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RESEARCH ARTICLE

PREREQUISITES, PUSH FACTORS, CHALLENGES, AND FUTURE PERSPECTIVES OF MINI-GRIDS: A REVIEW

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Abstract

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Mini-grids are considered by stakeholders in the electricity sector as one of the key solutions to accelerate the electrification process. Their development is driven by global concerns regarding climate change, the decarbonization of electrical networks, and the growing of energy demand. Among their many advantages are improved reliability, increased flexibility, and enhanced energy security. However, these mini-grids face several challenges, including high investment costs, technical complexity, regulatory constraints, and interconnection issues. This document aims to provide information on the concept of mini-grids, their classification, the push factors for their adoption for electrification, as well as lessons learned from countries that have successfully achieved electrification through mini-grids. It also presents the strategies and technologies for their development. The insights offered by this study may be useful for researchers, engineers, developers, and policymakers in designing stable, efficient, and high-performing mini-grids.

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Introduction:-

A mini-grid is a network of electricity generators, and potentially energy storage systems, connected to a distribution network that supplies electricity to a localized group of customers, fulfilling their total energy demand[1]. It is made up of a power source, a storage system, inverters, and communication tools [2] when the source is intermittent; otherwise, the storage system and inverters are eliminated in the mini-grid.Several authors present mini-grids as an alternative for rural electrification [3], [4], [5], [6]. They emerge as a third option for rural electrification, following the large-scale extension of the grid and small-scale off-grid solutions such as home solar systems or solar lanterns [7]. A mini-grid can function in three different modes: grid-connected, isolated, or hybridIn grid-connected mode, the mini-grid is linked to the main electricity grid, allowing it to import or export electricity based on demand. In isolated mode, the mini-grid operates independently, relying on decentralized energy sources to generate, store, and distribute electricity within the local area[8], [9]. The mini-grids designed in this manner seem unsuitable for urban applications, as urban areas typically receive electricity from national or regional grids that are often interconnected [4]. Recently, this technology has emerged as a solution to electrify developing countries, thanks to the concerted efforts of governments, international organizations, and the private sector. Sri Lanka, Nepal, Tanzania, and some regions of India have seen notable advancements in mini-hydropower grids, whereas countries like Mali, Indonesia, Cambodia, and the Philippines have largely relied on diesel mini-grids. This indicates the potential for integrating

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hybrid solutions in these regions [10]. In both Bangladesh and India, photovoltaic solar energy plays a leading role in their energy systems[10]. African nations such as Tanzania, Mali, and Morocco are recognized as pioneers in electrification through the use of mini-grids. However, the largest hybrid PV/diesel generation installations are found in Koro (384 kW) and Bankass (384 kW) in Mali, as well as in Tsumkwe (202 kW) in Namibia [11].Since mini-grids are primarily implemented in remote areas, there is a lack of case studies focusing on their operations in villages that are already connected to the main grid, but this technology is starting to attract researchers' attention due to its reliability and affordability. The authors [12], [13], [14], [15] have analyzed the techno-economic performance of mini-grids. Studies by authors [15], [16], [17], [18], [19] focused on the optimal sizing of mini-grids and the appropriate use of resources. Papers [20] and [21] analyze the reliability, economic viability, and environmental impact of a microgrid system when integrated with renewable energy resources. The study [22] reviews the evolution of off-grid renewable mini-grids in Sub-Saharan Africa (SSA) over the past two decades. The review shows that solar photovoltaic (PV) is the most widely used and easiest to implement technology for mini-grids in SSAand that these mini-grids are often oversized to cover demand. The document [11] reviewed the literature on various aspects of integrating hybrid renewable energy systems in developing countries. Its analyses show that, in general, Asian countries have relatively succeeded in establishing mini-grids, with more beneficiaries from these systems compared to African countries.Development financial institutions (DFIs) are the primary providers of loans in Sub-Saharan Africa (SSA), offering concessional loans at more favorable rates than commercial lenders. However, the high transaction costs of DFIs are ill-suited for small mini-grids. Local commercial banks consider the business models of mini-grids to be very risky, leading them to either deny loans or offer prohibitive interest rates [23], [24]. Exchange rate risk presents a significant challenge for mini-grid developers in Sub-Saharan Africa (SSA). These projects typically incur capital costs in foreign currencies, while revenues are generated in the local currency. This creates a mismatch between capital investments and revenues, especially when the local currency weakens against foreign currencies. Projects funded in currencies like dollars, pounds, or euros are particularly vulnerable to this financial disparity[25].While the loan program has provided advantages for mini-grid projects, many developers still struggle to secure funding. Despite the Tanzanian government's international financial support for mini-grid development, developers continue to be apprehensive about the uncertainties and risks associated with these investments[26].India leads in electricity provision through mini-grids, supported by its energy transition policy and government commitment, which have led to the installation of approximately 14,000 operational mini and micro-grid systems [27]. This paper examines the concept of mini-grids, the incentives for electrification through these mini-grids, the challenges they face, the optimization of these networks through new technologies, as well as a case study on mini-grids in India, a country ranked as a "mini-grid superstar" by the International Energy Agency (IEA) in 2018 [28].

Definition

There is no universal definition of the mini-grid concept, but several authors have attempted to provide their perspectives on this subject, defining the term "mini-grid" based on size, installed capacity, or the number of households it serves. Guillou and Girard [29] define a mini-grid as a decentralized collective electricity supply system that can function independentlyor in grid-connected mode. It combines production and distribution while eliminating the "transport" dimension present in conventional grids. Werner et al. [30] state that the only distinguishing characteristic is a production and distribution system disconnected from the grid. Schnitzer et al. use the term "micro-grids," referring to systems with a capacity of up to around 100 kW. Tenenbaum et al. [4] also differentiate micro-grids from mini-grids, with the key distinction being the targeted markets. Mini-grids are defined as isolated networks typically ranging from several tens of kilowatts to tens of megawatts in output power. These systems are designed to serve several hundred customers, particularly in rural areas of developing countries. In contrast, micro-grids are defined as very small-scale systems producing power from a few hundred watts to a few kilowatts, generally serving fewer than 150 residential customers. Some authors also use the term "pico-grid" to describe systems with a capacity of less than 1 kW[31].

Evolution of Mini-Grids

Mini-grids have been in existence for more than a century. In countries with middle or high-income levels, such as Brazil, China, Italy, Spain, Sweden, the United Kingdom, and the United States, they were frequently the initial means of electrification. As these economies progressed, the early mini-grids were integrated into larger, expanding national power grids[32]. Second-generation mini-grids are typically developed to serve areas that are not connected to the main grid or where the cost of extending the grid is too high. These systems offer a more cost-effective solution for electrifying remote or underserved regions. They are usually managed by local communities and entrepreneurs, utilizing mini-hydropower and diesel generation technologies [33]. A new generation of mini-grids has recently emerged, characterized by the use of modular generation technologies, primarily solar photovoltaic systems. These grids often incorporate storage and backup solutions, advanced control systems, and smart prepaid meters. The size of photovoltaic systems mainly depends on meteorological data such as solar radiation and ambient temperature [33]. These mini-grids are often presented as recently implemented solutions that have attracted the interest of governments and international investors since the early 2000s [34]. The International Renewable Energy Agency (IRENA) reports that more than 10,000 isolated mini-grids operate in countries such as India, China, and Bangladesh [35]. Senegal and Madagascar are among the top ten countries in the world with the most installed mini-grids to date, with over 270 and 100 mini-grids, respectively [36]. A study by UNIDO (United Nations Industrial Development Organization) provides examples of successful mini-grids in six African countries (Chad, Gambia, Guinea-Bissau, Côte d'Ivoire, Tanzania, and Zambia) and two Asian countries (India and Sri Lanka) [37], [38]. Solar mini-grids could offer renewable electricity to more than 380 million people across Africa by 2030 [39].

Composition of a Mini-Grid

Production resources can be based on fossil fuels (diesel), renewable energy sources (solar photovoltaic, micro-hydropower, wind), or hybrid systems that use a combination of different resources(diesel-PV, PV-hydropower, diesel-PV-hydro, etc.). The main components of a mini-grid include one or more power sources, synchronizers, one or more transformers, a backup battery bank if applicable, switching equipment, inverters, load and power balancing software, and wiring. The distribution network can transmit either direct current (DC) or alternating current (AC), with variable voltage levels[40]. Fig 1 shows us the structure of a mini-grid with several energy sources.

