CHAPTER 1

INTRODUCTION

1.1 Importance of energy

Energy is a fundamental driver of economic development, social progress and essential for improving quality of life. Energy is central to sustaining the world's growing population, through development of industry, agriculture, transport, communication, health, education, domestic etc. As the world grapples with the challenges of climate change and resource depletion, the importance of renewable energy sources has increased. Globally, there is a growing emphasis on transitioning to sustainable energy sources to address climate change, energy security, and economic stability. The energy landscape remains heavily reliant on fossil fuels, which supply approximately 80% of total energy needs [1, 2]. This dependence has profound environmental consequences, including greenhouse gas emissions, air pollution, and global warming, necessitating an urgent transition to sustainable energy sources [3]. As shown in **Fig. 1.1**, fossil fuels continue to dominate the global energy supply mix from 1990 to 2022, despite the growing share of renewable energy [4].

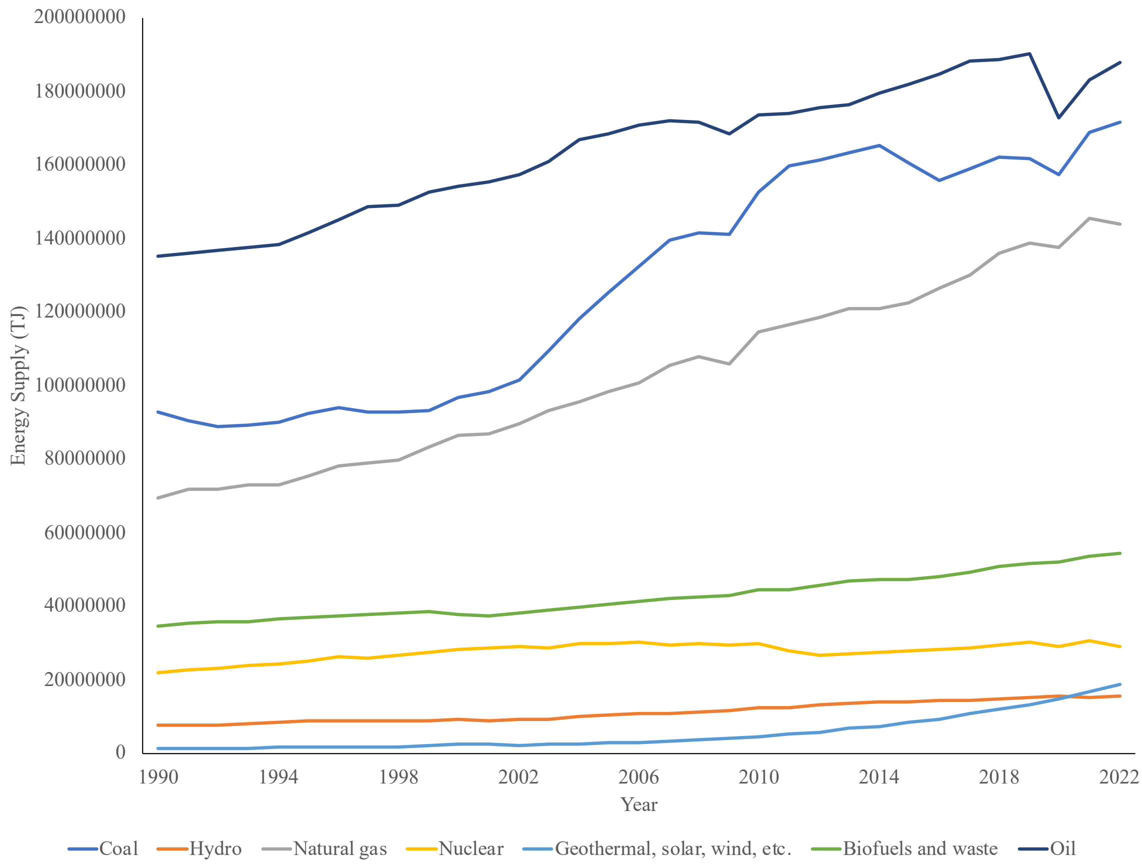

Fig 1.1: Total energy supply by source, World, 1990–2022 (Author's representation based on data by World Energy Balances) [4]

For a rapidly developing nation like India, energy security is crucial, both to meet the needs of its expanding economy and to ensure a resilient and sustainable future. India has established itself as a prominent leader in the renewable energy sector, significantly expanding its energy portfolio to meet increasing energy demands while advancing towards sustainability [5].

The International Energy Agency (IEA) has highlighted the need to triple annual investments in clean energy by 2030 to meet climate targets outlined in the Paris Agreement, including limiting global warming to well below 2°C. Furthermore, energy inequality remains a pressing issue, with approximately 760 million people still lacking access to electricity, predominantly in sub-Saharan Africa and parts of Asia [6, 7]. Addressing this disparity is essential for achieving Sustainable Development Goal 7 (SDG 7), which seeks to ensure access to affordable, reliable, sustainable, and modern energy for all [8].

India, the third-largest global energy consumer, mirrors global energy trends with a heavy dependence on fossil fuels such as coal, oil, and natural gas. **Fig. 1.2** highlights India's energy supply mix from 1990 to 2022, showing the persistent reliance on fossil fuels, albeit with a notable increase in renewable energy contributions in recent years [4].

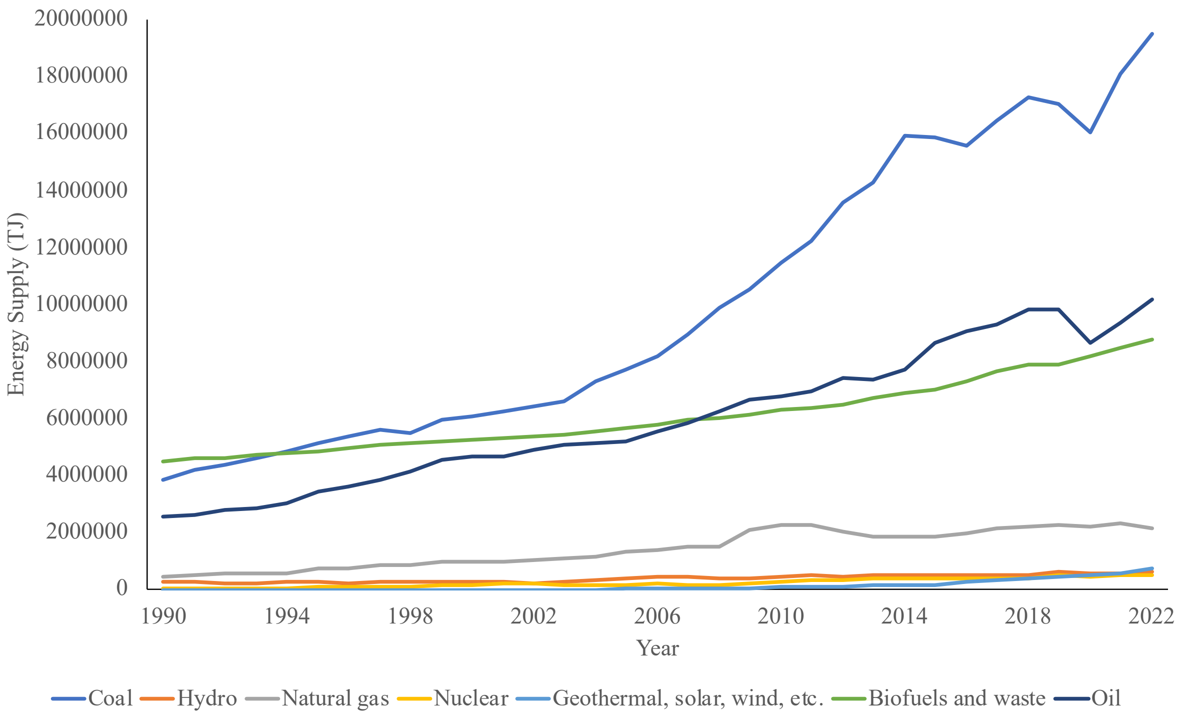

Fig 1.2: Total energy supply by source, India, 1990–2022 (Author's representation based on data by World Energy Balances) [4]

As of December 2024, the country's installed electricity generation capacity stands at 456 GW, distributed across various sources, including coal, gas, diesel, nuclear, hydro, and renewables. As shown in **Fig. 1.3**, coal remains the dominant source, accounting for a significant percentage of total installed capacity [9]. Renewables, however, are gaining momentum, reflecting India's commitment to transitioning to a low-carbon energy system and combating climate change.

