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Scope of Solar Energy in Rural Electrification: A Global Perspective with Special Reference to India

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Abstract: *Over 1.06 billion people worldwide lacked access to electricity as of 2016, with the majority of those people being located in rural areas in developing countries in South Asia and Sub-Saharan Africa. Solar photovoltaic (PV) technology represents one of the most viable and scalable solutions for providing electricity to rural areas; due to the rapidly decreasing cost of this technology, the ability to be built in modular/scalable sizes, and because it operates independent from centralized grid infrastructure. The purpose of this paper is to review the status of solar energy deployment globally in rural electrification , focusing on India's national solar programmes such as the Jawaharlal Nehru National Solar Mission (JNNSM) and Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY). Key technologies that will be discussed are Solar Home Systems (SHS), Solar Mini-Grids and Solar Pumping Systems as routes to rural electrification using solar energy. Global and India-specific data related to installed capacity, levelised cost of energy (LCOE), employment created and socio-economic impacts will be analysed. The major barriers to solar rural electrification will be highlighted as financing barriers, technical sustainability of systems and policy gaps; along with suggested future research directions.*

Keywords: Solar energy, rural electrification, solar photovoltaic, solar home systems, mini-grids, JNNSM, India, renewable energy, energy access, sustainable development

I. INTRODUCTION

Electricity access is widely regarded as an essential prerequisite to achieving economic development, education, health care, and social well-being. Over 84% of the unelectrified population lived in rural areas and primarily resided in sub-Saharan Africa and South Asia (IEA, 2017). Grid extension (the traditional approach for rural electrification) has been found to be prohibitively expensive and technically difficult in rural, remote communities with low density of population. In developing countries, the average cost of extending the national grid to rural homes in remote areas ranges between USD 1,500 and USD 3,000 per connection and can exceed USD 10,000 per household in mountainous or island areas (World Bank, 2008). Due to these costs, off-grid and decentralized renewable energy solutions — particularly solar photovoltaic (PV) technology — are gaining a great deal of interest from governments, development organizations, and the private sector.

There are several reasons why solar energy is particularly well suited for rural electrification. Solar radiation is a geographically abundant resource and is available in nearly every location in the rural environment. Solar photovoltaic (PV) systems are modular in nature; available in a variety of configurations, including household (5-20 Wp solar home systems) and aggregated into village-scale mini-grids (10 kW to hundreds of kW). The most important factor contributing to solar energy's growing attractiveness as a rural electricity generation option will be the dramatic decrease in the price of solar PV technology. The global average levelised cost of electricity (LCOE) for utility-scale solar PV dropped from approximately USD 0.36/ kWh in 2010 to a much more competitive USD 0.10/ kWh in 2017 (IRENA, 2018), making it very competitive with diesel generation and grid supply as sources of electricity for remote rural communities. One of the places in the world where this transition to solar energy will have a dramatic socio-economic impact will be in India. India has a population of over 1.3 billion; however, by 2015, there were over 300 million people without access to reliable electricity (Government of India, 2015). In 2010, India launched the Jawaharlal Nehru National Solar Mission (JNNSM), first goal to generate 20,000 MW of solar photovoltaic electricity by 2022 (later revised to 100,000 MW). The rural off-grid component of the JNNSM represents an extremely important aspect of sustainable development, poverty reduction, and climate change mitigation. This paper will assess global and Indian solar rural electrification through 2017, evaluate key technology pathways, and identify research and policy gaps.

II. LITERATURE REVIEW

The academic and policy literature on solar energy for rural electrification is extensive and growing. Chaurey and Kandpal (2010) completed one of the first complete analyses of Solar Home Systems (SHS) in India, finding that SHS's will provide basic lighting and communications at a lower cost to communities located more than 5 km from any grid than would diesel generation. They took a sample of more than 6,000 SHS installations in the states of Rajasthan and Uttarakhand and found that households that adopted SHS systems spent approximately 40-60% less on energy (annually) than households relying on kerosene for energy.

On a global scale, Bhattacharyya (2012) completed a study of off-grid electricity access models in Sub-Saharan Africa and South Asia and determined that solar mini-grids were best suited for communities with a population size of 200-500 households, while solar home systems were best suited for widely dispersed communities. The International Energy Agency projected (2011) that overall global investment of about $48 billion per year would be necessary to achieve universal electricity access by 2030, and that off-grid solar PV energy would be the least expensive way to electrify approximately 70% of the world's unelectrified communities.