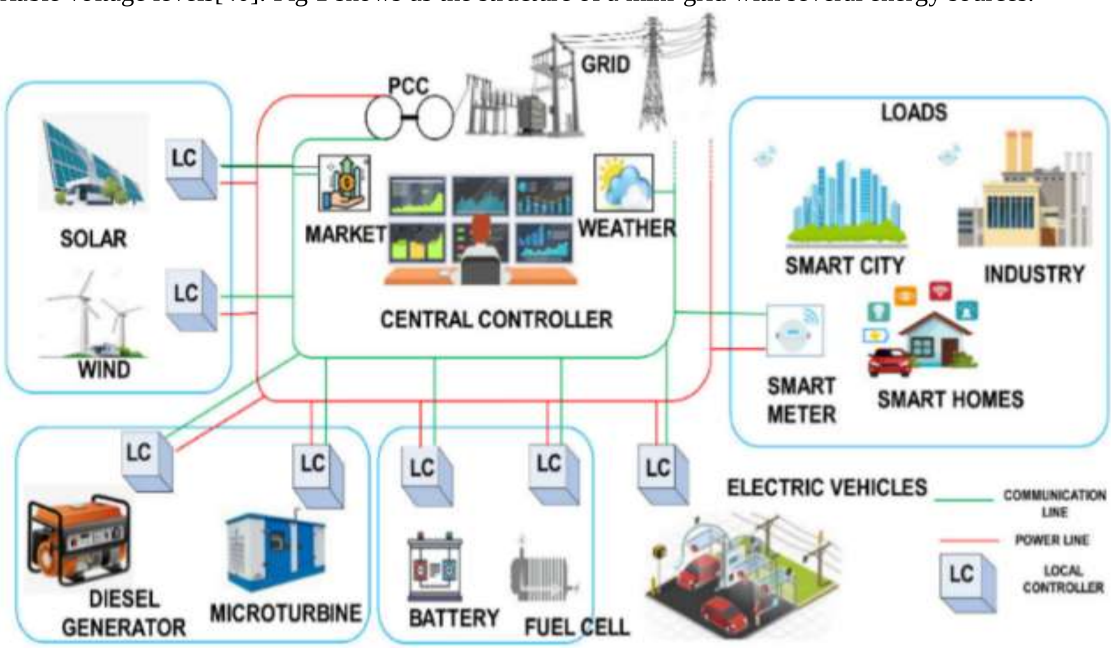

Fig 1:- Mini-grid structures with Multiple Energy Sources [8].

Classification of Mini-Grids

Brix Pedersen [7] suggested a classification of mini-grids based on the number of consumers they serve and the type of supply they provide. The categories include: village mini-grids in direct current (DC) ranging from 0.2 to 5 kW, serving up to 100 households; Anchor-Business-Community (ABC) mini-grids, with capacities between 0.2 to 15 kW, which serve an anchor load (such as telecommunications towers or lodges) and the surrounding community; village mini-grids in alternating current (AC), which range from 1 to 300 kW; large AC mini-grids serving off-grid towns with capacities exceeding 300 kW and up to 2 MW; grid-connected mini-grids with single-wire ground return, typically ranging from 0.2 to 50 kW; and large ABC mini-grids connected to the grid, with capacities from 1 to 5 MW, integrated into existing mini-grid networks. Artur [44] suggests the following classification of mini-grids: Pico-grids, which include low-cost DC grids ranging from 0.5 to 5 kW; small AC grids with capacities between 0.2 to 15 kW; Anchor-Business-Community (ABC) grids; larger AC grids ranging from 15 to 300 kW; and Power Purchase Agreement (PPA) grids, which have capacities from over 300 kW to 110 MW. Fig 2 illustrates this latest classification.

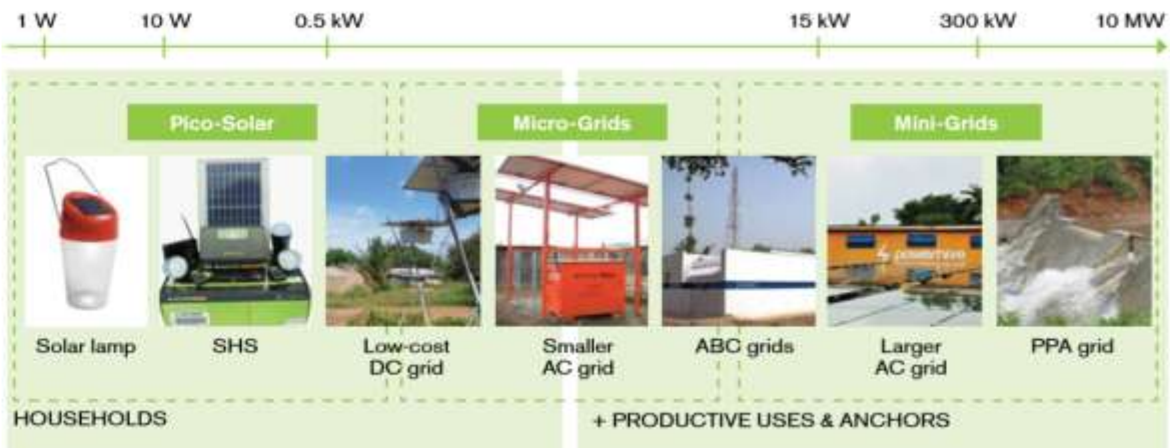

Fig 2:- Classification of Mini-Grids [41].

IRENA [31] categorizes mini-grids according to their produced power (

Table 1).

Table 1:- Categorization of Local Grid Systems Proposed by IRENA [31].

Definition	Commonly Used Size	Proposed Categorization by IRENA
Mini-grids	10 to several MW	0 to 100 MW
Micro-grids	1 to 10 kW	5 to 100 kW
Nano-grids	0.5 to 1 kW	0 to 5 kW
Pico-grids	0 to 0.5 kW	0 to 1 kW

Guillou and Girard [29]identify four primary types of mini-grids: mini-grids created by private individuals or entrepreneurs, managed on a shared network; mini-grids set up by user associations or mutual aid groups, which are not always operated commercially; government-initiated mini-grids, managed on a commercial basis; and community projects that are not run for profit.

Incentive Factors for Electrification through Mini-Grids

The liberalization of the electricity market serves as a major incentive for the expansion of mini-grids, as a more open market with fewer restrictions would attract investors. Factors driving the growth of renewable energy (RE) penetration include increased reliability, improved energy security, technological advancements, regulatory considerations, and the need to address emissions reductions[42], as well as reduced energy costs and increased flexibility [8]. The requirement for decarbonizing the electrical grid and reducing greenhouse gas emissions is one of the main drivers encouraging the deployment of decentralized renewable energy resources. Although often unreliable, grid electricity is typically cheaper due to economies of scale and/or administrative tariffs that fail to cover the full costs of production, transmission, and distribution [43]. Additionally:

- **Rapid Acceleration of Electrification** :Countries that have implemented an integrated planning program and an electrification strategy, including grid expansion, the installation of home solar systems, and the creation of mini-grids, have recorded a significant increase in access to electricity [44].
- **Economics**: Mini-grids, in particular, have a high potential for poverty reduction as they enable productive use of electricity [45]. Mini-grids are also often positively compared to individual off-grid solutions, such as home solar systems, because they allow for productive uses , and off-grid [46] electrification is often less expensive than base technologies [47].
- **Technological Evolution**: Technologies such as electric vehicles, heat pumps, and energy storage support the integration of renewables by increasing flexibility within energy systems. These technologies also unlock increased demand for renewable energy, particularly variable renewable energy (VRE), by coupling renewables with end uses across the electricity, transportation, heating, and cooling sectors [44].

Challenges Faced by Mini-Grids

Although the acceptance of mini-grids as a viable technology for rural electrification is growing, several obstacles hinder their development faces challenges, including unclear regulations, financing limitations for developers, and affordability issues for customers [47]. Through a survey of stakeholders in South Asia and Sub-Saharan Africa, IRENA [48] identified the barriers to the development of mini-grid systems, as illustrated in Fig 3. Stakeholders pointed to political instability as the primary challenge.