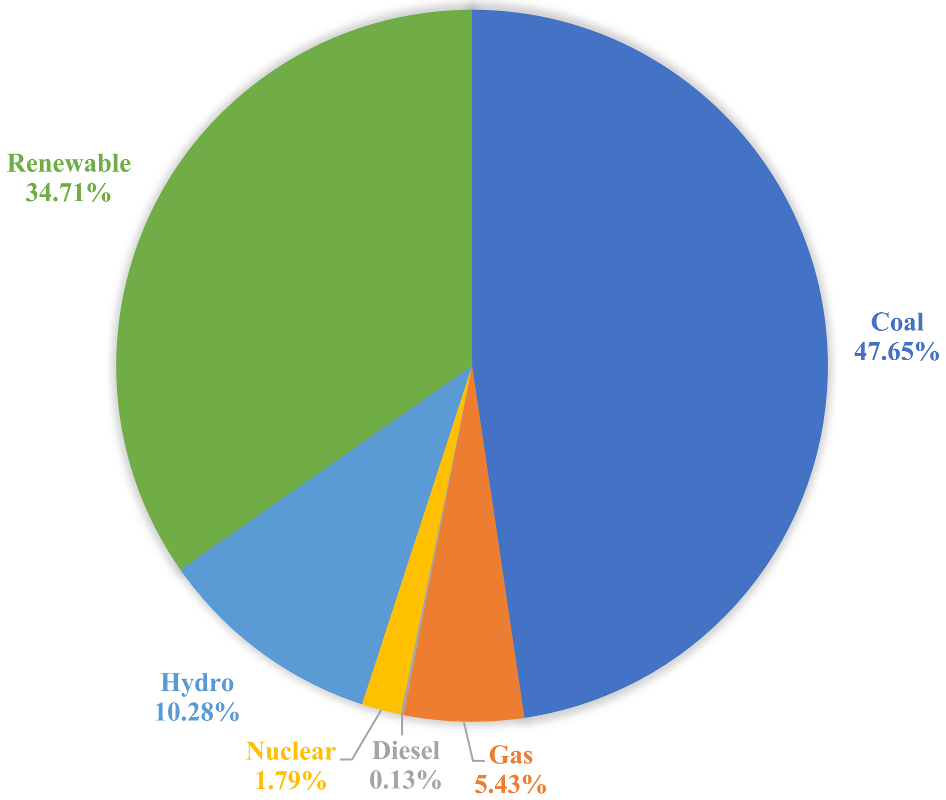

Fig 1.3: Sector-wise India's installed capacity of electricity, 456 GW as of December 2024 (Author's representation based on data by CEA) [9]

India aims to achieve 500 GW of non-fossil fuel-based energy capacity by 2030, aligning with its broader commitment to sustainability and energy security [10]. Initiatives like the National Solar Mission and the Green Energy Corridor are actively addressing barriers such as grid intermittency, inadequate energy storage infrastructure, and disparities in rural electricity access [11, 12]. These efforts focus on enhancing renewable energy integration and improving grid infrastructure, yet achieving these objectives requires continued investments, robust policy frameworks, and innovation to ensure sustainable energy growth.

Despite progress, the adoption of renewable energy at the user level, such as residential and small commercial installations and agricultural applications like solar irrigation, remains below its potential. This gap highlights the need for integrated energy planning and better strategies to harness solar energy fully [13-17]. Achieving a balanced global energy transition requires a multifaceted approach, including policy reforms, technological innovations, and financial investments in renewable energy and energy efficiency [18, 19]. Enhanced international cooperation to support developing nations in overcoming infrastructure and financing barriers is also essential. The growing prominence of energy storage, smart grids, and hydrogen technologies presents additional opportunities to accelerate the shift to a sustainable energy future, addressing both the energy access gap and the global climate crisis [20-22].

1.2 Renewable energy: A global and Indian perspective

Renewable energy addresses global challenges like climate change, energy security, and economic stability. Its adoption reduces greenhouse gas emissions, diversifies energy supplies, and mitigates fossil fuel dependency risks. Advances in technology and declining costs have accelerated global renewable energy deployment [23]. Renewable energy sources, such as solar, wind, hydro, biomass, and geothermal, are sustainable alternatives that contribute to energy resilience while minimising environmental impacts.

Renewable projects also bring socioeconomic benefits, such as job creation, improved energy access, and reduced pollution. These factors make renewable energy a cornerstone of sustainable development [24].

The adoption of renewable energy has seen rapid growth across the globe, driven by international climate commitments, technological advancements, and falling costs. As of 2023, renewable energy accounted for about 30% of global electricity production, with solar and wind emerging as the fastest-growing sources [25]. Countries like China, the United States, and Germany are leading the global renewable energy transition, with substantial investments in solar and wind energy infrastructure [26].

India has emerged as a global leader in renewable energy, leveraging its abundant natural resources to significantly increase the share of renewables in its energy mix. As of 2024, the country achieved an installed renewable energy capacity of over 158 GW, with solar energy leading the transition, supported by the government's ambitious policies and initiatives such as the National Solar Mission [9]. **Fig. 1.4** presents the percentage breakdown of sector-wise contributions from renewable energy sources, highlighting solar, wind, bioenergy, and small hydro power as major contributors to this capacity. The growth of renewables has been geographically diverse, with Gujarat, Rajasthan, Karnataka, Tamil Nadu, and Maharashtra emerging as the leading states. As of March 31, 2024, Gujarat accounted for 14.41% of the national renewable energy capacity, followed by Rajasthan (14.22%), Tamil Nadu (11.63%), Karnataka (11.25%), and Maharashtra (9.20%), collectively contributing 61% of the total capacity [27].

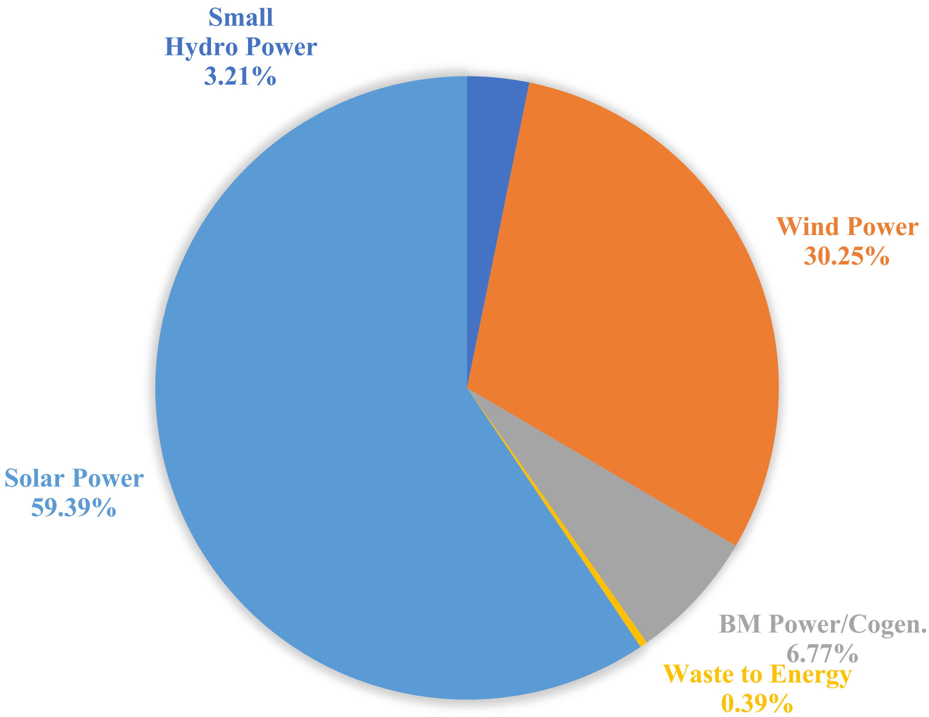

Fig 1.4: Percentage of renewable energy sources, 158 GW (Author's representation based on data by CEA) [9]

India has set ambitious targets for renewable energy deployment over the past few years, with an emphasis on increasing the share of renewables in the country's energy mix. The following are some of the year-wise renewable energy targets that India has set.

