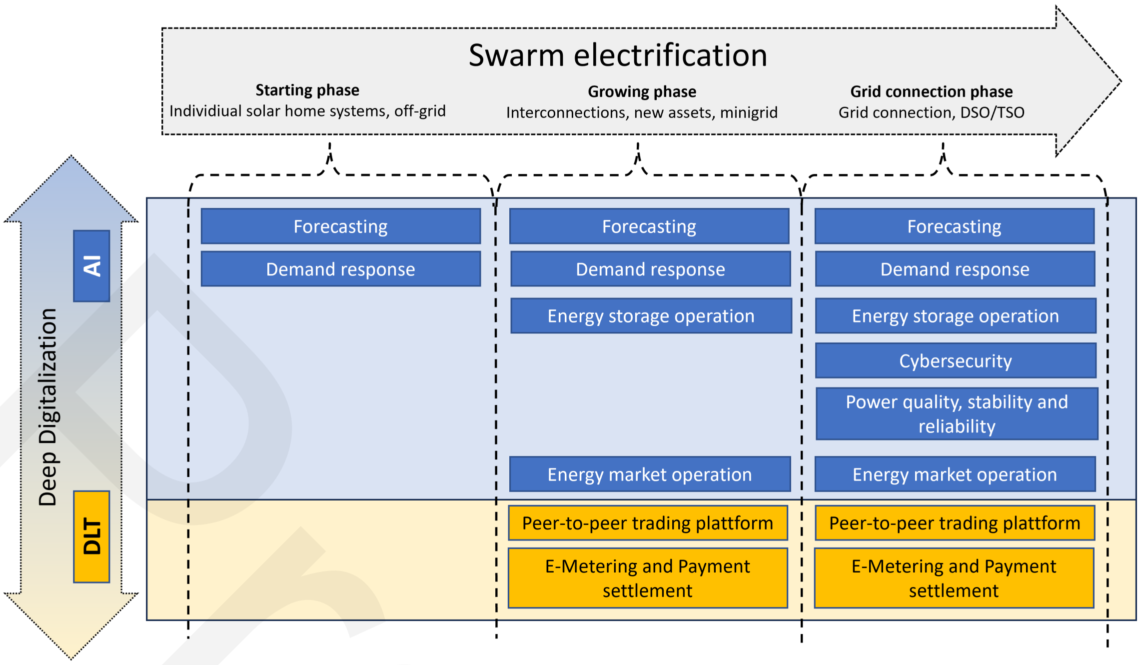


Figure 5: Swarm electrification phases and applications of digital technologies

- A comprehensive review of AI and DLT applications, identifying those of particular relevance to SE, thereby facilitating a targeted approach to integrating these technologies.
- A detailed examination and categorization of the applications, explicitly mapping out the timeline of their significance across the various stages of SE. This provides a clear framework for understanding when each application becomes critical in the evolution of swarm electrification.

The recommendation from this review is to leverage digital technologies as a cohesive force throughout the SE stages and to bridge the gap between local participants and centralized planners.

Future studies should concentrate on expanding the number of case studies to explore implementation issues and practical challenges associated with deep digital technologies in rural electrification settings.

Acknowledgement

We extend our deepest gratitude to the institutions and communities related to the case studies which greatly enriched the substance of this review. Our heartfelt thanks goes to Eco Moyo Education Centre in rural Kenya, which welcomed us during three insightful field trips from 2022 to 2024. The opportunity to observe and monitor the implementation of a new solar battery off-grid system, along with the repurposing of an older system, provided invaluable real-world insights.

Our appreciation extends to the Horizon 2020 project ENERGICA for facilitating our field research in rural Madagascar. The exploration of interconnected nanogrids in several villages not only broadened our understanding of sustainable energy solutions in remote areas but also underscored the significance of community engagement and capacity building in the success of such projects.