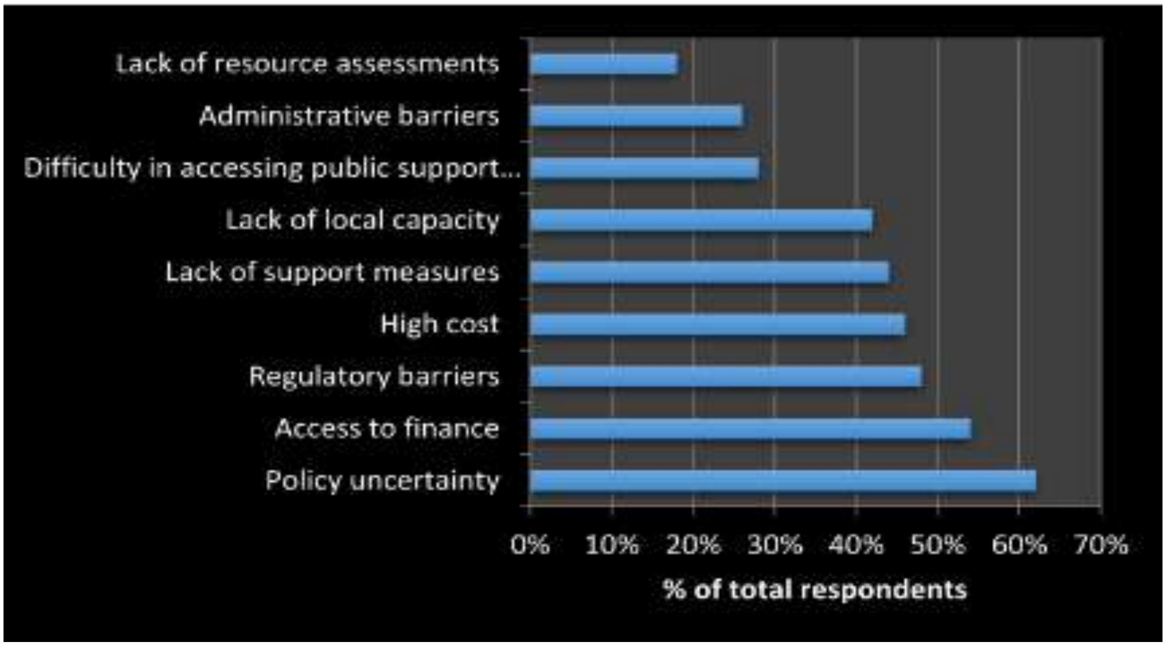

Fig 3:-Barries to mini-grids development **[48]**.

Regulation and Policy

The lack of adequate regulation and planning has been highlighted as a significant constraint on the development of mini-grids. For example, despite the successful implementation of mini-grids in Indonesia, there were no specific rules or policies regarding what would happen when the main grid arrived in a village powered by mini-grids, leading to the abandonment of some micro-hydro projects [49]. Coordination among energy sector stakeholders, the private sector, and local communities is crucial for the successful implementation of these projects. This can be effectively observed through a clear definition of roles and responsibilities among the various stakeholders. For instance, India has implemented successful models through Village Electricity Committees (VEC) in the states of West Bengal and Chhattisgarh. In contrast, many projects under the country's Village Energy Security Program, launched in 2004, were abandoned in 2012 due to failures. Of the 65 projects initiated, over half were not functioning[50]. The main reason for the failure of the projects was the absence of a clear definition of stakeholders' roles and responsibilities, which led to inadequate community involvement[50].Authors [51], [52],[53] have analyzed the daily operations of mini-grids and assert their influence on local political and social dynamics. Manetsgruber et al. [54] surveyed various stakeholders about the challenges related to the operation of mini-grids and found that uncertainty in legal and/or policy frameworks was the primary concern. To overcome these challenges, countries such as Indonesia, Rwanda, and Nigeria, along with certain Indian states, have established compensation and exit strategies to support mini-grid operators in the event of integration into the conventional grid [33]. Nigeria, Peru, and Tanzania have incorporated mini-grids into their national electrification strategies[29]. A notable example highlighting the significance of community involvement from the project's inception to its execution is the 202 kW solar photovoltaic/diesel hybrid mini-grid installed in Tsumkwe (Namibia) in 2012, which remains operational to this day[55]. Another case in pointillustrating the importance of regulations to foster private sector integration is presented in reference [56]by conducting a case study of six mini-grids developed and operated by a private company in Thiès, Senegal. An analysis of the national power access plans of 20 countries, as referenced in [57], with the highest number of unelectrified households, shows that 14 of these countries have national plans for rural electrification, while 12 have shown a strong commitmentto decentralized electricity production. However, only 10 countries have allocated investment budgets for this purpose, and 12 have implemented policy instruments to address decentralized energy distribution. Table 2displays the outcomes of the analysis.

Table 2:- Highlighting decentralized electrification in the national plans of chosen countries[58].

Country	Population lacking access (M)	National plan	Commitment to decentralised electrification	Investment budget	Policy instrument
India	269.51	x	x	x	x
Nigeria	74.73	x	x	x	x
Ethiopia	70.88	x	x	x	x
D R Congo	63.77				
Bangladesh	59.94	x	x	x	x
Tanzania	44.14	x	x	x	x
Uganda	30.91	x	x	x	x
Kenya	29.46	x	x	x	x
Myammar	24.92	x	x	x	x
Mozambique	21.44	x	x	x	x
Sudan	20.79				
Madagascar	19.62				
Angola	18.31	x	x	x	x
DPR Korea	16.99				
Niger	16.41	x	x		x
Malawi	15.04	x			
Burkina Faso	14.21	x	x		x
Chad	12.48				
Mali	12.33	x			
South Sudan	11.01				

Viability and profitability issues of mini-grids

The research on mini-grids has frequentlyhighlighted the financial viability gap is often cited as one of the major challenges faced by mini-grids[26], [35], [36]. Comello et al. assessed the levelized cost of electricity (LCOE) for a typical village in Gujarat, India, and discovered that solar mini-grids with batteries, priced at $0.380 per kWh, were considerably costlier than the central grid, which could deliver electricity at just $0.062 per kWh. For sub-Saharan Africa, Baurzhan et al. [59]determined that the unit cost of off-grid photovoltaic solar systems was $0.830 per kWh, while the unit cost of conventional grid power varied between $0.080 and $0.160 per kWh. Bhattacharyya [47]asserted that considering these pricedifferences, it is unlikely that poor customers would adopt mini-grids. Zubi et al. [60]acknowledge that the affordability of photovoltaic solar energy remains a challenge in areas lacking electricity access. However, they propose that strategies like high-value-added applications, energy-efficient solutions (such as LED lights), and cost reduction measures could make this technology more attractive. Reference [61] notes that mini-grid users in India place much higher value on local power supply compared to grid-connected power and are ready to pay around $1.05 per kWh. To surpass the challenge financial sustainability, governments and donor organizations have provided funding to investors to alleviate the impact of capital expenses. A study presented in [47] analyzed the comparative advantages and disadvantages of three types of mini-grid initiatives: those funded by donosr and funders, those driven by supply chain organizations, and those led by NGOs or communities. A summary is presented in

Table 3.

Table 3:- Comparison of factors influencing technical capability[47].