- The government has set a target of achieving 175 GW of renewable energy capacity by 2022, which includes 100 GW of solar power, 60 GW of wind power, 10 GW of bioenergy, and 5 GW of small hydro power [28].

- The National Electricity Plan (NEP) envisages achieving a renewable energy capacity of 275 GW by 2025, which includes 140 GW of solar power, 60 GW of wind power, 10 GW of bioenergy, and 5 GW of small hydro power [29].
- India's Nationally Determined Contribution (NDC) under the Paris Agreement calls for achieving 40% of the country's installed power capacity from non-fossil fuel sources by 2030, which is equivalent to a renewable energy capacity of 450 GW [30].
- The government has also set a longer-term target of achieving 500 GW of renewable energy capacity by 2030, which would include a significant expansion of solar and wind power, as well as other forms of renewable energy such as bioenergy, small hydro power, and ocean energy [31].

The increasing renewable energy capacity is supported by various government policies, schemes, and incentives at both utility and user levels. Initiatives such as subsidies for solar panel installations, the Green Energy Corridor for grid integration, and dedicated renewable energy zones have played a critical role in promoting adoption. **Fig. 1.5** illustrates the trend in cumulative installed capacity of renewable energy sources (RES), showcasing India's consistent growth trajectory in renewable energy deployment over the past decade [27].

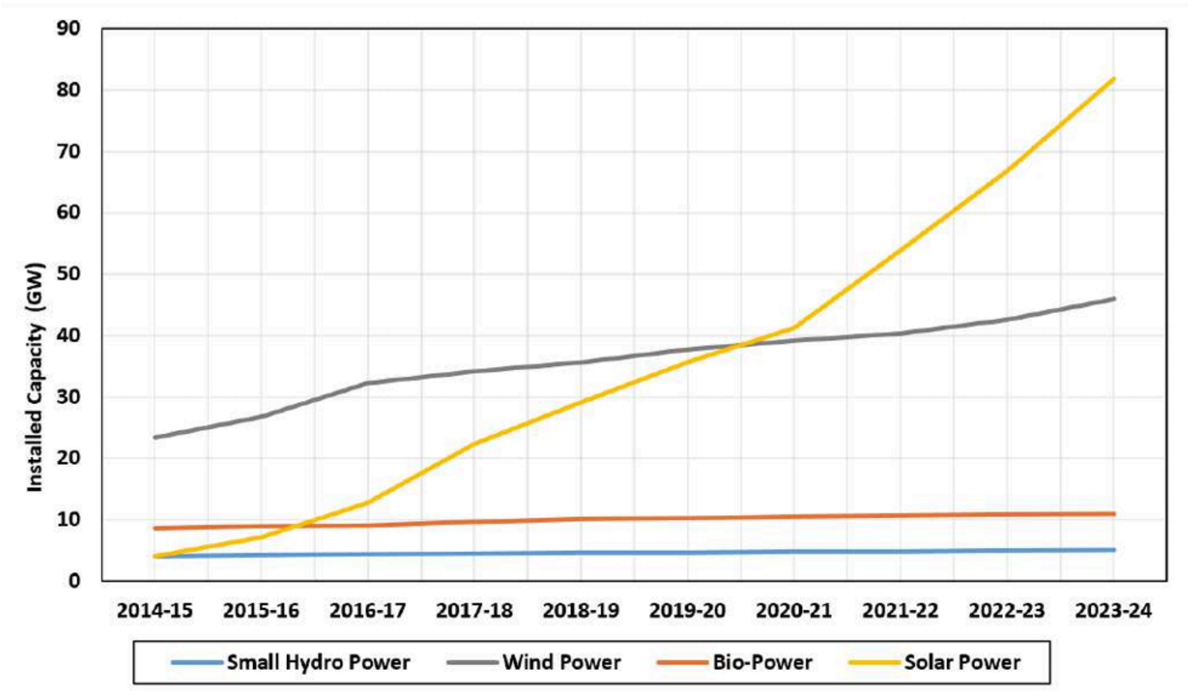

Fig 1.5: Trend in RES cumulative installed capacity [27]

Despite remarkable progress, several challenges persist. Issues such as grid integration, the high cost and land acquisition for large-scale solar farms, and the need for advanced energy storage solutions to manage intermittency remain critical. Addressing these challenges is pivotal to achieving the nation's ambitious renewable energy targets. Furthermore, meticulous planning at both central and state levels is required to unlock the estimated renewable energy potential by State/UT, as shown in **Table 1.1** and detailed further in **Table 1.2** which shows the State-wise installed capacity of Renewable Power as on 30.11.2024, which highlights the distribution of installed capacities across various states and union territories [27, 32].

Table 1.1: Estimated renewable energy potential by State/UT (in MW) [27]

State/UT	Wind Power (MW)	Small Hydro Power (MW)	Biomass Power (MW)	Bagasse Cogeneration (MW)	Solar Power (MW)	Large Hydro (MW)
Andhra Pradesh	1,23,336.00	409.32	1,999.49	279.60	38,440.00	2,596.00
Arunachal Pradesh	246.00	2,064.92	18.46	0.00	8,650.00	50,394.00
Assam	459.00	201.99	321.89	0.00	13,760.00	643.00
Bihar	4,023.00	526.98	964.37	346.60	11,200.00	1,301.00
Chhattisgarh	2,749.00	1,098.20	353.68	0.00	18,270.00	300.00
Goa	14.00	4.70	32.97	0.00	880.00	0.00
Gujarat	1,80,790.00	201.97	2,637.84	554.70	35,770.00	550.00
Haryana	593.00	107.40	1,353.55	362.10	4,560.00	0.00
Himachal Pradesh	239.00	3,460.34	69.71	0.00	33,840.00	18,305.00
UT of Jammu & Kashmir	1.00	1,707.45	82.82	0.00	1,11,050.00	12,971.50
Jharkhand	16.00	227.96	146.31	0.00	18,180.00	300.00
Karnataka	1,69,251.00	3,726.49	1,798.83	1,762.10	24,700.00	4,414.40
Kerala	2,621.00	647.15	778.41	0.00	6,110.00	2,472.75
Madhya Pradesh	55,423.00	824.05	2,516.42	0.00	61,660.00	2,819.00
Maharashtra	1,73,868.00	786.46	2,629.55	3,917.00	64,320.00	3,144.00
Manipur	0.00	99.95	62.31	0.00	1,050.00	615.00
Meghalaya	55.00	230.05	68.54	0.00	5,860.00	206.00
Mizoram	0.00	168.90	58.24	0.00	9,090.00	1,926.00
Nagaland	0.00	182.18	53.09	0.00	7,290.00	325.00
Orissa	12,129.00	286.22	298.72	0.00	25,780.00	2,824.50
Punjab	428.00	578.28	3,022.11	414.40	2,810.00	1,300.73
Rajasthan	2,84,250.00	831.67	1,299.55	0.00	1,42,310.00	4,110.20
Sikkim	0.00	266.64	4.73	0.00	4,940.00	6,051.00
Tamil Nadu	95,107.00	604.46	1,560.08	639.30	17,670.00	1,785.20
Telangana	54,717.00	102.25	1,678.36	117.40	20,410.00	1,302.00
Tripura	0.00	34.35	38.45	0.00	2,050.00	106.00
Uttar Pradesh	510.00	460.75	2,800.35	492.50	22,800.00	501.00

Uttarakhand	0.00	1,664.31	93.34	215.10	16,800.00	13,481.35
West Bengal	1,281.00	392.06	1,741.74	0.00	6,260.00	809.20
Andaman & Nicobar	1,245.00	7.27	18.13	0.00	0.00	0.00
Chandigarh	0.00	0.00	0.15	0.00	0.00	0.00
Dadar & Nagar Haveli & Diu	17.00	0.00	2.16	0.00	0.00	0.00
Delhi	0.00	0.00	0.00	0.00	2,050.00	0.00
Lakshadweep	31.00	0.00	1.39	0.00	0.00	0.00
Puducherry	408.00	0.00	5.00	0.00	284.40	0.00
Others	0.00	0.00	0.00	0.00	790.00	0.00
Total	11,63,856.00	21,133.62	28,446.91	13,181.40	7,49,990.00	1,33,410.43

Table 1.2: State-wise installed capacity of renewable power as on 30.11.2024 [32]