Furthermore, we are grateful to the Centro Universitario de Investigaciones en Energías at Universidad Mayor de San Simon (UMSS) in Cochabamba, Bolivia and the Académie de recherche et d'enseignement supérieur (ARES) in Belgium. The research exchange conducted at UMSS and the insights gained from the deployment of solar home systems in Raqaypampa have been instrumental in shaping our perspectives on rural electrification.

Declarations

Declaration of generative AI and AI-assisted technologies in the writing process: During the preparation of this work the author(s) used ChatGPT in order to improve language and write the initial code for plotting Figure 1. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Glossary

AI Artificial intelligence. 6–8, 10–13

DESCO Distributed Energy Service Company. 5

DLT Distributed ledger technology. 6–10, 12, 13

DSM Demand side management. 8, 10–12

DSO Distribution System Operator. 3

GHG Greenhouse gases. 6

ICT Information and communication technology. 3, 7, 8

IoT Internet of things. 6–9

LEC Local energy community. 3, 6, 10

ML Machine learning. 7, 10–12

P2P Peer-to-peer. 8, 9, 12

PAYG Pay-As-You-Go. 4, 7

PV Photovoltaic. 6, 7, 10

SDG Sustainable Development Goal. 1, 5, 6

SE Swarm electrification. 1–13

SHS Solar home systems. 1–3, 5–8, 12

TSO Transmission System Operator. 3

References

Adwek, George et al. (June 2020). *The solar energy access in Kenya: a review focusing on Pay-As-You-Go solar home system*. doi: 10.1007/s10668-019-00372-x.

Ahmad, Tanveer et al. (2020). "A review on renewable energy and electricity requirement forecasting models for smart grid and buildings". In: *Sustainable Cities and Society* 55.October 2019, p. 102052. issn: 22106707. doi: 10.1016/j.scs.2020.102052.

Allee, Andrew et al. (June 2021). "Predicting initial electricity demand in off-grid Tanzanian communities using customer survey data and machine learning models". In: *Energy for Sustainable Development* 62, pp. 56–66. issn: 23524669. doi: 10.1016/j.esd.2021.03.008.

Andriarisoa, Mirana Njakatiana et al. (2023). "Peer-to-Peer Energy Trading Using Blockchain in Sub-Saharan Africa: Towards a Policy and Regulatory Framework". In: *Energy Transition in the African Economy Post 2050*. doi: 10.4018/978-1-7998-8638-9.ch006.

Antonanzas-Torres, Fernando et al. (2021). "Environmental Impact of Solar Home Systems in Sub-Saharan Africa". In: *Sustainability* 13.17. issn: 2071-1050. url: https://www.mdpi.com/2071-1050/13/17/9708.

Antonopoulos, Ioannis et al. (2020). "Artificial intelligence and machine learning approaches to energy demand-side response: A systematic review". In: *Renewable and Sustainable Energy Reviews* 130.May, p. 109899. issn: 18790690. doi: 10.1016/j.rser.2020.109899.

Babajide, Abisoye et al. (2020). "Powering the Commercial Sector in Nigeria using urban swarm solar electrification". In: *Sustainability (Switzerland)* 12.10. issn: 20711050. doi: 10.3390/SU12104053.

Baig, Mirza Jabbar Aziz et al. (2022). "A Low-Cost, Open-Source Peer-to-Peer Energy Trading System for a Remote Community Using the Internet-of-Things, Blockchain, and Hypertext Transfer Protocol". In: *Energies* 15.13. issn: 1996-1073. url: https://www.mdpi.com/1996-1073/15/13/4862.

Beath, Hamish et al. (2023). "Maximising the benefits of renewable energy infrastructure in displacement settings: Optimising the operation of a solar-hybrid mini-grid for institutional and business users in Mahama Refugee Camp, Rwanda". In: *Renewable and Sustainable Energy Reviews* 176, p. 113142. issn: 1364-0321. doi: https://doi.org/10.1016/j.rser.2022.113142.

Bertram, Lea et al. (2023). "Peer-to-Peer Electricity Trading Between Nanogrids in Madagascar". In: *2023 IEEE PES/IAS PowerAfrica*, pp. 1–5. doi: 10.1109/PowerAfrica57932.2023.10363306.