Characteristics	**Mini-Grids Supported by Financiers**	**Mini-Grids Supported Developed by Supply Chain Entities**	**NGO/Community Supported Mini-Grids**
Capacity to aggregate demand to achieve	Low	Low	Moderate

financial viability			
Flexibility to tailor technical solutions to variable demand and environmental	Low/NA	Moderate	High
Flexibility to adapt programmes across geographic and environmental conditions and different consumer behavior	Low/NA	Moderate	High
Capacity to manage O&M risks and optimize O&M Service delivery	Low	High	Low
Ability to optimize supply chain	Low	High	Low
Technical capacity to deliver high quality service throughout the project life	Low	High	Low
Capacity to aggregate demand to reduce administration costs significantly	Low	Moderate	Moderate

Technical challenges

- **Load and demand management:** Mini-grids that use intermittent sources require additional components to balance the energy flow in the grid, considering seasonal variations and load fluctuations. Artificial intelligence can be leveraged to forecast electricity production and demand parameters [62]. Throughout the thesis[63], five rule-based energy management strategies, each with increasing levels of complexity, were designed and analyzed. These strategies were compared to a linear programming optimization method in terms of both energy efficiency and economic performance. The results indicate that the best-performing rule-based strategy achieves a performance level nearly equivalent to the linear programming approach, which is regarded as the "optimal" solution.
- **Harmonics :** The presence of harmonics poses a risk to the stability and reliability of the power grid's operation unless preventive measures are taken [64]. In the case of a continuous link for a DC mini-grid, the heat generated by the capacitor increases, worsened by the high-frequency charging and discharging process. As a result, the safety of electrical energy storage devices is at greater risk, as they become more vulnerable to these harmonics[65]. Several researchers have proposed various methods to reduce harmonics, primarily classified into active filtering techniques, which eliminate harmonics of all orders, and passivefiltering techniques, aimed at eliminating higher-order harmonics [66]. These filters are placed at the point of common coupling (PCC), which is either between the mini-grid and the main grid or between the distributed energy resources (DERs) and the loads within the mini-grid[67]. There are Active Power Filters (APF) capable of actively managing harmonic distortion by adding harmonic currents into the system[19]. Another method involves using advanced control algorithms that allow control of the power flow and voltage levels within the mini-grid to minimize harmonic distortion [68].
- **Protection :** As mini-grids are decentralized and integrate multiple energy sources, protection issues can emerge, potentially having a significant impact on the system[69]. One of the main challenges of mini-grid protection systems is that they must respond to both faults within the islanded grid and faults on the connected grid [70], and quickly disconnect the mini-grid from the main grid as needed to protect the loads within the mini-grid [71]. Protection devices such as circuit breakers respond promptly to obvious anomalies to prevent their spread and avoid further damage to the grid [72].
- **Stability and quality of service:** Stability refers to the system's ability to return to normal operation following a disturbance [73]. There are three types of stability in a grid: steady-state stability, dynamic stability, and transient stability [74]. There are three main factors that contribute to stability problems: (a) a reduction in system inertia, leading to a decline in angular stability and causing voltage and frequency instability; (b) weakened voltage stability due to reduced energy distribution support; and (c) low-frequency power oscillations caused by changes in the power-sharing ratio between distributed generators[75].Disturbances can be small (daily load changes) or large (equipment failure). illustrates the system stability curve over time[73]:

Stable system, $\frac{d\delta}{dt} = 0$, for a short duration;

Unstable system, $\frac{d\delta}{dt} > 0$, for a long duration.

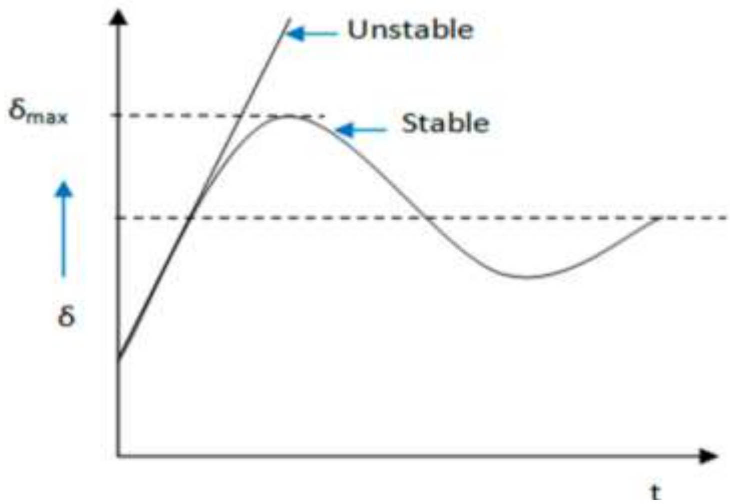

Fig 4:- System stability VS time [73].

Improving the stability of mini-grids can be achieved through the implementation of energy storage solution, sophisticated protection systems, and enhanced surveillance methods [8]. Given the decentralized nature of mini-grids and the incorporation of various energy sources, issues related to power quality can emerge, greatly affecting system operations[76]. Among the major power quality challenges faced by mini-grids are voltage sag and voltage swell. These issues can lead to various complications, including damage to equipment, lower system efficiency, and potential power outages[20].

• **Cybersecurity**:
Digital security represents a significant challenge in the development of mini-grids. With their increasing expansion and interconnection, these systems become more vulnerable to cyberattacks. The most well-known case of a cyberattack on a power grid occurred in Ukraine in 2015 [77]. The outages occurred due to unauthorized access by a third party into the company's computer and SCADA (Supervisory Control and Data Acquisition) systems. As a result, seven 110 kV substations and twenty-three 35 kV substations were disconnected for three hours. Subsequent reports discovered thatthe cyberattack also affected other parts of the distribution network, forcing operators to switch to manual mode. In response to repeated and sophisticated attacks, the country implemented several measures, such as strengthening infrastructure and security systems, developing incident detection and response capabilities, international cooperation, and training and raising staff awareness of cyber threats and best practices in cybersecurity to reduce human error risks [77].

Social Challenges
Other concerns include social, sustainability, organizational, and security issues. Social acceptance is largely influenced by how satisfied communities are. Engaging the community is vital for the success of projects and plays a key role in ensuring their sustainability. However, this involvement can be hindered by limited access to information, resulting in a lack of awareness. For instance, in Nepal, a major barrier to the development of renewable energy systems is the insufficient public awareness [78]. References [79] and [60] highlight the lack of attention given to the social integration of mini-grids by obtaining stakeholder buy-in. Insights from Nepal, Indonesia, Sri Lanka, and India highlight the crucial role of local communities in the successful operation of mini-grids across the entire project lifecycle. However, these communities often face difficulties due to a shortage of skilled local workers to handle the operation, management, and maintenance of the systems. To address this, it is essential to train community members for these roles and engage them early in the project development process, including in decision-making, to ensure the mini-grids function effectively [11]. The sustainability challenges of mini-grids, especially those reliant on diesel generation and subsidies, have also been highlighted in the literature[80].

Mini-Grids and the Transition to the Main Grid
Reference [81] presents several scenarios that may occur when the main grid arrives, which are illustrated in Figure 5. Mini-grids connected to the main grid must have the ability to isolate themselves (islanding), so that in the event

of a failure in the mini-grid's production, the main grid supplies electricity to the mini-grid. Conversely, in the case of overproduction, the mini-grid can send the excess power to the conventional grid. This connection requires best practices and standardized technologies to ensure the safety, efficiency, reliability, and best value for mini-grid operators, utilities, and their customers [81]. The connection can be made on a low-voltage network using a common coupling point or on a medium-voltage network through a substation equipped with a bidirectional MV/LV transformer and smart bidirectional meters [82].Connected mini-grids appear to be more economically viable compared to isolated ones. Ismaïl et al. [83] reviewed the existing literature on how to utilize excess energy in hybrid renewable energy production systems and found that energy costs can be minimized if surplus energy is used. Ahmad et al. [12] and Rajbongshi et al. [84] conducted a study on the techno-economic viability of grid-connected and off-grid hybrid systems. They concluded that grid connection is more economically viable compared to an off-grid system. These connection modes are illustrated inFig 6.

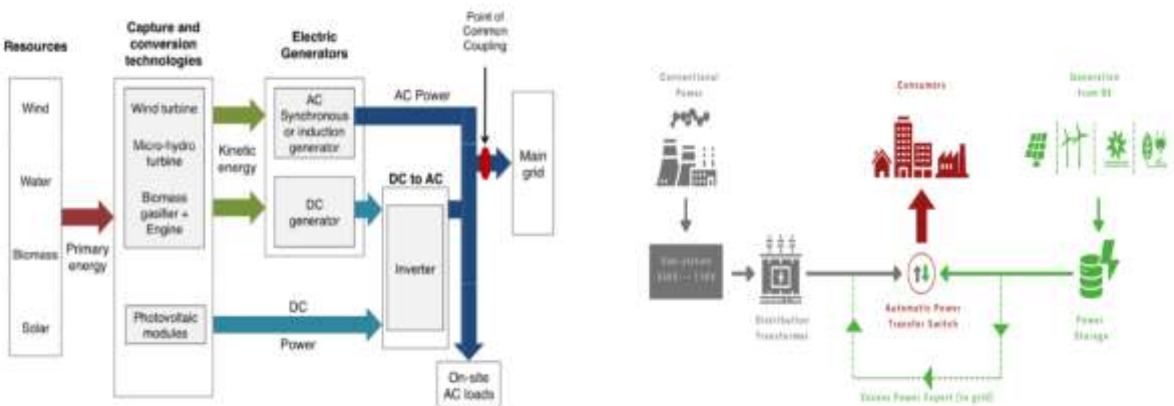

Fig 5:- Connecting a mini-grid powered by renewable energy sources to the main Low Voltage (LV) [81] and Medium and Medium Voltage (MV) grids[85].