S. No.	States/ UTs	Small Hydro Power (MW)	Wind Power (MW)	Bio Power (MW)	Solar Power (MW)	Large Hydro (MW)	Total Capacity (MW)
1	Andhra Pradesh	163.31	4096.65	574.39	4653.60	1610.00	11097.95
2	Arunachal Pradesh	140.61	-	0.00	14.72	1115.00	1270.33
3	Assam	34.11	-	2.00	182.69	350.00	568.80
4	Bihar	70.70	-	140.22	267.00	-	477.92
5	Chhattisgarh	76.00	-	275.00	1270.52	120.00	1741.52
6	Goa	0.05	-	1.94	50.24	-	52.23
7	Gujarat	91.64	12368.48	116.60	15936.11	1990.00	30502.83
8	Haryana	73.50	-	292.62	1956.35	-	2322.47
9	Himachal Pradesh	1000.71	-	10.20	139.89	10281.02	11431.82
10	Jammu & Kashmir	189.93	-	0.00	74.15	3360.00	3624.08
11	Jharkhand	4.05	-	19.10	187.09	210.00	420.24
12	Karnataka	1284.73	6724.37	1909.95	8975.65	3689.20	22583.90
13	Kerala	276.52	63.50	2.50	1313.66	1904.15	3560.33
14	Ladakh	44.49	-	0.00	7.80	89.00	141.29
15	Madhya Pradesh	123.71	2844.29	134.94	4910.08	2235.00	10248.02
16	Maharashtra	384.28	5216.38	2984.05	8363.55	3047.00	19995.26
17	Manipur	5.45	-	0.00	13.79	105.00	124.24
18	Meghalaya	55.03	-	13.80	4.28	322.00	395.11
19	Mizoram	45.47	-	0.00	30.35	60.00	135.82
20	Nagaland	32.67	-	0.00	3.17	75.00	110.84
21	Odisha	115.63	-	59.22	609.95	2154.55	2939.35
22	Punjab	176.10	-	567.25	1387.05	1096.30	3226.70
23	Rajasthan	23.85	5195.82	126.06	24776.69	411.00	30533.42
24	Sikkim	55.11	-	0.00	7.56	2282.00	2344.67
25	Tamil Nadu	123.05	11317.24	1045.45	9427.06	2178.20	24091.00
26	Telangana	90.87	128.10	221.67	4842.10	2405.60	7688.34
27	Tripura	16.01	-	0.00	21.04	-	37.05

28	Uttar Pradesh	49.10	-	2265.89	3288.86	501.60	6105.45
29	Uttarakhand	233.82	-	142.24	593.07	4035.35	5004.48
30	West Bengal	98.50	-	348.36	310.47	1341.20	2098.53
31	Andaman & Nicobar Islands	5.25	-	0.00	29.91	-	35.16
32	Chandigarh	-	-	0.00	76.26	-	76.26
	Dadra & Nagar Haveli and	-	-	-	-	-	-
33	Daman & Diu	-	-	3.75	48.12	-	51.87
34	Delhi	-	-	84.00	292.38	-	376.38
35	Lakshadweep	-	-	0.00	4.97	-	4.97
36	Puducherry	-	-	0.00	52.64	-	52.64
37	Others	-	4.30	0.00	45.01	-	49.31
	Total (MW)	5084.25	47959.13	11341.20	94167.83	46968.17	205520.58

1.2.1 Status of renewable energy in Assam

Assam, a state in northeastern India, has also made progress in renewable energy adoption, particularly in solar and small hydropower projects. The state has an installed renewable capacity of approximately 568 MW, with solar energy contributing a significant portion. Assam's geographical conditions, characterized by moderate solar insolation and ample river systems, offer significant potential for renewable energy development [32, 33].

However, the state faces unique challenges, including frequent flooding, which affects infrastructure stability, and limited grid connectivity in remote areas. To address these challenges, the government of Assam, in collaboration with central authorities, has initiated several projects focused on improving renewable energy infrastructure and enhancing grid reliability [34, 35].

The region faces unique energy challenges, particularly in rural areas. The state's dependence on conventional energy sources, coupled with limited grid connectivity in remote regions, necessitates exploring alternative energy solutions. Solar PV energy, with its ability to directly generate electricity, offers a promising solution for decentralized energy supply in rural areas.

1.2.2 Renewable purchase obligation (RPO) targets

To accelerate the adoption of renewable energy, the Government of India has implemented RPO targets, requiring electricity distribution companies (DISCOMs), open access consumers, and captive power producers to procure a mandated percentage of their total energy consumption from renewable sources. These obligations are categorized into Solar RPO and

Non-Solar RPO, ensuring a diversified renewable energy portfolio. Assam, like other states, must align with these targets to support national energy transition goals and meet its renewable energy commitments under India's Nationally Determined Contributions (NDCs) [36, 37].

The enforcement of RPO targets has been instrumental in driving investments in renewable energy projects, fostering long-term power purchase agreements (PPAs) between DISCOMs and renewable energy developers, and encouraging private sector participation. However, challenges persist, particularly in states with lower renewable energy generation potential, grid infrastructure constraints, and financial limitations of DISCOMs. To address these challenges, mechanisms such as Renewable Energy Certificates (RECs) provide an alternative compliance pathway for obligated entities facing difficulties in directly procuring renewable power [38]. Strengthening enforcement measures, enhancing financial incentives, and improving grid infrastructure are crucial for ensuring the successful implementation of RPO targets and achieving a more resilient and sustainable energy ecosystem.

1.3 Solar energy in global and Indian perspective

Among renewables, solar PV technology has emerged as a cornerstone of this transition, benefiting from declining costs, scalability, and versatility for both large-scale and decentralized applications. The rapid deployment of solar PV is pivotal for achieving global climate goals, addressing energy inequality, and reducing reliance on fossil fuels. To maximize the impact of solar PV, sustained investments, robust policy frameworks, and innovations in energy storage and grid management are essential. The combination of large-scale solar farms and decentralized solar solutions is expected to play a crucial role in creating a sustainable and equitable global energy system.

The global growth of solar PV systems has been remarkable over the past two decades, driven by advancements in technology, declining costs, and supportive policies. As of 2023, the global installed solar PV capacity has reached approximately 1.6 terawatts (TW), reflecting a significant increase from 1.2 TW in 2022, with around 446 gigawatts (GW) of new systems commissioned during the year [39, 40]. This growth trajectory aligns with projections indicating a nearly ten-fold increase in capacity by 2040, driven by technological advancements and declining costs. The rapid expansion of PV installations, which have grown by 41% annually since 2009, underscores the transformative potential of solar energy in the global energy landscape [41, 42]. Global trends in solar PV energy reflect significant advancements in technology, efficiency, and applications, driving a transition towards sustainable energy solutions. Key technologies in solar PV systems include monocrystalline, polycrystalline, and thin-film technologies, each offering distinct advantages. Monocrystalline panels are recognized for their superior efficiency, often achieving higher energy outputs compared to polycrystalline counterparts; for instance, monocrystalline systems can generate significantly more electricity annually under similar conditions [43]. Conversely, polycrystalline panels are generally more cost-effective, making them a popular choice for budget-conscious installations. Thin-film technologies, such as cadmium telluride (CdTe), provide additional benefits like flexibility and lightweight characteristics, which facilitate integration into various applications, including building materials. Recent innovations, such as multi-junction and bifacial solar cells, have achieved efficiencies exceeding 40%, while new materials like perovskites promise lower production costs and enhanced flexibility [44]. The choice of technology often balances efficiency, cost, and application flexibility, reflecting the diverse needs of the solar energy landscape. The global market is witnessing a decrease in PV module prices and an increase in large-scale applications, supported by favourable policies like feed-in tariffs and tax incentives. Countries like China, the United States, and Germany are leading in installations, with China alone surpassing 253 GW of capacity by 2021. As the demand for renewable energy grows, ongoing research and development are crucial for overcoming challenges and enhancing the efficiency and economic viability of solar technologies [45].

India's solar energy sector has experienced remarkable growth, driven by the government's ambitious targets and commitment to harnessing the country's abundant solar resources. The establishment of solar parks has been a game-changer in scaling up solar energy capacity in India. These parks provide shared infrastructure and streamlined processes, enabling large-scale solar project implementation [46]. The government has also emphasized rooftop solar programs, with subsidies and incentives for residential, institutional, and commercial installations. These initiatives aim to encourage decentralized power generation and improve energy access in both urban and rural areas [47].