In terms of economic viability, Szabo et al.(2011) conducted a study on geospatial least-cost electrification alternatives for Africa that concluded, for communities over 10 km from existing infrastructure, the most economically viable electrification technology was solar photovoltaic mini-grids (Bennett & Mulaudzi, 2012). Solar photovoltaic mini-grids could electrify 490 million people (within Sub-Saharan Africa) more economically than electric grid extension (Palit & Chaurey, 2011; IRENA, 2015).

On the technology front, Kalogirou (2013), in reviewing solar energy conversion technology, indicated that by 2012 the commercial efficiencies of mono-crystalline silicon photovoltaic modules had increased to 15–20%. Between 2011 and 2014, installations of solar home systems grew from approximately 3 million worldwide (2011) to more than five million (2014), with Bangladesh, India, and Kenya being top markets for these products. The Lighting Global Programme, a joint effort of the World Bank and the International Finance Corporation, certified over 25 million sales of off-grid solar products in 130 countries by the end of 2017.

According to the REN21 Global Status Report of 2016, India had 900 MW of off-grid solar capacity installed by 2015, making it second largest solar energy producer after china. The MNRE Annual Report of 2016-17 showed that more than 1,200,000 solar home lighting systems and 1,470,000 solar lanterns had been distributed to rural India as part of the JNNSM program through March 2016. Laufer and Schafer (2011) documented failure rates of 20 to 40 percent in solar home systems after three years when there was no after-sales service network in place,Palit and Chaurey (2011) in India also supported these results thus highlighting the need for institutional support.

III. METHODOLOGY

Research Design

This study employs a qualitative and descriptive review-based research design. Secondary data is drawn from international energy reports, governmental publications, peer-reviewed academic journals, and institutional databases.

Data Sources

- IEA World Energy Outlook Reports (2011-2017)
- IRENA Renewable Capacity Statistics and Technology Briefs (2014-2018)
- REN21 Global Status Reports (2013-2017)
- World Bank ESMAP Reports (2008-2017)
- Ministry of New and Renewable Energy (MNRE), Government of India -- Annual Reports (2013-2017)
- IPCC Fifth Assessment Report (2014)
- Peer-reviewed journal articles (2002-2017) in Energy Policy, Renewable Energy, and Energy for Sustainable Development.

Data Analysis Method

A descriptive and trend-based analytical approach was adopted. The analysis examines: (1) global and Indian solar PV installed capacity and off-grid deployment; (2) LCOE across solar technologies; (3) electricity access statistics (millions of people); (4) employment generation; and (5) socio-economic outcomes from case study regions. Data are drawn from the above sources and triangulated where possible.

IV. GLOBAL SOLAR ENERGY SCENARIO FOR RURAL ELECTRIFICATION

Global Installed Solar PV Capacity

Between 2010 and 2017, the global installed capacity of solar photovoltaic power (PV) expanded to about 402 GW from 40 gigawatts (GW), a tenfold increase in seven years (IRENA). While much of this growth occurred in utility-scale and rooftop grid-connected systems in China, the European Union (EU), the United States (US), and Japan, off-grid solar is the fastest-growing sub-sector relevant for rural electrification. By the end of 2017, there were approximately 5.6 GW of off-grid solar capacity installed globally and the outputs from solar home systems, lanterns, and mini-grids were able to provide electricity to approximately 150 million people (IRENA; IEA).

Year	Global Capacity (GW)	Off-Grid Solar (GW)	People with Access (Billions)	Unelectrified (Billions)
2010	40	0.8	5.43	1.20
2012	100	1.5	5.56	1.10
2014	177	2.8	5.67	1.06
2016	295	4.2	5.83	1.06
2017	402	5.6	5.94	1.00

Table 1: Global Solar PV Capacity and Electricity Access Statistics (2010-2017)
Source: IRENA (2018); IEA (2017); World Bank (2017)

Solar Home Systems (SHS)

The use of solar home systems as an approach to rural electrification is widespread as one of the most popular installations of off-grid solar technology. The standard solar home system can be defined as a solar photovoltaic (PV) module (from 5 watts peak [Wp] to 100 Wp), a rechargeable battery, a charge controller, and direct current (DC) outlets for providing light and mobile phone charging capability. By 2017, the worldwide number of solar home systems has surpassed 28 million units globally; during this timeframe, Bangladesh had approximately 4+ million installed solar home systems as part of its Solar Home Programme (IDCOL, 2017). The price of a standard 20 Wp solar home system has decreased from approximately USD 150 to 200 in 2010 to approximately USD 80 to 120 in 2017. The reduced price of the solar home

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system means that an average rural household switching from kerosene to solar home systems as their primary energy source will save, on average, between 30 and 50% on their annual energy costs (IRENA, 2016).