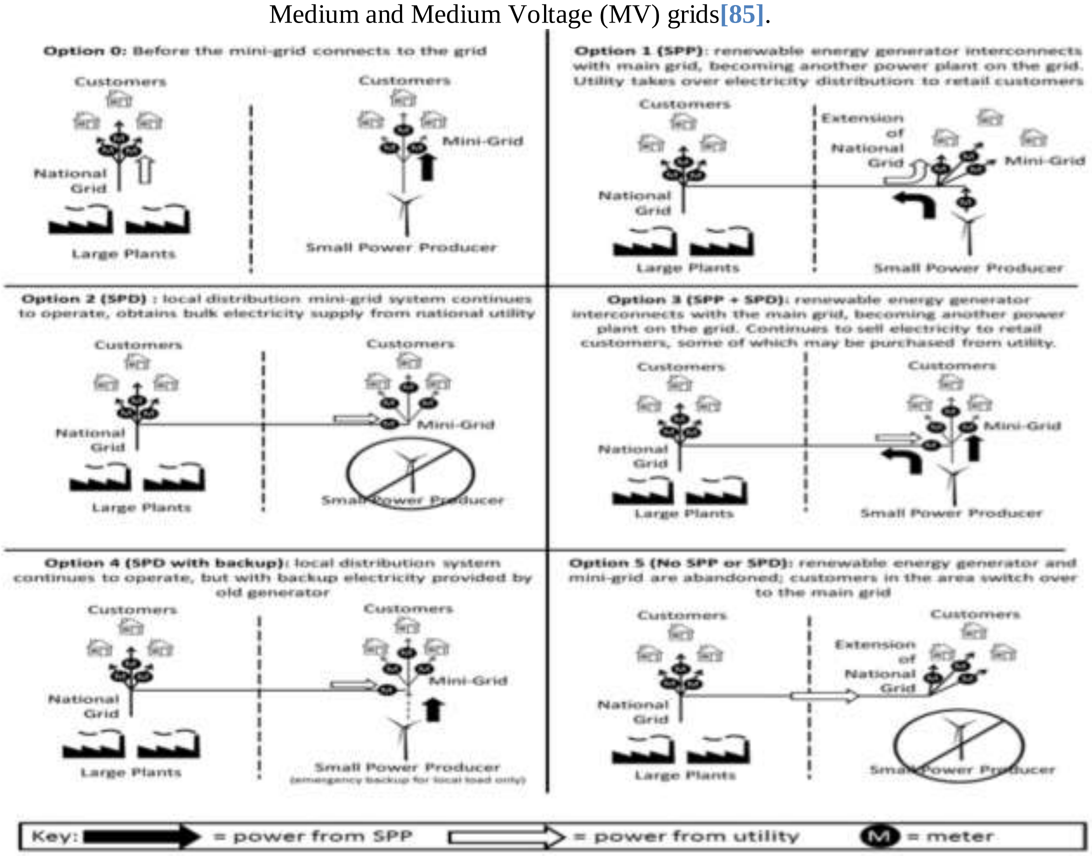

Fig 6:- Mini-Grid Connection Options to a Main Grid [81].

Optimizing Mini-Grids through New Technologies
As most mini/micro-grids rely on distributed generation sources like solar photovoltaics and wind power, which are often intermittent and unpredictable, it is crucial to optimize their use to tackle energy security challenges[71]. New technologies can be used to achieve this.

Artificial Intelligence (AI) and Machine Learning (ML):
The creation of new technologies and protocols to facilitate the use of AI and ML in mini-grid development is essential for ensuring efficient data collection and analysis[86]. This progress could include the implementation of sophestcated sensors and data analysis tools, along with the development of new algorithms to process and analyze vast amounts of data in real-time. Examples of applying these technologies for mini-grid optimization can be found in the studies [86], [87], [88].

Blockchain:
Blockchain is a distributed digital ledger that offers a secure and transparent method for recording transactions. When applied to mini-grids, blockchain can facilitate a decentralized energy market, allowing participants to engage in peer-to-peer energy trading. Furthermore, blockchain enhances security and transparency in tracking energy transactions, helping to minimize fraud and boosting the efficiency of the energy market [89]. Another advantage of blockchain technology in mini-grids is its ability to incentivize the use of renewable energy. Participants in the mini-grid can earn blockchain-based tokens or tokens linked to renewable energy certificates for using sources like solar and wind power. These tokens can encourage the shift toward a more sustainable and decentralized energy system, while also providing economic benefits to mini-grid participants[64]. Although blockchain technology offers promising benefits for mini-grids, its implementation comes with several challenges. For instance, scalability and energy efficiency can be difficult to achieve, particularly in mini-grids with limited computational power. Additionally, the regulatory landscape for blockchain-driven energy markets is still developing, which creates uncertainty for both mini-grid developers and participants[90]. Current research and development are aimed at enhancing the scalability and energy efficiency of blockchain technology, as well as establishing stronger regulatory frameworks for blockchain-driven energy markets[91].

Potential Research Areas for Mini-Grids
The prospects for energy transition drive researchers to envision technologies that promote the decarbonization of energy systems, such as decentralized energy production through the utilization of renewable energy sources and energy storage, heat pumps, and also the manufacturing of electric vehicles, with end-use applications across electricity, transportation, and heating/cooling sectors [44].A highly promising area of mini-grid research is the advancement of community-based mini-gridswith private or public investors. By granting local communities the management of their energy systems, these mini-grids can encourage greater social equality and empower communities to proactively address their energy needs [92].

The Transportation Sector:
This sector has attracted significant attention lately due to the surge in electric vehicles, which has driven the need for reliable and efficient charging infrastructure. Mini-grids can play a crucial role by providing local energy sources for electric vehicle charging stations, thereby easing the burden on the main power grid and offering a more resilient and flexible energy solution[93].

Urban Areas:
Due to the continuous growth of urban populations, it is necessary to have reliable and sustainable t energy systems capable of meeting the energy requirements of these communities [94], as well as installing electric vehicle charging stations to prevent overloading the grid.

Case Study: India
The Indian Energy Mix
India's energy mix consists of various sources like coal, natural gas, hydroelectricity, solar, wind, and nuclear, but coal has historically dominated electricity production. India has implemented an energy transition policy aimed at gradually reducing its dependence on fossil fuels and working towards the goals of the Paris Agreement. In 2019, the government has set a goal to achieve 500 GW of renewable energy capacity by 2030. Four years later, a capacity of 180 GW has already been installed, with an additional 88 GW planned for the short term India is the world's fourth-largest in installed wind energy capacity and ranks sixth in solar energy capacity. Overall, it stands fifth

globally in total renewable energy installations. In 2022, the country aimed to reach 175 GW of renewable energy capacity[95]. ndia's energy landscape is highlighted by its total installed capacity of 403.759 GW as of the end of 2022, with 113.22 GW coming from renewable sources[96]. Fig 7 shows the evolution of India's energy mix.

In 2021, fossil fuels were responsible for 76% of India's electricity production. Coal makes up the largest portion of India's energy mix, contributing 73% to the total production. Natural gas, oil, and nuclear energy together made up less than 7% of India's electricity supply [97]. In 2023, India's energy demand was primarily met by coal (45%), oil (25%), and natural gas (6%), while renewable sources accounted for 24%, with biofuels being the main contributor [98]. Fig 8 below shows India's progress toward achieving its renewable energy targets in its future energy production[99].