As of January 2025, India had installed over 100 GW of solar power capacity, accounting for nearly half of its total renewable energy capacity. To meet the ambitious target of achieving solar power by 2030, the government continues to implement supportive policies, including renewable purchase obligations, net metering mechanisms, and preferential tariffs for solar power [48].

The government's focus on research and development in solar technologies, coupled with declining costs of solar photovoltaic modules, has further accelerated the adoption of solar energy. Additionally, international collaborations, such as the International Solar Alliance (ISA), headquartered in India, have positioned the country as a global leader in promoting solar energy deployment worldwide. While India has made impressive strides, challenges such as land availability, grid integration, and financial viability of small-scale projects persist. Addressing these issues through enhanced policy frameworks, public-private partnerships, and technological innovations will be crucial to achieving India’s solar energy goals and ensuring a sustainable energy future.

1.3.1 Status of solar energy installations in Assam

Assam has made notable progress in solar energy adoption, with several on-grid and off-grid solar projects implemented across the state. The Assam Power Distribution Company Limited (APDCL) has been at the forefront of promoting rooftop solar installations, particularly in urban areas, to reduce the state's reliance on conventional energy sources [49].

In rural areas, off-grid solar projects, including solar water pumps and mini solar grids, have been instrumental in improving energy access. Despite these developments, the overall installed solar capacity in Assam remains modest compared to other states, highlighting the need for enhanced policy support and investment to fully realize the state's solar potential [50].

Despite advancements in solar technology and government policies, the adoption of solar energy remains low in rural Assam due to various socio-economic, technological, and infrastructural barriers. The current research fails to adequately address the following aspects:

a) Limited assessment of solar potential: Existing studies do not comprehensively assess the potential of solar energy for rooftop installations, barren land utilization, and irrigation systems in Assam’s rural regions. There is a need to evaluate how solar PV can effectively meet the energy requirements for irrigation and EV charging.
b) Lack of integrated energy planning: Few studies explore the integration of solar energy with electric vehicle charging infrastructure, especially in rural settings [51, 52]. This research

aims to fill this gap by evaluating the feasibility of using excess electricity generated from solar irrigation systems for EV charging.

c) Barriers to solar adoption: Limited research has been conducted on understanding the barriers and drivers that influence the adoption of solar PV-based systems in Assam. Factors such as awareness, financial incentives, technological accessibility, and policy frameworks need to be investigated to develop effective strategies for promoting solar energy.

1.3.2 Key drivers for desired growth of solar energy in Assam

The expansion of solar energy in Assam is driven by a combination of favourable policies, increasing energy demand, and financial incentives. Key contributing factors include government subsidies, decent solar insolation levels, and the promotion of decentralized solar solutions in rural areas. Financial incentives from both central and state governments have significantly reduced the cost of solar installations, making them more accessible for residential, commercial, and agricultural users [53].

Despite not having a geographical advantage like high solar insolation regions in western India, Assam has been focusing on deploying solar solutions in off-grid regions, aiming to improve energy access for remote communities that are not connected to the central grid. This approach has been instrumental in enhancing rural electrification efforts [54]. Additionally, supportive regulatory frameworks, including net metering policies and renewable energy purchase obligations, have encouraged private investments and further development of the solar sector in Assam [55].

Moreover, the rise of solar-powered irrigation systems and rooftop solar installations has played a crucial role in promoting self-sustaining energy models. With technological advancements, improved battery storage solutions, and financial mechanisms such as low-interest loans and subsidies, the adoption of solar energy is expected to accelerate in the state, contributing to long-term energy security and sustainability.

1.3.3 Solar energy supportive policies and programs

India has implemented a range of supportive policies and programs to accelerate solar energy adoption and meet its ambitious renewable energy targets. Collaborating with the Ministry of New and Renewable Energy (MNRE), state governments like Assam have introduced initiatives such as subsidies for rooftop solar installations, net metering frameworks, and financial support for decentralized solar projects. These measures aim to expand solar energy deployment and reduce reliance on conventional fossil fuels [56].

Key national programs include the PM-KUSUM initiative, which focuses on installing solar water pumps to support irrigation and sustainable agriculture. By providing financial incentives to replace diesel-powered pumps, the program contributes to reducing greenhouse gas emissions while improving energy access for farmers. Additionally, PM-KUSUM includes decentralized solar energy generation, enabling rural areas to benefit from localized electricity production, further reducing dependence on grid power [57].

The PM Surya Ghar: Muft Bijli Yojana, launched in 2024, aims to achieve 10 million residential rooftop solar installations by FY 2026-27. With a financial outlay of ₹750.21 billion, the program integrates the existing Phase II Rooftop Solar Programme and targets free or low-cost electricity for households consuming up to 300 units per month. It also supports the development of rooftop solar ecosystems, including regulatory mechanisms, vendor networks, and maintenance infrastructure, ensuring sustainable operations. Residential consumers can apply for subsidies via a national portal, simplifying access and increasing participation [58].

In addition, the government has introduced various other supportive measures, such as solar parks for large-scale installations, viability gap funding (VGF) for solar projects, and incentives for manufacturing solar photovoltaic (PV) modules under the Production-Linked Incentive (PLI) scheme. The PLI scheme not only enhances domestic manufacturing but also reduces dependence on imported solar components, contributing to energy security [59-61].

Programs such as the National Solar Mission continue to provide a strategic framework for achieving solar energy goals, with a focus on achieving grid parity and large-scale deployment. The mission's emphasis on research and innovation has led to cost reductions in solar PV technologies, further accelerating adoption [62].

These initiatives collectively address India’s energy and climate objectives, focusing on localized implementation, job creation, and strengthening energy security. By promoting solar energy through targeted policies and financial mechanisms, India continues to advance its leadership in the global energy transition while aligning with its Nationally Determined Contributions (NDCs) under the Paris Agreement [63].

1.4 Solar photovoltaic systems: types and applications

Promoting solar energy in India requires a comprehensive and multi-faceted approach involving technological advancements, financial mechanisms, and supportive policy frameworks. Key strategies include the expansion of rooftop solar (RTS) systems, encouragement of ground-mounted solar (GMS) installations, and promotion of solar photovoltaic water pumping (SWP) systems for agricultural applications. Additionally, the development of enabling regulatory frameworks, financial incentives to attract private investment, and advancements in energy storage technologies are essential to scaling up solar energy deployment and ensuring a sustainable energy transition.

Photovoltaic system components and design

The design of a photovoltaic (PV) system integrates multiple components that function cohesively to convert solar energy into usable electrical energy. A comprehensive assessment of key system components is presented, focusing on their roles in optimizing functionality, enhancing efficiency, and ensuring reliability across diverse environmental conditions.

Photovoltaic modules serve as the primary component responsible for converting solar radiation into direct current (DC) electricity. These modules are composed of solar cells made from materials such as monocrystalline or polycrystalline silicon, which are central to the system's energy generation. The efficiency of these modules determines the percentage of solar energy converted into electricity, while their power output, measured in watts, defines the module's performance. Key electrical characteristics, such as Open-Circuit Voltage (V_{oc}) and Short-Circuit Current (I_{sc}), are critical for ensuring compatibility with other system components [64].

The system controller plays a crucial role in governing the operation of the PV system, ensuring efficient energy management and safety. A microcontroller unit (MCU) executes algorithms for Maximum Power Point Tracking (MPPT), battery management, and load control. It interfaces with sensors, monitors system performance, and triggers protective actions. MPPT optimizes power extraction from PV modules by operating them at their maximum power point, improving system efficiency by up to 30% through algorithms like Perturb and Observe (P&O) or Incremental Conductance (IncCond). Additionally, the DC-DC converter, which can function as either a buck or boost converter, adjusts the voltage level for different parts of the system. A buck converter reduces voltage for battery charging, while a boost converter increases voltage to drive loads. Power switching devices such as MOSFETs and IGBTs are used for high-speed switching in converters and inverters, with MOSFETs preferred for low-to-medium power applications and IGBTs for high-power applications [65].

Sensors and monitoring elements measure voltage, current, and temperature, providing real-time data for system optimization and fault detection. The system user interface (UI) displays critical parameters such as power generation, battery status, and load consumption, and may include interactive features for configuration and control [66].