Bhatia, Mikul et al. (2014). "Capturing the Multi-Dimensionality of Energy Access". In: *Livewire Knowledge Note Series*, pp. 1–8. url: http://documents.worldbank.org/curated/en/937711468320944879/pdf/88699-REVISED-LW16-Fin-Logo-OKR.pdf.

Bjarghov, Sigurd et al. (2021). "Developments and Challenges in Local Electricity Markets: A Comprehensive Review". In: *IEEE Access* 9, pp. 1–1. issn: 21693536. doi: 10.1109/access.2021.3071830.

Cali, Umit; et al. (2021). "Digitalization of Power Markets and Systems Using Energy Informatics". In: doi: https://doi.org/10.1007/978-3-030-83301-5.

Cali, Umit et al. (2022). "Prioritizing Energy Blockchain Use Cases Using Type-2 Neutrosophic Number-Based EDAS". In: *IEEE Access* 10, pp. 34260–34276. doi: 10.1109/ACCESS.2022.3162190.

Chen, Tianyi et al. (2019). "Realistic Peer-to-Peer Energy Trading Model for Microgrids using Deep Reinforcement Learning". In: *Proceedings of 2019 IEEE PES Innovative Smart Grid Technologies Europe, ISGT-Europe 2019*. doi: 10.1109/ISGTEurope.2019.8905731.

Christidis, Konstantinos et al. (2021). "A framework for designing and evaluating realistic blockchain-based local energy markets". In: *Applied Energy* 281.September 2020, p. 115963. issn: 03062619. doi: 10.1016/j.apenergy.2020.115963.

Claessens, Bert J. et al. (July 2018). "Convolutional Neural Networks for Automatic State-Time Feature Extraction in Reinforcement Learning Applied to Residential Load Control". In: *IEEE Transactions on Smart Grid* 9.4, pp. 3259–3269. issn: 19493053. doi: 10.1109/TSG.2016.2629450.

Coll-Mayor, Debora et al. (2023). "Distributed Ledger Technologies for the Energy Sector: Facilitating Interoperability Analysis". In: *IEEE Open Access Journal of Power and Energy* 10, pp. 593–604. doi: 10.1109/OAJPE.2023.3297199.

Condon, Felipe et al. (2023). "EnergyAuction: IoT-Blockchain Architecture for Local Peer-to-Peer Energy Trading in a Microgrid". In: *Sustainability* 15.17. issn: 2071-1050. doi: 10.3390/su151713203.

Dagnachew, Anteneh G. et al. (2020). "Scenario analysis for promoting clean cooking in Sub-Saharan Africa: Costs and benefits". In: *Energy* 192, p. 116641. issn: 0360-5442. doi: https://doi.org/10.1016/j.energy.2019.116641.

Demidov, Iurii et al. (2020). "System Platform Enabling Peer-to-Peer Electricity Market Model for Off-Grid Microgrids in Rural Africa". In: *International Conference on the European Energy Market, EEM* 2020-Septe. issn: 21654093. doi: 10.1109/EEM49802.2020.9221915.

— (2023). "Energy Management System for Community-Centered Off-Grid System with a Blockchain-Based P2P Energy Market". In: pp. 1–6. doi: 10.1109/EEM58374.2023.10161848.

Di Santo, Katia Gregio et al. (2018). "Active demand side management for households in smart grids using optimization and artificial intelligence". In: *Measurement: Journal of the International Measurement Confederation* 115.September 2017, pp. 152–161. issn: 02632241. doi: 10.1016/j.measurement.2017.10.010.

Dihle, Rikke Enger et al. (2023). "Flexibility in Solar and Battery Off-Grid Systems - Case Study Eco Moyo Education Centre in Kenya". In: *EU PVSEC 2023*. doi: 10.4229/EUPVSEC2023/5DV.2.5.