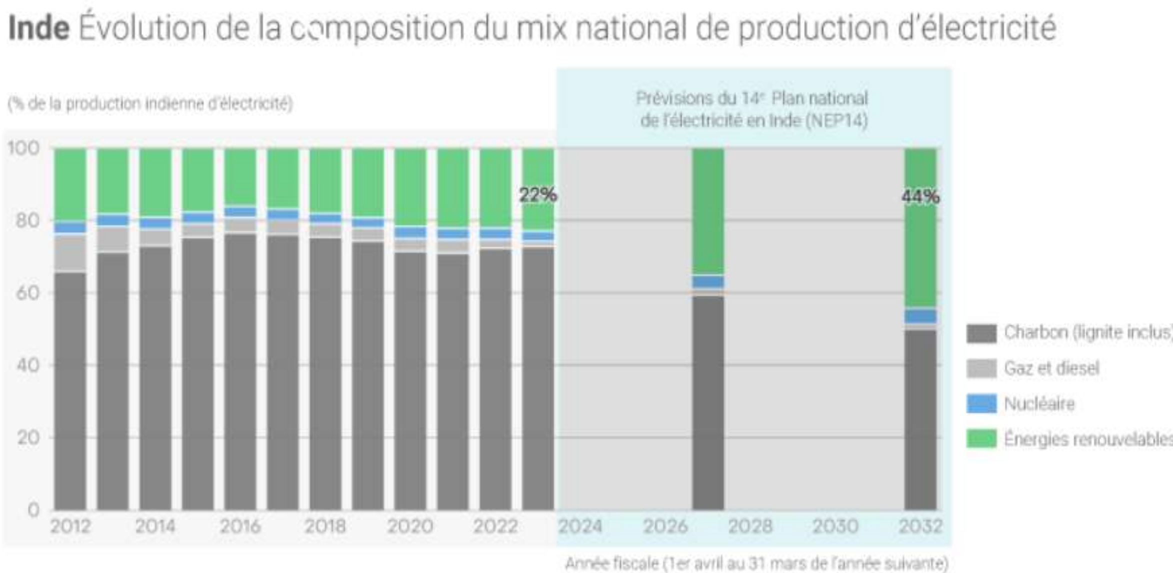

Fig 7:- Evolution of India's Energy Mix [100].

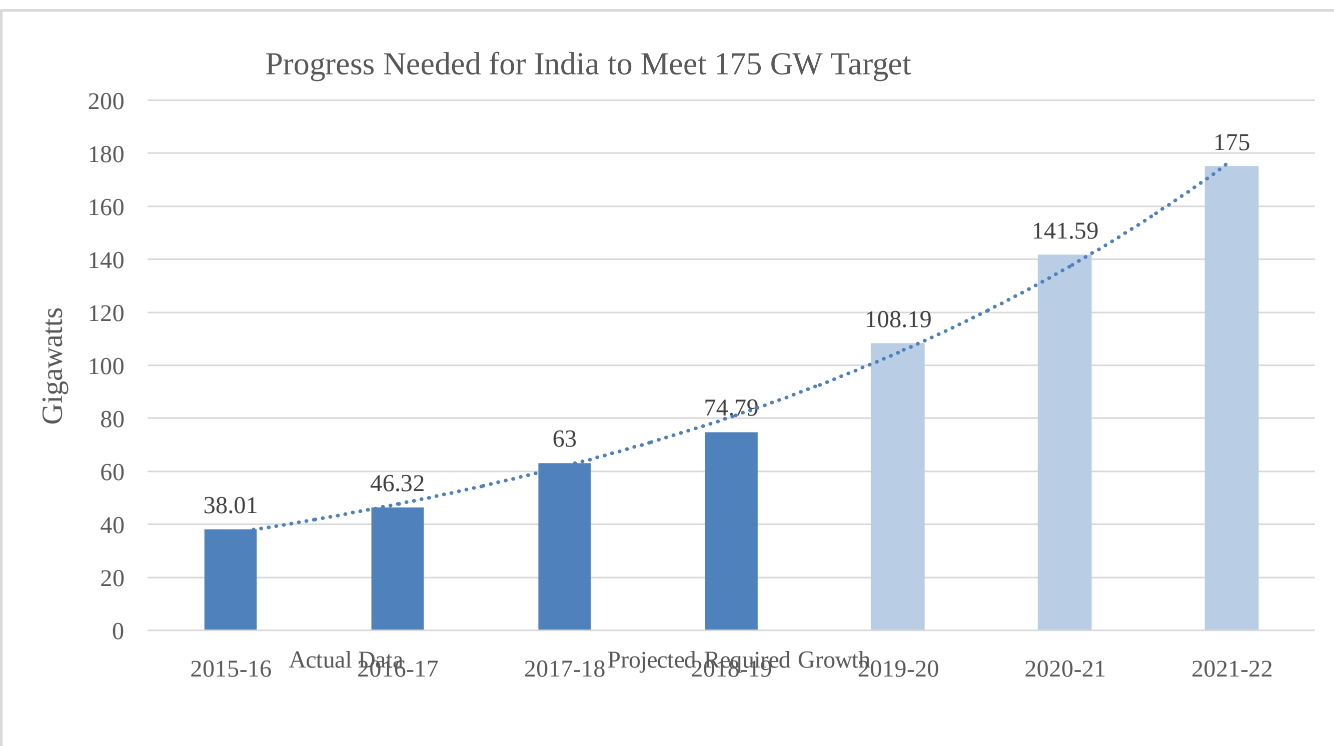

Fig 8:- India's Progress in Achieving Its Future Energy Production Goals [99].

Rural Electrification in India: The Star Performer of Mini-Grids

Despite considerable public investment in this project, connection and electrification rates remain below the targets set by the government[101]. The plan is to develop these mini-grids alongside the main grid, with the goal of eventually connecting them. Mini-grids, unlike smaller-scale solutions like pico lighting or home solar systems, have the potential to significantly drive economic growth and productivity. They enable the use of advanced equipment that can produce valuable products and services[102]. These two approaches are not necessarily mutually exclusive. When small generation and distribution systems are set up with the potential for future connection to the main grid, they can complement the central power grid[103]. Interconnecting grids avoids the need to use mini-grids with large storage systems, as the grid is available for charging support. Mini-grids connected to the main grid also offer greater system reliability by isolating from the central grid during periods of failure or natural disaster [104]. India is a leading player in the global mini-grid market [27]. Approximately 14,000 mini and micro-grid systems installed in India are managed and maintained by the government, private companies, and charitable organizations [105]. As part of the Saubhagya initiative launched in 2017, the government aims to electrify the 572 unelectrified villages in India and improve household power penetration, which is currently at 8% [104]. In 2018, the International Energy Agency (IEA) acknowledged India as a "star performer" for reaching the significant milestone of connecting over half a billion people since 2000 and for electrifying all of itscommunities [28].