The Battery Management System (BMS) is essential for regulating battery charging and discharging, ensuring safety and longevity by preventing overcharging, deep discharges, and thermal instability. Cooling mechanisms such as heat sinks and cooling fans manage thermal conditions, preventing overheating of power electronics and maintaining system stability. Protection mechanisms, including fuses and relays, safeguard against overcurrent and short circuits, while additional protection circuits mitigate risks associated with reverse polarity, lightning surges, and grid-related faults [67].

A communication module facilitates remote monitoring and control through protocols like Wi-Fi, Zigbee, GSM, or RS-485, integrating IoT platforms for diagnostics and analytics. A real-time clock (RTC) enables precise scheduling of load management and energy data logging. Energy flow within the system is directed to priority loads based on system conditions, with auxiliary outputs providing backup power for secondary loads [68].

Passive components such as capacitors, inductors, and diodes contribute to the overall system stability. Capacitors smooth DC output and store energy for transient conditions, inductors manage energy transfer in DC-DC converters, and diodes ensure unidirectional current flow, preventing energy backflow [69].

A well-designed photovoltaic system ensures seamless integration of all components, achieving optimal energy output while maintaining safety and reliability. Advanced power electronics and protective mechanisms enhance performance under variable environmental conditions. This integrated approach ensures the system's adaptability, longevity, and alignment with sustainability goals.

1.4.1 Rooftop solar (RTS) systems

RTS involve installing photovoltaic panels on residential, commercial, or industrial building rooftops to generate electricity. These systems can be either grid-connected or off-grid, depending on whether they interact with the power grid. Grid-connected systems allow users to feed surplus electricity into the grid through net metering, while off-grid systems require battery storage to ensure a continuous power supply. RTS systems are advantageous in urban environments, where land constraints limit the feasibility of large-scale installations. The Government of India has introduced various incentives, including capital subsidies, tax benefits, and net metering policies, allowing consumers to offset their electricity bills by feeding excess power back into the grid [70].

RTS systems enable residential and commercial consumers to generate their own electricity, lower energy costs, and contribute to national renewable energy targets. Despite these benefits, challenges such as high upfront installation costs, inconsistent regulatory frameworks across states, and limited consumer awareness continue to hinder widespread adoption. Addressing these barriers through targeted financial assistance, streamlined approval processes, and public awareness campaigns is crucial to unlocking the full potential of RTS systems.

1.4.2 Ground-mounted solar (GMS) systems

GMS consist of large-scale photovoltaic installations that are deployed on open land areas to generate electricity. These systems are typically used in solar parks, utility-scale power plants, and large commercial projects, benefiting from centralized infrastructure, grid connectivity, and streamlined land acquisition processes. Unlike RTS, GMS installations allow for optimal panel orientation and large-scale deployment, making them more efficient per unit area. Government policies have facilitated the development of solar parks by offering financial incentives, providing land, and creating supportive infrastructure [71].

The scalability of GMS systems allows for significant capacity additions, which are essential to achieving India's ambitious solar energy targets. However, persistent challenges such as land acquisition disputes, transmission infrastructure bottlenecks, and potential environmental impacts must be addressed to ensure continued growth. Effective resolution of these issues through policy reforms and stakeholder engagement is critical for the sustained expansion of ground-mounted solar installations.

1.4.3 Solar photovoltaic water pumping (SWP) systems

Solar Photovoltaic Water Pumping (SWP) systems use photovoltaic panels to power water pumps for irrigation and drinking water supply. These systems are particularly beneficial in rural and off-grid regions, where access to conventional electricity is limited. SWP systems replace diesel or electric pumps, reducing operational costs and carbon emissions while ensuring reliable water access for agricultural activities [72].

SWP systems have been a cornerstone of India's efforts to integrate renewable energy into agriculture. They enable small and marginal farmers to irrigate their fields without relying on costly and polluting energy sources. To make these systems more accessible, the government provides substantial subsidies, covering a significant portion of the installation costs. This support not only promotes sustainable agricultural practices but also improves energy equity and supports rural development. Continued efforts to scale up SWP adoption will require additional investments, awareness campaigns, and technical support to farmers.

1.5 Integration with electric vehicles (EVs) and infrastructure

The integration of photovoltaic systems with electric vehicle (EV) infrastructure enhances sustainability by providing renewable energy for transportation. EVs are categorized into Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Hybrid Electric Vehicles (HEVs), each with varying dependence on electrical and internal combustion energy sources. The charging infrastructure consists of Level 1 (slow), Level 2 (medium), and Level 3 (fast) charging stations, which can be integrated with solar microgrids to enhance efficiency. PV-powered EV charging stations reduce carbon footprints and grid dependency by utilizing direct solar energy conversion for transportation needs [73, 74].

A crucial application of solar-powered EV charging is in electric rickshaws (e-rickshaws), which are widely used in India as an affordable and sustainable mode of urban and peri-urban transportation. E-rickshaws typically operate on lithium-ion or lead-acid batteries, requiring frequent charging cycles. Solar charging stations equipped with direct current (DC) fast charging capabilities can significantly enhance the operational efficiency of these vehicles while reducing dependence on conventional grid electricity [75, 76].

Another innovative approach is the deployment of solar photovoltaic water pumping (SWP) system-based microgrids for EV charging. These microgrids utilize excess solar energy from SWP systems, particularly during non-irrigation periods, to charge EVs efficiently. By leveraging decentralized solar microgrids, rural and semi-urban areas can establish independent charging networks for electric vehicles, reducing the burden on conventional grid infrastructure. SWP-based microgrids enable localized energy management, ensuring optimal utilization of renewable resources while supporting the growing demand for sustainable transportation solutions [77, 78].

Expanding solar-integrated EV infrastructure requires advanced power electronics, including bidirectional inverters for vehicle-to-grid (V2G) applications. Challenges such as energy storage limitations and grid synchronization need to be addressed to improve system efficiency. Future advancements in solar-integrated EV charging will involve smart-grid solutions, decentralized energy management systems, and improved battery technologies to facilitate seamless energy transitions between renewable energy generation and electric mobility [79-81].

1.6 Motivation and research gap

As stated above, rising energy needs and heavy reliance on imported fossil fuel exacerbate GHG emissions with additional burden on foreign exchequer in India. Renewable energy system, especially solar energy has been identified as viable alternative in India with proven success. It is worth noting that solar energy, as an abundantly available renewable resource, is also potential to addressing energy challenges, and contribute to achieve Sustainable Development Goals (SDGs) such as SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 11 (Sustainable Cities and Communities). Overall, there has been growth of the solar power installations in India covering all scale of installations (viz., roof top, ground mounted, solar PV irrigation) in recent time primarily due to supportive government policies and favourable eco-system generated by advent of tools and techniques for assessment of resources and mapping of system performance. However, the deployment and growth of solar installations is not uniform all over the country. Assam is one of the states of India (located in north eastern region) which experiences energy deficiency. Low level of energy (electricity) access to different sectors including crop production has severely impacted the economic development in Assam. Solar

PV options, especially the decentralized options such as RTS, GMS and SWP are desired to grow in Assam to address economic backwardness.

Effective decentralized renewable energy planning requires precise mapping of spatial and temporal variations in distributed solar energy resources. Further, performance of solar PV system is also governed by several spatial and temporal varying parameters linked with ambient weather condition (temperature, wind, dust), optics of apparent movement of sun and solar technology used for conversion. An appropriate computational tool incorporating the above-mentioned spatial and temporal variability is desired to handle several uncertainties concerning solar energy generation and subsequent applications. Such a tool should include capabilities for integrating real-time ground data, high-resolution spatial mapping, lifecycle performance simulation, and socio-economic impact analysis. Examples include features like dynamic climate modelling, incorporation of local resource data, and adaptive forecasting mechanisms to address the specific needs of decentralized energy planning. Candidature of decentralized solar PV among the conventional alternatives (grid electricity and diesel power system) could be judged by such a comprehensive computational tool. The benefits of GHG reduction and revenue generation potential of selected options (RTS, GMS and SWP) of decentralized solar could also be assessed through such tool. It is expected that such a comprehensive spatial model will be useful in addressing the lower level of energy access, promoting the growth of decentralized solar energy in Assam (India).