Dong, Jingya et al. (2022). "Decentralized peer-to-peer energy trading strategy in energy blockchain environment: A game-theoretic approach". In: *Applied Energy* 325, p. 119852. issn: 0306-2619. doi: https://doi.org/10.1016/j.apenergy.2022.119852.

Dumitrescu, Raluca et al. (2020). *Swarm Electrification: From Solar Home Systems to the National Grid and Back Again?* Springer International Publishing, pp. 63–80. isbn: 9783030419523. doi: 10.1007/978-3-030-41952-3{_}4.

Esmat, Ayman et al. (Jan. 2021). "A novel decentralized platform for peer-to-peer energy trading market with blockchain technology". In: *Applied Energy* 282. issn: 03062619. doi: 10.1016/j.apenergy.2020.116123.

Fuchs, Ida et al. (2022). *Optimal Design and Installation of Solar Home Systems for Bottom-up Grids: Comparative Case Studies from Kenya and Norway*. Tech. rep. 8th World Conference on Photovoltaic Energy Conversion, pp. 1453–1458. doi: 10.4229/WCPEC-82022-4CV.1.3.

Fuchs, Ida et al. (2023). "Swarm electrification: Harnessing surplus energy in off-grid solar home systems for universal electricity access". In: *Energy for Sustainable Development* 77, p. 101342. issn: 0973-0826. doi: https://doi.org/10.1016/j.esd.2023.101342.

Gorla, Praveen et al. (2023). "Decentralized Renewable Resource Redistribution and Optimization for Beyond 5G Small Cell Base Stations: A Machine Learning Approach". In: *IEEE Systems Journal* 17.1, pp. 988–999. DOI: 10.1109/JSYST.2022.3141823.

Groh, Sebastian (2015). "The Role of Access to Electricity in Development Processes: Approaching Energy Poverty through Innovation". In: *PhD Thesis, Department of Development and Planning, Aalborg University* 2, p. 174.

Groh, Sebastian et al. (2014a). "A System Complexity Approach to Swarm Electrification". In: *Energy for Sustainable Development – Mini-grid and Hybrid Systems* 2014.Yearbook, University of Flensburg. DOI: 10.14324/000.cp.1469412.

Groh, Sebastian et al. (2014b). "Swarm electrification-suggesting a paradigm change through building microgrids bottom-up". In: *Proceedings of 2014 3rd International Conference on the Developments in Renewable Energy Technology, ICDRET 2014*, pp. 1–2. DOI: 10.1109/icdret.2014.6861710.

Groh, Sebastian et al. (2015). "Decentralized Solutions for Developing Economies - Addressing Energy Poverty Through Innovation". In: DOI: 10.1007/978-3-319-15964-5.

Groh, Sebastian et al. (2022). "The Bangabandhu Tariff—Improving Access to Sustainable Electricity and Co-Benefits of Climate Change Through Community Power Purchase Agreements". In: ed. by Sazzad Hossain et al., pp. 505–516.

Halden, Ugur et al. (2023). "Anomaly Detection in Power Markets and Systems". In: *2023 IEEE Power Energy Society General Meeting (PESGM)*, pp. 1–5. DOI: 10.1109/PESGM52003.2023.10252380.

Hardjono, T. et al. (2020). "Toward an interoperability architecture for blockchain autonomous systems". In: *IEEE Transactions on Engineering Management* 67 (4), pp. 1298–1309. DOI: 10.1109/tem.2019.2920154.

Hernandez-Matheus, Alejandro et al. (Dec. 2022). "A systematic review of machine learning techniques related to local energy communities". In: 170. ISSN: 18790690. DOI: 10.1016/j.rser.2022.112651.

Hoffmann, Martha M. et al. (2019). "Simulating the potential of swarm grids for pre-electrified communities – A case study from Yemen". In: *Renewable and Sustainable Energy Reviews* 108.July 2018, pp. 289–302. ISSN: 18790690. DOI: 10.1016/j.rser.2019.03.042.