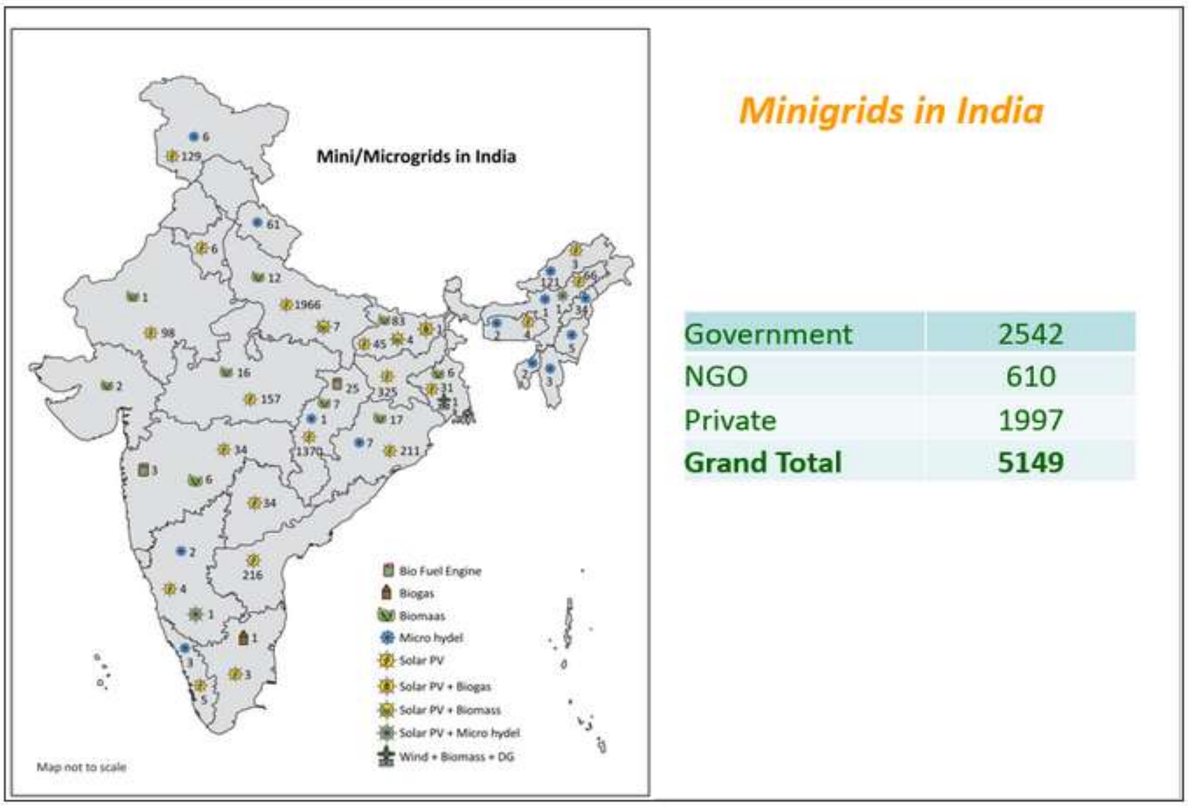

Fig 9:-Minigrids in India in 2019 [28].

The Indian Government's Contribution to Mini-Grid Development

Robust government support and advancements in the economic landscape have positioned India as one of the leading renewable energy marketsglobally. The government has introduced policies, programs, and created a favorable environment to encourage foreign investmentand accelerate the expansion of the renewable energy industry[106]. A new generation of energy companies, some of which are private firms, is emerging. These companies not only develop and operate wind and solar farms but also participate in their manufacturing and construction through in-house engineering services, manage the maintenance of installations throughout their lifespan, and sometimes even acquire a portion of the energy produced [107]. This shift makes mini-grids based on renewable energy, particularly those linked to each other and/or the main grid, making them a viable option not just for rural areas, but potentially even more beneficial for urban installations. With a degree of pricing equalityfacilitated by regulation, and the integration of artificial intelligence, there is potential for an improvement in the current paradigm of the inefficient power distribution model to a more advanced, market-drivenelectricity distribution model [28].

Table 4:- Indian Government's Mission to Promote Renewable Energies [108], [109].

Mission/Scheme	Active Form	Type&Size of component	Significance
National Wind Mission	2015	Wind	Goal of 60,000 MW generation by wind energy by 2022 against the Rs 10,000,000 crore investment
Jawaharlal Nehru National Solar Mission	2010	Solar,40 GW rooftop, 60 GW small and large solar PV plants	Phase 1: 2010-13, phase 2: 2013-17, phase 3: 2017-22 It is predicted to abate over 170 tons of CO_2
National Mission for enhanced energy efficiency (NMEEE)	2010	23 million tons fuel saving every year and GHG emissions reduced by 96,55 million tons every year.	NMEEE goals is to fortify the market for energy efficiency by forming conductive regulatory and strategic organization and has visualized fostering state-of the-art and sustainable commercial framework to the energy efficiency sec tor
Solar cities development program	2011	Solar	Over all 60 cities/towns are planned to be reinforced as solar cities during the 11th plan period
NMEEE-USAID PACE-D TA program	2009	solar PV rooftop	Constructing an enabling environment at the national as well as the state level
National Biomass Cook-stoves Initiative (NBCI)	2009	Biomass	It lay emphasis on improvement of specialized potential inside the nation bye innovative techniques, accreditation and observing administrations and fortifying R&D program in key specialized research Centre.
Solar power Generation Based Incentive	2008	Solar	In order to promote and develop RE based on infrastructure, it provides incentives in term of solar feed in tariff rate as Rs 12 for Solar PV systems as Rs 10 for solar thermal based power plants
Generation based incentive for wind power	2008	wind	It was designed to encourage investment in new and large wind based IPPs to achieve target of 10500 MW of wind energy installed capacity at the end of 2012
India-Brazil-South Africa Declaration on clean Energy	2007	Multiple RE sources	secure, reliable, sustainable green energy production to meet global energy demand
Village Energy Security Test Projects (VESP)	2004	Biomass energy	Toward the end of January 2011, a sum of 79 VESP tasks were authorized in 9 states of 65 of these ventures were completely appointed, now more than half of them not functioning
Central Financial Assistance (CFA) for Biogas Plants	2004	Biogas	To make Biogas Development and Training Centers (BDTCs) accessible, for correspondence and attention purposes, and to bolster the repair of old and non-operational plants
Government Assistance for Small Hydropower Stations (SHP)	2003	SHP	Extended economic and monetary incentives for the development SHP

Government Assistance for Wind Power Development	2002	Wind	To promote the development of wind energy it provides the provision of preferential loans for wind turbine stockholder

A report from the World Bank [110] compares international regulations concerning access to sustainable energy, renewable energy sources, and energy efficiency. In theenergy access section, eight sub-indicators are evaluated, each on a scale of 100 points. The final score is calculated throughaveraging these sub-factors. India ranks first with a score of 84 points in this section.

Table 5:- Regulation indicators for energy access in selected countries [47], [110]

Country	**Total**	**Electrification plan**	**Scope of plan**	**Grid electrification framework**	**Framework for Mini-grids**	**Framework for stand Alone systems**	**Affordability**	**Utility Transparency**	**Utility Credit worthiness**
India	84	80	75	100	77	69	100	96	76
Kenya	82	100	50	67	66	93	100	96	86
Philippines	82	100	75	67	85	62	100	87	82
Uganda	78	100	63	67	64	93	100	79	59
Tanzania	75	100	50	100	96	73	100	83	0
Bangladesh	68	80	25	33	74	80	100	100	54
Bottom Ranking Counties									
Sierra Leone	17	0	0	0	35	40	50	8	0
Chad	14	0	0	17	30	11	50	4	0
Haiti	13	0	0	0	43	11	50	0	0
Central Africa Republic	11	0	0	0	10	11	0	17	50
Somalia	3	0	0	0	5	22	0	0	0

Legend: red ≤ 33; yellow 33 < x < 67, green ≥ 67

Mini-Grids and the expansion of the Conventional Indian Network

The expansion of the grid in India is largely subsidized, with small users in rural areas benefiting from cross-subsidies provided by bigger users. This situation makes icauses it to bet more challenging for mini-grids to contend against the electricity tariffs of the network, posing one of the main threats to the thefunctioningof mini-grids in India [111]. Some researchers have studied the future of Indian mini-grids after rural villages have been electrified by the central grid. Harish et al. [112] examined the adoption of solar lighting systems (SLS) in six districts of Karnataka revealed that, despite being connected to the grid, households chose SLS due to the grid's unreliability. Consumers tend to adopt a technology when they perceive it as more reliable or advantageous than other options[113]. Sharma et al. [114] provide empirical data on the adoption and usage of solar mini-grids was gathered through a survey conducted in 54 communities equipped with both a national network and a solar mini-grid. The survey data comes from 2,648 households and 544 non-agricultural rural businesses spread across 54 communities in 19 districts of the Indian states of Uttar Pradesh and Bihar. Their findings indicate that in the surveyed villages, rural businesses have turned to alternative energy solutions at a significantly greater than rural households. The insufficient quality of electricity supplyaffects the efficiency and profitability of businesses, making them more likely to turn to grid alternatives if they provide reliable energy [114]. While over 90% of user businesses find mini-grids reliable, sufficient,of high-quality, and easy to repair, but less than 50% of them hold a comparative opinion regarding the electric grid [114]. Furthermore, 60% of the households surveyed stated that grid electricity was their primary source of power, while only around 30% of businesses mentioned grid electricity as their main source.
Fig **10** and Fig 11 illustrate user perceptions on main grid and mini-grid systems.