Existing tools and know-how appear inadequate to provide holistic approach of the assessment vis-à-vis planning of decentralized solar energy in typical rural areas of Assam incorporating the realistic ground data at lifecycle scale. The inadequate realistic assessment of potential benefits of solar energy is considered as one of the factors against its promotion. The current research work is aimed to address the above gaps with the development of a geospatial tool that incorporates the spatial and temporal factors of the representative study region. This model is designed to be adaptable and scalable, featuring methodologies such as modular computational architecture, integration of spatial and temporal variability, and customization capabilities for region-specific parameters. These features ensure its applicability to any region in the world with similar challenges, thereby offering a universal framework for decentralized solar energy planning.

Existing tools for solar resource assessment include GIS-based platforms, satellite data analysis tools, and simulation software like PVsyst, HOMER, RETScreen, SolarGIS, and Python PVLib. GIS-based platforms excel in spatial mapping and resource visualization, while HOMER is effective for optimizing hybrid energy systems. RETScreen is widely used for energy efficiency and project feasibility analysis. SolarGIS provides highly detailed solar radiation data and analytics, and Python PVLib supports advanced performance simulations of PV systems. However, each tool has limitations, such as a lack of integration across spatial, temporal, and lifecycle dimensions, making them insufficient for comprehensive decentralized energy planning. These tools have seen significant advancements in recent years, enabling improved accuracy in solar potential mapping and performance simulations. Moreover, the integration of real-time ground data, socio-economic factors, and local climatic conditions remains limited. This highlights the need for an advanced geospatial framework that overcomes these limitations and supports robust planning and assessment of decentralized solar energy in rural areas like Assam.

1.7 Problem statement and description

Despite the rapid expansion of solar energy deployment across India, the uptake of decentralized solar PV systems such as RTS, GMS, and SWP remains limited in energy-deficient and geographically diverse regions like rural Assam. The spatial heterogeneity of solar irradiance, combined with a lack of region-specific tools for planning, has led to suboptimal system placement, inefficient resource allocation, and underutilization of government schemes.

A significant challenge lies in the absence of an integrated, geospatially aware planning framework that can evaluate decentralized solar options while accounting for regional variability in solar resources, land availability, environmental benefits, and socio-economic feasibility. While RTS and GMS systems can be planned based on spatially resolved solar maps, the integration of lifecycle analysis and greenhouse gas (GHG) reduction benefits remains underexplored in localized contexts.

Moreover, existing planning models often overlook the operational dynamics and surplus energy potential of SWP systems. Unlike RTS and GMS systems, which typically supply consistent electrical loads, SWP systems exhibit operational intermittency, primarily functioning during irrigation periods. This presents a unique opportunity to utilize excess electricity generated during non-operational hours, particularly for EV charging or grid export, to enhance the system's value proposition and energy utilization efficiency. However, such integrated techno-economic assessments are largely absent in the literature and practice.

In addition, the scalability of decentralized solar PV technologies is hindered by a variety of barriers, technical, economic, policy-related, and behavioural. While central and state governments have introduced several subsidy-linked initiatives (e.g., PM Surya Ghar for RTS and PM-KUSUM Component A/B for GMS and SWP), their uptake remains low due to poor alignment with ground realities, limited business model innovation, and lack of vendor-user engagement strategies.

To address these interconnected issues, this research aims to develop a comprehensive GIS-based framework for decentralized solar energy planning and feasibility assessment in rural Assam. The framework will (i) quantify solar potential with environmental co-benefits, (ii) assess the techno-economic feasibility of SWP systems integrated with EV charging options, and (iii) analyze the institutional and policy ecosystem to develop scalable business models aligned with existing schemes. Collectively, these efforts are expected to strengthen decentralized solar energy adoption and rural energy access in the region.

1.8 Objectives of the research

The objectives of this thesis, along with their details, are as follows:

1. To conduct a spatial and temporal analysis of solar photovoltaic systems potential and assessment of its benefits in rural Assam

   Conduct a comprehensive spatial and temporal analysis of rooftop solar (RTS), ground-mounted solar (GMS), and solar photovoltaic water pumping (SWP) systems potential in representative rural regions of Assam. Utilize GIS-based methodologies for optimized resource allocation and regional energy planning, and apply Python PVlib for simulation purposes. Identify the total solar potential from all sources (RTS, GMS, and SWP) and evaluate the environmental benefits by estimating Life Cycle GHG Emissions. This objective provides a foundational understanding of solar energy potential, enabling efficient resource utilization while minimizing environmental impacts.

2. To conduct a comprehensive techno-economic and feasibility assessment of SWP system with integration of electric vehicle charging

   Evaluate the techno-economic feasibility of SWP systems compared to diesel and grid-electricity operated pumps using metrics such as Net Present Value (NPV), Payback Period (PBP), and GHG Emissions. The analysis incorporates government schemes like PM-KUSUM Component B, to understand the financial feasibility of SWP systems and their role in promoting renewable energy adoption in rural areas. Additionally, the assessment explores the potential for SWP systems to generate surplus electricity during non-operational periods, which can be utilized for charging electric vehicles (EVs) or fed into the local grid to address peak demand periods.

3. To investigate barriers, enablers, and develop business models for scaling solar photovoltaic energy systems

   Identify and analyse the barriers and enablers influencing the deployment and scalability of RTS and GMS systems in rural Assam. The research examines financial, infrastructural, regulatory, and socio-cultural constraints while exploring key enablers such as government incentives, technological advancements, and community-driven initiatives. For RTS systems, explore integration with government schemes such as PM Surya Ghar. Similarly for GMS assess opportunities under PM-KUSUM Component A, which facilitates solar power generation through decentralized installations. Business models will be developed considering vendor and consumer perspectives, incorporating innovative financing mechanisms such as subsidies, low-interest loans, leasing, and community solar ownership structures. The financial feasibility and implementation strategies will be evaluated in the context of existing government policies and incentives, ensuring alignment with local socio-economic conditions. This research aims to formulate scalable and sustainable business models that drive widespread adoption of solar energy systems, enhancing rural electrification and contributing to long-term energy security in Assam.

1.9 Organization of the Thesis

This thesis is structured into six comprehensive chapters, each focusing on critical aspects of assessing, optimizing, and implementing solar PV energy systems in rural Assam, India. The chapters are designed to systematically address the research objectives, starting from the foundational concepts to the practical implications and recommendations. A detailed outline of each chapter is provided below.

Chapter 1: Introduction

The introductory chapter establishes the groundwork for the research by presenting the background, motivation, and objectives of the study. It delves into the global and national energy scenarios, highlighting the escalating demand for sustainable energy solutions. The chapter emphasizes the significance of renewable energy, particularly solar PV technology, in addressing energy deficits in rural India. It discusses the unique opportunities and challenges within the solar energy sector in rural Assam, setting the stage for the subsequent analysis. The chapter also outlines the research questions, scope, and methodology employed in the thesis.

Chapter 2: Review of Literature

This chapter provides a comprehensive review of existing literature on renewable energy systems, with a particular focus on solar PV technologies and their integration into rural energy frameworks. It examines previous studies on the techno-economic assessments of solar PV systems, environmental impact analyses, and the socio-economic benefits of renewable energy deployment in rural settings. The literature review critically analyses various models and methodologies used in assessing solar energy potential and identifies gaps in current research. This analysis establishes the theoretical foundation and justifies the need for the research conducted in this thesis.

Chapter 3: Comprehensive model for solar photovoltaic potential assessment and life cycle emission estimation in rural Assam

This chapter is divided into two sections:

Part A: Spatial and temporal assessment of solar photovoltaic potential

Part B: Lifecycle GHG emission estimation

In this chapter, a comprehensive model is developed to assess the solar photovoltaic potential and estimate life cycle emissions in rural Assam. The study conducts a spatial and temporal analysis of solar energy potential from various sources, including rooftop solar installations, ground-mounted solar farms, and solar photovoltaic water pumping systems. Utilising Geographic Information System (GIS) and Python PVLib for detailed modelling of solar potential from Rooftop Solar (RTS), Ground-Mounted Solar (GMS), and Solar Photovoltaic Water Pumping (SWP) systems., the research identifies optimal locations for resource allocation and regional energy planning. The model incorporates environmental assessments, quantifying the potential reduction in greenhouse gas emissions through the adoption of solar PV systems. The findings aid in formulating strategies for maximizing solar energy utilization in the representative area.