Huang, Chiou Jye et al. (2019). "Multiple-Input Deep Convolutional Neural Network Model for Short-Term Photovoltaic Power Forecasting". In: *IEEE Access* 7, pp. 74822–74834. ISSN: 21693536. DOI: 10.1109/ACCESS.2019.2921238.

IEA (2022). *TRACKING SDG7 A joint report of the custodian agencies*. Tech. rep. URL: www.worldbank.org.

IRENA (2019). *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables*. Tech. rep. IRENA.

Jamil, Faisal et al. (2021). "Peer-to-Peer Energy Trading Mechanism based on Blockchain and Machine Learning for Sustainable Electrical Power Supply in Smart Grid". In: *IEEE Access*, pp. 39193–39217. ISSN: 21693536. DOI: 10.1109/ACCESS.2021.3060457.

Kempener, Ruud et al. (2015). *Off-grid Renewable Energy Systems: Status and methodological issues*. Tech. rep. IRENA.

Kirchhoff, Hannes et al. (2016). "Developing mutual success factors and their application to swarm electrification: microgrids with 100 % renewable energies in the Global South and Germany". In: *Journal of Cleaner Production* 128, pp. 190–200. ISSN: 09596526. DOI: 10.1016/j.jclepro.2016.03.080.

Kirchhoff, Hannes et al. (2022). "Control and Stability of Modular DC Swarm Microgrids". In: *IEEE Journal of Emerging and Selected Topics in Power Electronics* X.X, pp. 1–1. ISSN: 2168-6777. DOI: 10.1109/jestpe.2022.3168545.

Koepke, Mathias et al. (Dec. 2016). "Against the Odds: The Potential of Swarm Electrification for Small Island Development States". In: 103, pp. 363–368. ISSN: 18766102. DOI: 10.1016/j.egypro.2016.11.300.

Koirala, Binod Prasad et al. (2016). "Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems". In: *Renewable and Sustainable Energy Reviews* 56, pp. 722–744. ISSN: 18790690. DOI: 10.1016/j.rser.2015.11.080.

Kulkarni, Vedika et al. (2020). "A Blockchain-based Smart Grid Model for Rural Electrification in India". In: *8th International Conference on Smart Grid, icSmartGrid 2020*, pp. 133–139. DOI: 10.1109/icSmartGrid49881.2020.9144898.

Kuzlu, Murat et al. (2020). "Realizing the potential of blockchain technology in smart grid applications". In: *2020 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference, ISGT 2020*, pp. 1–5. DOI: 10.1109/ISGT45199.2020.9087677.

Ledwaba, Lehlogonolo P.I. et al. (2021). "Smart microgrid energy market: Evaluating distributed ledger technologies for remote and constrained microgrid deployments". In: *Electronics (Switzerland)* 10.6, pp. 1–23. ISSN: 20799292. DOI: 10.3390/electronics10060714.

Levin, Todd et al. (2016). "Can developing countries leapfrog the centralized electrification paradigm?" In: *Energy for Sustainable Development* 31, pp. 97–107. ISSN: 0973-0826. DOI: https://doi.org/10.1016/j.esd.2015.12.005.

Magnasco, Annika et al. (2016). "Data Services for Real Time Optimization of DC Nanogrids with Organic Growth". In: *Energy Procedia* 103.April, pp. 369–374. ISSN: 18766102. DOI: 10.1016/j.egypro.2016.11.301.

Maji, Ibrahim Kabiru (2019). "Impact of clean energy and inclusive development on CO2 emissions in sub-Saharan Africa". In: *Journal of Cleaner Production* 240, p. 118186. ISSN: 0959-6526. DOI: https://doi.org/10.1016/j.jclepro.2019.118186.

Mantellassi, Stefano et al. (2019). "Digitalisation & solar in emerging markets - Task Force Report". In: ed. by Solar Power Europe.

Marahatta, Anup et al. (2021). "Evaluation of a lora mesh network for smart metering in rural locations". In: *Electronics (Switzerland)* 10.6, pp. 1–16. ISSN: 20799292. DOI: 10.3390/electronics10060751.