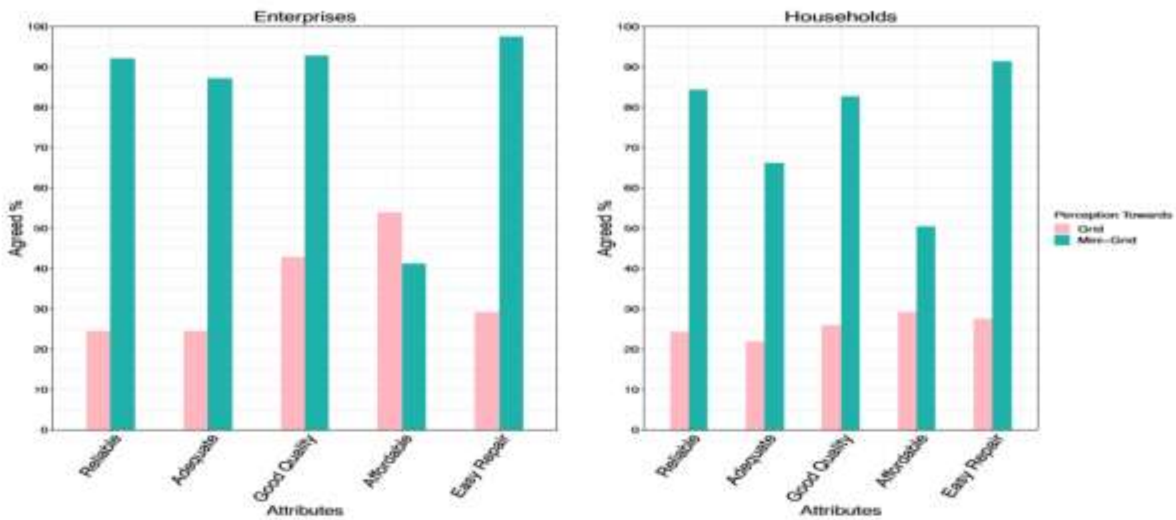

Fig 10:- User Perceptions of Main Grid Electricity vs. Mini-Grids [114].

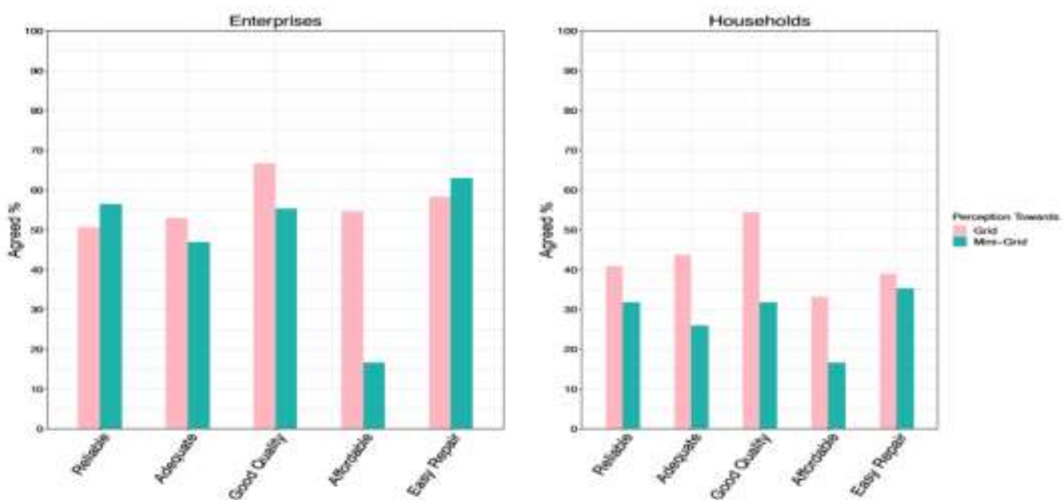

Fig 11:- User Perceptions of Main Grid Electricity vs. Mini-Grids [114].

Stakeholder Perspectives on the Development of Mini-Grids

The examination of opportunities, obstacles, and threats to mini-grids development by stakeholder group shows divergences in perceptions of the issues, particularly between stakeholders more involved in mini-grids and those focused on the main grid. Despite these differences, all participants support mini-grids as a tool for electrification and development [115]. **Table 6** summarizes the different perceptions of the stakeholders.

Table 6:- Stakeholder Opinions on Mini-GridsDevelopment in India [115].

	Stakeholder perspectives of :	
	Minigrid benefits and opportunities	Minigrid Threats and barriers
ONG/advisory groups	* Alternative to grid's unreliability * Needed for generation, since grid insufficient transmission capacity in rural areas simple solution for rural households who are willing to pay for electricity * Meet consumer’s basic needs (lighting	More expensive than the grid per kWh of energy * Technical limits to power provision * Restrained by limited external funding and requires sustainable local investment * Need to regulate consumption (e.g. via meters)

	and mobile phone charging) *Quick impact solutions to rural electrification	to combat increasing demand *Different government leadership promotes different paths to electrification * Large systems are too expensive with long paybacks cannot compete with grid for cost recovery * Need continuing impact evolutions * Not all consumers value electricity enough to pay
Government - renewable energy agencies	*Grid unreliability creates space for minigrid development * Local generation and consumption is best *Decreasing cost of electricity *Increasing demand due to increasing awareness of minigrid systems *Possible solution to national electricity shortages *Provide economic co-benefits	* Limited impact where the grid exists *Need to pay back infrastructures costs if/when threatened by grid (exit clause of minigrid policy may not be enough
Government-National grid representatives	Minigrids can provide better service than the grid in some cases: grid expansion is limited *Electricity problems in UP create demand for quality electricity *Growing consumer base and demand	*No need for minigrids, grid will reach everywhere in 5 years Not valuable due to niche market *Developers are too worried about profit, do not prioritize consumers *Technical improvements to grid transmission and distribution systems expected to eliminate need for minigrids
Minigrid developers	*Benefit public(co-benefits) *Consumers value reliability *Consumers in remote villages are willing tp pay for electricity *Decentralized generation decreases transmission losses to remote villages *Increasing aspirational need of consumers allows minigrid growth (e.g., more power to run televisions *Minigrids currently have a strong business case that is anticipated to continue	Limited use to small appliances * Stopgap solution until grid comes *Different than grids

Discussion:-

Several authors argue that mini-grids can solve issues related to access to reliable energy services, rural electrification, and CO_2 emissions. Despite their advantages, challenges to the development of these small networks persist, including technical and social challenges, lack of regulation, high financing costs, and the viability and profitability of mini-grids. The International Renewable Energy Agency (IRENA) reported a decrease of approximately 75% of the cost of electricity generated from photovoltaic solar energy and about 25% from onshore wind farms between 2009 and 2018 [116]. Thus, there is currently a great business opportunity for generating electric power from distributed renewable energy sources, consequently, focus needs be focused on reducing the integration costs of this equipment [42]. India's success story in mini-grids development has been significantly shaped by government commitment. A critical analysis of current off-grid development methods in India indicates that the success of decentralized interventions relies on three main combined determinants: political support, community participation, and productive linkages. Other factors, such as the technology used, sources of funding, and the size of installations, also play a determining role [117]. Mini-grids have enabled India to accelerate its electrification, decarbonize its energy system, provide reliable energy services, and reduce rural poverty. Major challenges to connecting to mini-grids include energy prices that are 25 times higher compared to those of the national network grid and the uncertain future of mini-grids, which are often viewed as a temporary solution. Energy transition perspectives drive researchers to envision new technologies to access reliable, sustainable, and affordable energy services while combating climate change. Future research should focus on developing mini-grids in urban environments, integrating mini-grids into the transport sector, and optimizing mini-grids by incorporating new technologies such as blockchainandartificial intelligence.

Conclusion:-

Mini-grids have the potential to accelerate electrification, improve the dependability of energy services, and contribute to the transition to a low-carbon energy system. Despite their numerous advantages, these mini-grids face political, regulatory, technical, and social challenges. Stakeholders such as policymakers, mini-grid developers, and consumers must play a crucial role in their development to tackle challenges associated with the energy crisisand the reliability of energy services. Researchers in this field should focus on developing community mini-grids, their integration into urban areas to enhance electric vehicle charging stations, and the use of emerging technologies like artificial intelligence andblockchain to tackle mini-grid challenges. In India, mini-grids have played a crucial part inaccess to electricity and reducing greenhouse gas emissions. The Indian government is committed to promoting renewable energy and electrification through mini-grids. However, some challenges, such as access to financing, clarification of regulations concerning the future of mini-grids with the arrival of the main grid, and the high cost of energy produced by mini-grids, must be addressed to allow for their full-scale development and make them an affordable solution for electrification in India.

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