Solar Mini-Grids

Solar mini-grids provide a more reliable electricity supply than traditional electricity sources for rural villages, agricultural operations, and healthcare facilities needing consistent use of electricity - examples include small-scale businesses, irrigation systems, and clinics - all of which typically require more than just a single source of electricity. A complete solar mini-grid generally comprises a central solar photovoltaic array (10 kW to multiple MW) along with battery storage and a local distribution system. Till 2017, over 3000 solar mini-grids have been installed throughout Sub-Saharan Africa and South Asia, with estimated combined generation capacity of about 150 MW (IRENA, 2016). In most instances, the cost per kilowatt-hour associated with providing power through solar mini-grids is substantially lower (between $0.20-$0.40/kWh) than supplying electricity via diesel generators (between $0.30-$0.70/kWh).

Technology	System Size	Typical Users	LCOE (USD/kWh)	Battery Life
Solar Home System	5-100 Wp	1 household	0.40-0.80	3-5 years
Solar Lantern	0.5-5 Wp	1-2 persons	0.50-1.50	2-3 years
Solar Mini-Grid	10 kW-1 MW	100-1,000 HH	0.20-0.40	5-10 years
Solar Water Pump	0.5-10 kW	10-50 farmers	0.15-0.30	10-15 years

Table 2: Key Parameters of Solar Technology Pathways for Rural Electrification
Source: IRENA (2016); World Bank ESMAP (2015); Lighting Global (2017)

LCOE Trends and Cost Competitiveness

LCOE has decreased drastically and has been the primary driving force behind the economic viability for solar rural electrification. According to IRENA (2018), the global average LCOE (levelized cost of electricity) for utility-scale solar PV has decreased from 36 cents (USD) in 2010 to 10 cents (USD) by 2017 (a reduction of 72%) in just seven years. While the cost of off-grid systems is still higher than grid-based systems because of the need for battery storage, the ongoing trends are equally compelling. The price for lithium ion battery storage has decreased significantly (73%) between 2010 and 2016 from 1,000 USD/kWh to 273 USD/kWh (Bloomberg NEF, 2017).

Technology	2010	2012	2014	2016	2017
Utility Solar PV	0.36	0.25	0.18	0.12	0.10
Solar Mini-Grid	0.60	0.50	0.40	0.30	0.22
Solar Home System	1.00	0.85	0.70	0.55	0.45
Diesel Generator	0.30	0.31	0.28	0.22	0.21
Kerosene Lamp	1.50	1.50	1.40	1.35	1.30

Table 3: LCOE Trends for Solar and Competing Technologies (USD/kWh, 2010-2017)
Source: IRENA (2018); Bloomberg NEF (2017); IEA (2017)

V. INDIA: NATIONAL SOLAR PROGRAMMES AND RURAL ELECTRIFICATION

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Jawaharlal Nehru National Solar Mission (JNNSM)

The Government of India launched the Jawaharlal Nehru National Solar Mission (JNNSM) in 2010 with an initial target for generating 20,000 MW of solar energy by 2022. Between 2010 and 2015, the national solar mission was extended to include an additional 100,000 MW of solar power with an additional 48,000 MW of rooftop solar and another 52,000 MW from utility scale solar installations.

In addition to supporting utility scale generation, rural electrification using off-grid solar technology was a component of this mission, and involved installing 2,000 MW of off-grid solar applications, such as solar home lighting systems, solar streetlights, solar pumping systems and village solar mini-grids (MNRE, 2016).Until March 2017, the total amount of solar PV installed capacity in India was approximately 12,288 MW (12.3 GW), which represents an incredible growth in solar capacity since almost no solar PV had been deployed in India prior to 2010 (MNRE, 2017).

By March 2017, over 1.5 million solar home lighting systems, 1.47 million solar lanterns, and over 118,000 solar streetlights had been installed in rural areas of India under JNNSM (MNRE Annual Report, 2016- 2017). In March 2016, there were approximately 109,000 solar water pumps installed in India, and all of the solar water pumps were installed with government subsidies.

RGGVY, DDUGJY, and SAUBHAGYA Scheme

The Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY), which started in 2005, aimed to provide all Indian villages with electricity and connect low-income (BPL) households to the grid for free. By 2012, the government classified 99.8% of villages as "electrified" – meaning that at least 10% of residents had access to electrical services and the public spaces (such as schools) could access the same services. However, this created a false impression about the availability of electric service because millions of rural households were not able to connect.