Markovics, Dávid et al. (June 2022). "Comparison of machine learning methods for photovoltaic power forecasting based on numerical weather prediction". In: *Renewable and Sustainable Energy Reviews* 161. ISSN: 18790690. DOI: 10.1016/j.rser.2022.112364.

Mbuya, Benson; et al. (2019). "Short-term load forecasting in a hybrid microgrid: a case study in Tanzania". In: J. Electri.

Mehra, Varun et al. (2016). "A novel application of machine learning techniques for activity-based load disaggregation in rural off-grid, isolated solar systems". In: DOI: 10.1109/GHTC.2016.7857308.

Moghaddam, Mohsen Parsa et al. (2022). "2 - 5D Giga Trends in future power systems". In: ed. by Mohsen Parsa Moghaddam et al., pp. 19–50. DOI: https://doi.org/10.1016/B978-0-323-91698-1.00015-7.

Moner-Girona, Magda et al. (2019). "Decentralized rural electrification in Kenya: Speeding up universal energy access". In: *Energy for Sustainable Development* 52, pp. 128–146. ISSN: 0973-0826. DOI: https://doi.org/10.1016/j.esd.2019.07.009.

Moradzadeh, Arash et al. (2020). "Short-Term Load Forecasting of Microgrid via Hybrid Support Vector Regression and Long Short-Term Memory Algorithms". In: *Sustainability* 12.17. ISSN: 2071-1050. DOI: 10.3390/su12177076.

Narayan, Nishant et al. (2019). "Quantifying the Benefits of a Solar Home System-Based DC Microgrid for Rural Electrification". In: pp. 1–22. DOI: 10.3390/en12050938.

Nasir, Mashood et al. (2019). "A Decentralized Control Architecture Applied to DC Nanogrid Clusters for Rural Electrification in Developing Regions". In: *IEEE Transactions on Power Electronics* 34.2, pp. 1773–1785. ISSN: 08858993. DOI: 10.1109/TPEL.2018.2828538.

Noor, Sana et al. (2018). "Energy Demand Side Management within microgrid networks enhanced by blockchain". In: *Applied Energy* 228.April, pp. 1385–1398. ISSN: 03062619. DOI: 10.1016/j.apenergy.2018.07.012.

Norwegian SEC (2019). "Cheaper, faster, cleaner - Speeding up distributed solar solutions to meet development and climate goals". In: April.

Nzalé, Francois (2020). "Cost-Optimized Mini-grid Design with Tree-Star Configuration". In: *Master Thesis, Power Systems Laboratory, ETH Zurich*.

Peña, Robert Alfie S. et al. (2023). "Development of an Energy Monitoring System with Forecasting for Off-Grid Microgrids". In: *2023 10th International Conference on Power and Energy Systems Engineering (CPESE)*, pp. 200–205. DOI: 10.1109/CPESE59653.2023.10303213.

Pittalis, Marco et al. (2023). "Quantifying impacts and benefits of advanced remote monitoring solutions for the operation of mini grids in sub-Saharan Africa". In: *Energy for Sustainable Development* 77, p. 101335. ISSN: 0973-0826. DOI: https://doi.org/10.1016/j.esd.2023.101335.

Prevedello, Giulio et al. (2021). "The benefits of sharing in off-grid microgrids: A case study in the Philippines". In: *Applied Energy* 303, p. 117605. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2021.117605.

Richard, Lucas et al. (2022a). "A Decentralized and Communication-free Control Algorithm of DC Microgrids for the Electrification of Rural Africa". In:
Richard, Lucas et al. (Sept. 2022b). "Development of a DC Microgrid with Decentralized Production and Storage: From the Lab to Field Deployment in Rural Africa". In: *Energies* 15.18. ISSN: 19961073. DOI: 10.3390/en15186727.
Sheridan, Stephen et al. (Nov. 2022). "The potential for swarm electrification as a flexible tool for last-mile energy access". In: Institute of Electrical and Electronics Engineers (IEEE), pp. 1–6. ISBN: 9781665455053. DOI: 10.1109/upec55022.2022.9917819.
Sheridan, Steve et al. (2023). "Swarm electrification: A comprehensive literature review". In: *Renewable and Sustainable Energy Reviews* 175, p. 113157. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2023.113157.
Shibu, N. B. Sai et al. (2024). "Optimizing Microgrid Resilience: Integrating IoT, Blockchain, and Smart Contracts for Power Outage Management". In: *IEEE Access* 12, pp. 18782–18803. DOI: 10.1109/ACCESS.2024.3360696.
Siano, Pierluigi et al. (2019). "A Survey and Evaluation of the Potentials of Distributed Ledger Technology for Peer-to-Peer Transactive Energy Exchanges in Local Energy Markets". In: *IEEE Systems Journal* 13.3, pp. 3454–3466. ISSN: 19379234. DOI: 10.1109/JSYST.2019.2903172.
Soltowski, Bartosz et al. (2018). "A Simulation-Based Evaluation of the Benefits and Barriers to Interconnected Solar Home Systems in East Africa". In: *2018 IEEE PES/IAS PowerAfrica, PowerAfrica 2018* 2, pp. 491–496. DOI: 10.1109/PowerAfrica.2018.8521058.
Soltowski, Bartosz et al. (2019). "Bottom-up electrification introducing new smart grids architecture-concept based on feasibility studies conducted in Rwanda". In: *Energies* 12.12. ISSN: 19961073. DOI: 10.3390/en12122439.
Soltowski, Bartosz et al. (2022). "A field trial of off-grid SHS Interconnection in Rwanda's Northern Province". In: *Energy for Sustainable Development* 66, pp. 69–78. ISSN: 23524669. DOI: 10.1016/j.esd.2021.11.004.
Teufel, Bernd et al. (2019). "Blockchain energy: Blockchain in future energy systems". In: *Journal of Electronic Science and Technology* 17.4, p. 100011. ISSN: 1674862X. DOI: 10.1016/j.jnlest.2020.100011.
The European Commission (2018). "Directive (EU) 2018/2001 of the European parliament and of the European council 11 December 2018 on the promotion of the use of energy from renewable sources". In: Directive (EU) 2018/2001.
— (2019). "Directive (EU) 2019/944 of the European parliament and of the council of 5 June 2019 on common rules for the internal market for electricity and amending ". In: Directive 2012/27/EU.
Unger, Kurtis et al. (2011). "Simulation of rural electrification via cellular-enabled micro-inverter". In: *Proceedings - 2011 IEEE Global Humanitarian Technology Conference, GHTC 2011*, pp. 1–6. DOI: 10.1109/GHTC.2011.9.
Wang, Xinlin et al. (2021). "Demand-side management for off-grid solar-powered microgrids: A case study of rural electrification in Tanzania". In: *Energy* 224, p. 120229. ISSN: 03605442. DOI: 10.1016/j.energy.2021.120229.
Yadav, Prabhakar et al. (Feb. 2019). "Pay-As-You-Go financing: A model for viable and widespread deployment of solar home systems in rural India". In: *Energy for Sustainable Development* 48, pp. 139–153. ISSN: 23524669. DOI: 10.1016/j.esd.2018.12.005.
Yang, Jiawei et al. (2022). "Hierarchical Blockchain Design for Distributed Control and Energy Trading Within Microgrids". In: *IEEE Transactions on Smart Grid* 13.4, pp. 3133–3144. DOI: 10.1109/TSG.2022.3153693.
Zia, Muhammad F. et al. (2020). "Microgrid transactive energy: Review, architectures, distributed ledger technologies, and market analysis". In: *IEEE Access* 8, pp. 19410–19432. ISSN: 21693536. DOI: 10.1109/ACCESS.2020.2968402.
Zyl, Nicolette Pombo-van (2022). "Projects and Leaders". In: *African Power and Energy Elites*.