In 2015, the RGGVY program was merged into the Deen Dayal Upadhyaya Gram Jyoti Yojana (DDUGJY), which would attempt to provide all rural areas with 24x7 electrical service, and also that solar off-grid systems should be used for rural communities that are too far away to connect to a traditional electrical grid.

In September 2017, the government announced the SAUBHAGYA (Pradhan Mantri Sahaj Bijli Har Ghar Yojana) program, intended to achieve universal electrical connectivity within households by March 2019. Solar-off-grid technologies were specifically identified for remote households, including solar home systems and mini-grids; the goal of this program is to provide electrical service to approximately 4 million households using solar off-grid solutions (PIB, 2017).

State-Level Solar Capacity and Rural Electrification Status

State	Solar Capacity (MW)	Off-Grid Solar (MW)	Unelectrified HH (Lakh)	Key Programme
Rajasthan	1,812	45	2.8	JNNSM Phase II
Gujarat	1,119	28	0.9	JNNSM + State Policy
Tamil Nadu	1,627	38	1.4	TNEDCL Solar
Uttar Pradesh	430	62	28.5	RGGVY/DDUGJY
Odisha	112	41	18.2	MNRE Off-Grid
Jharkhand	98	37	12.6	JNNSM Off-Grid

Table 4: State-wise Solar Capacity and Rural Electrification Status in India (March 2017)
Source: MNRE Annual Report (2016-17); CEA (2017); REN21 (2017)

VI. Environmental Impact

Among the various ways to produce electricity, photovoltaic (PV) systems are recognised as having the lowest lifecycle greenhouse gas (GHG) emissions. As documented by the Fifth Assessment Report of the IPCC (2014), crystalline silicon PV systems have a GHG intensity from cradle-to-grave of approximately 41 grams of carbon dioxide equivalents per kilowatt-hour (gCO2eq/kWh), while coal has a lifecycle GHG intensity of approximately 820 gCO2eq/kWh and natural gas approximately 490 gCO2eq/kWh. Thin-film PV technologies such as CdTe and CIGS have an even lower lifecycle GHG intensity ranging from 11 to 22 gCO2eq/kWh (IPCC, 2014). The benefit to the environment from the use of solar equipment in electrifying rural communities is more than just a reduction in carbon dioxide emissions. Switching from kerosene, which is the primary fuel for lighting for households in rural areas not connected to the grid, to solar electricity will significantly improve indoor air quality and eliminate the premature mortality risk related to indoor air pollution, which is estimated by the World Health Organisation (WHO) to be responsible for approximately 4.3 million premature deaths per year. Each small solar home system (SHS) with a capacity of 20 watts can displace approximately 100 to 150 kg of carbon dioxide per year by being used instead of kerosene (IRENA, 2016). The use of solar water pumping systems instead of diesel water pumping systems is expected to save about 0.8 litres of diesel per hour per pump for applications commonly found in Indian agriculture (NABARD, 2016).

Energy Source	Lifecycle CO2eq (g/kWh)	Indoor Air Pollution	Renewable?
Coal	820	None (outdoor)	No
Natural Gas	490	None (outdoor)	No
Kerosene Lamp (effective)	~1,200	Severe	No
Diesel Generator	~650	Moderate	No
Solar PV (c-Si)	~41	Zero	Yes
Solar PV (thin-film)	~15	Zero	Yes

Table 5: Lifecycle CO2eq Emissions Comparison for Rural Energy Sources
Source: IPCC (2014); IRENA (2016); IEA (2017)

VII. ECONOMIC AND SOCIAL IMPACT

Solar rural electrification's economic and social benefits extend far beyond providing light for these remote areas. IRENA's Renewable Energy and Jobs Annual Review (2017) indicates that there were an estimated 3.1 million employees in the global solar PV sector at the end of 2016. Many of these workers are involved in the installation, distribution, and maintenance of solar energy systems in rural areas of India, Bangladesh, China, and sub-Saharan Africa. For example, by 2016-17, it was estimated that the off-grid solar sector in India created about 300,000 jobs (MNRE, 2017). The adoption of solar home systems (SHS) has a direct effect on household financial health. A study involving 6,000 households in Bangladesh (IDCOL, 2016) showed that many of the SHS-adopting households saved USD 4-8 per month in kerosene purchases and received 4-8 hours of reliable electrical lighting each evening. A separate study (Practical Action, 2015) of solar mini-grids in Uttar Pradesh, India found that by providing electricity for productive uses such as flour milling, tailoring, mobile phone recharging, and cold storage of vegetables, the solar mini-grids resulted in households earning an average of INR 1,200-2,500 extra income per month.

VIII. CHALLENGES IN SOLAR RURAL ELECTRIFICATION

Financing and Affordability

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While capital costs may have decreased, the affordability of renewable energy systems still represents a major obstacle for rural households in the lowest income quintile. In fact, even a 20 Wp SHS (solar home system) can be unaffordable to the poorest rural households, as it typically costs USD 80-120 and represents several months' worth of their income. Government-subsidised programmes, such as the JNNSM Off-Grid programme, have tried to close some of the gap by providing some assistance, but overall there are no successful programs that meet the targets that they have set. Pay-as-you-go (PAYG) solar and micro-finance linked programs have been successfully used in Bangladesh and Kenya, but they have not scaled sufficiently in India (Lighting Africa 2016).

Technical Sustainability and After-Sales Service

A problem that is consistently seen in many countries of the world is the loss of solar energy systems due to degradation of batteries, malfunction of charge controllers, and damage to modules. This usually occurs within 2 to 5 years of their being installed, and there is not a sufficient service infrastructure in place for after sales service. Failure rates of solar energy systems in the absence of a service network range between 20% and 40% for three years (Laufer & Schafer 2011, Palit & Chaurey 2011). Local technical capacity and decentralised service networks are also needed in rural areas of India.

Grid Arrival Risk for Solar Mini-Grids

With expansion of national grid into remote areas that don't have electrical power systems, operators of solar mini grids could find their investments stranded due to arrival of a new national grid, especially if regulatory frameworks enabling interconnection/compensation between mini grids and national grids do not exist.Mini grid regulations international (including India), had not yet developed regulations encompassing stranded assets (IRENA 2016).

IX. RESEARCH GAPS

There has been a significant generation of literature about the issue of solar rural electrification in recent years, however, there are many important research needs that have not yet been adequately addressed:

Productive Use of Energy & Economic Impact: While there have been a growing number of studies conducted to evaluate the impact of solar electrification in rural area, very few have evaluated the long-term effects of solar electrification on rural businesses, agricultural productivity, or healthcare outcomes as a result of solar electrification (particularly in India).

Optimising Battery Storage for Rural Mini-Grids: There has been very little research on optimising the size, chemical type, and management system of batteries to meet the specific demand profiles of tropical rural mini-grids (heated and humidified). There is very little data comparing lead acid versus lithium-ion battery performance under partial state charge cycling as is commonly done in rural applications.

Long-Term Sustainability of Business Models: Comparative analyses of the long-term sustainability of government, private, cooperative and fee-for-service business models to operate solar rural systems after the first five years have not been systematically researched. Much of the evidence on the above business models is anecdotal as opposed to based on systematic longitudinal studies.

Mini-Grid Regulatory Framework: The regulatory and policy aspects regarding the deployment of solar mini-grids (for example, the issue of how to license them, establish the tariff structures, provide compensation for the arrival of the main grid, and protect consumers) in India have not received (i) enough analytical attention, and (ii) recognition that they represented major barriers to deployment (according to multiple stakeholders).

X. CONCLUSION

The solar industry has become the preferred option for rural electrification in low-income countries mainly because of its scalability, affordability, and sustainability. The price of solar photovoltaic systems (PV) has dropped sharply between

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2010 and 2017, making it a more economical way to achieve rural electrification than diesel generators or extending electricity grids from urban areas. By 2017, it was estimated that there were 28 million solar homes and more than 3,000 off-grid solar mini-grids in the world, providing electricity to around 150 million people. In India, the Jawaharlal Nehru National Solar Mission's (JNNSMx) off-grid solar component was responsible for installing 1.5 million solar home lighting systems and 1.47 million solar lanterns by 2016-17 to enhance rural electrification. India is leading globally with a 100 gigawatt (GW) target for solar installations by 2022 under its solar mission. However, there are still approximately 250 million people in India without reliable access to electricity, most of whom live in increasingly populated rural areas of Uttar Pradesh, Bihar, and the northeastern states. To reach out to them, we will need to expand solar capacity and to focus on creating positive long-term sustainable business practices, develop innovative finance structures, and establish an appropriate policy environment that supports mini-grids.

Solar-powered electrification in the countryside has multiple co-benefits, such as reducing the use of kerosene, eliminating indoor air pollution, and avoiding greenhouse gases. Because of these numerous co-benefits, the use of solar energy should be made a high priority within national and state plans to achieve electricity for all residents. It is important to view solar rural electrification as more than just an engineering project; it is a very important step toward improving humanity's quality of life, economic freedom, and promoting climate compatible wealth building. In order for the worldwide unelectrified rural population to receive the tremendous benefits created by solar, the knowledge gaps in research on solar must be resolved.

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