Chapter 4: Assessment of SWP system with integration of EV charging

This chapter presents a detailed techno-economic and feasibility assessment of solar photovoltaic water pumping (SWP) systems, including the integration of electric vehicle (EV) charging infrastructure. The analysis compares the performance, cost-effectiveness, and environmental benefits of SWP systems against traditional diesel-powered and grid-electricity-operated pumps. Key parameters such as initial investment, operation and maintenance costs, system efficiency, and life cycle emissions are evaluated. The integration of EV charging stations is analysed for its potential to enhance the economic viability and sustainability of SWP systems. The chapter concludes with recommendations for optimizing system design and implementation strategies.

Chapter 5: Barriers, enablers, and business models for scaling solar photovoltaic energy systems

This chapter investigates the barriers and enablers influencing the deployment and scalability of solar photovoltaic energy systems in rural Assam. Through qualitative and quantitative analyses, the research identifies critical challenges such as financial constraints, technological limitations, policy and regulatory hurdles, and socio-cultural factors affecting adoption rates. Business models are developed from both vendor and consumer perspectives, aiming to facilitate effective implementation and scaling of solar PV systems. The models incorporate existing government schemes and policies, proposing innovative financing mechanisms, stakeholder engagement strategies, and community participation frameworks. The chapter provides actionable insights to policymakers, entrepreneurs, and practitioners for promoting sustainable energy solutions.

Chapter 6: Summary and Conclusions

The final chapter synthesizes the key findings from the research, summarizing the contributions made to the field of renewable energy systems in rural contexts. It revisits the research objectives and discusses how they have been addressed through the studies conducted. The chapter highlights the implications of the findings for policy formulation, technological advancement, and socio-economic development. Recommendations are provided for stakeholders to enhance the adoption and scalability of solar PV systems. The chapter also suggests areas for future research, emphasizing the need for continuous innovation and collaboration in the renewable energy sector.

Appendices and List of Publications

The thesis concludes with appendices that include supplementary materials such as detailed data sets, methodological tools, and additional analyses that support the research findings. A comprehensive list of publications resulting from this research is provided, documenting the dissemination of knowledge through academic journals, conferences, and professional platforms.

References

[1] Ritchie, H., and Roser, M. Fossil fuels and their role in the global energy supply. *Our World in Data*. Retrieved on 21 February, 2024, from https://ourworldindata.org/fossil-fuels, 2020.

[2] Holechek, J. L., Geli, H. M., Sawalhah, M. N., and Valdez, R. A global assessment: can renewable energy replace fossil fuels by 2050?. *Sustainability*, 14(8):4792, 2022.

[3] Demirbas, A. (2006). Hazardous emissions, global climate change and environmental precautions. *Energy Sources, Part B: Economics, Planning, and Policy*, *1*(1), 75-84.

[4] International Energy Agency (IEA). World Energy Outlook. *IEA Report*, 2023. Retrieved on October 25, 2023, from https://www.iea.org/reports/world-energy-outlook-2023.

[5] Elavarasan, R.M., Shafiullah, G.M., Padmanaban, S., Kumar, N.M., Annam, A., Vetrichelvan, A.M., Mihet-Popa, L., and Holm-Nielsen, J.B.,. A comprehensive review on renewable energy development, challenges, and policies of leading Indian states with an international perspective. *Ieee Access*, 8:74432-74457, 2020.

[6] International Energy Agency (IEA). Net Zero by 2050: A Roadmap for the Global Energy Sector. *IEA Report*, 2021. DOI: 10.1787/c8328405-en.

[7] Sen, K.K., Singha, B., Karmaker, S.C., Hosan, S., Chapman, A.J., and Saha, B.B. Unveiling the effects of energy poverty on mental health of children in energy-poor countries. *Energy Research & Social Science*, 117, 103729.

[8] United Nations. Tracking SDG 7: The Energy Progress Report 2023. *World Bank, IEA, IRENA, UN Statistics Division, WHO*, 2023. Retrieved on September 15, 2023, from https://trackingsdg7.esmap.org/.

[9] Central Electricity Authority (CEA). Monthly Installed Capacity Report – December 2024. *Ministry of Power, India*, 2023. Retrieved on January 10, 2025, from https://cea.nic.in/installed-capacity-report/.

[10] *500 GW Non-fossil Fuel Target.* Ministry of Power, Government of India, 2023. Retrieved on October 28, 2024, from https://powermin.gov.in/en/content/500gw-nonfossil-fuel-target.

[11] Quitzow, R. Assessing policy strategies for the promotion of environmental technologies: A review of India's National Solar Mission. *Research Policy*, 44(1):233-243, 2015.

[12] Green Energy Corridor. *Ministry of Power, India*. Retrieved on January 10, 2025, from https://powermin.gov.in/en/content/green-energy-corridor.

[13] Borragán, G., Ortiz, M., Böning, J., Fowler, B., Dominguez, F., Valkering, P., and Gerard, H. Consumers' adoption characteristics of distributed energy resources and flexible loads behind the meter. *Renewable and Sustainable Energy Reviews*, 203:114745, 2024.

[14] Garlet, T.B., Ribeiro, J.L.D., de Souza Savian, F., and Siluk, J.C.M.. Paths and barriers to the diffusion of distributed generation of photovoltaic energy in southern Brazil. *Renewable and Sustainable Energy Reviews*, 111:157-169, 2019.

[15] Best, R., and Burke, P.J. Small-scale solar panel adoption by the non-residential sector: The effects of national and targeted policies in Australia. *Economic Modelling*, 120:106164, 2023.

[16] Lefore, N., Closas, A., and Schmitter, P. Solar for all: A framework to deliver inclusive and environmentally sustainable solar irrigation for smallholder agriculture. *Energy Policy*, 154:112313, 2021.

[17] Rahman, M.M., Khan, I., Field, D.L., Techato, K. and Alameh, K. Powering agriculture: Present status, future potential, and challenges of renewable energy applications. *Renewable Energy*, 188:731-749, 2022.

[18] Onabowale, O. Energy policy and sustainable finance: Navigating the future of renewable energy and energy markets. *World Journal of Advanced Research and Reviews*, 25:2235-2252, 2024.

[19] Adanma, U.M. and Ogunbiyi, E.O. Assessing the economic and environmental impacts of renewable energy adoption across different global regions. *Engineering Science & Technology Journal*, 5(5):1767-1793, 2024.

[20] Mitali, J., Dhinakaran, S., and Mohamad, A.A. Energy storage systems: A review. *Energy Storage and Saving*, 1(3):166-216, 2022.

[21] Moreno Escobar, J.J., Morales Matamoros, O., Tejeida Padilla, R., Lina Reyes, I., and Quintana Espinosa, H. A comprehensive review on smart grids: Challenges and opportunities. *Sensors*, 21(21):6978, 2021.

[22] Santhanam, K.S., Press, R.J., Miri, M.J., Bailey, A.V., and Takacs, G.A. *Introduction to hydrogen technology*. John Wiley & Sons, 2017.

[23] Adelekan, O.A., Ilugbusi, B.S., Adisa, O., Obi, O.C., Awonuga, K.F., Asuzu, O.F., and Ndubuisi, N.L. Energy transition policies: a global review of shifts towards renewable sources. *Engineering Science & Technology Journal*, 5(2):272-287, 2024.

[24] Halkos, G.E., and Tsirivis, A.S. Electricity production and sustainable development: The role of renewable energy sources and specific socioeconomic factors. *Energies*, 16(2):721, 2023.

[25] Ember. World passes 30% renewable electricity milestone. Retrieved on January 05, 2025, from https://ember-energy.org/latest-updates/world-passes-30-renewable-electricity-milestone/.

[26] Hassan, Q., Viktor, P., Al-Musawi, T.J., Ali, B.M., Algburi, S., Alzoubi, H.M., Al-Jiboory, A.K., Sameen, A.Z., Salman, H.M., and Jaszczur, M. The renewable energy role in the global energy Transformations. *Renewable Energy Focus*, 48:100545, 2024.

[27] Ministry of New and Renewable Energy. Renewable Energy Statistics 2023-24, Retrieved on 15 February, 2025, from http://www.mnre.gov.in, 2024.

[28] Rehman, S., and Hussain, Z. Renewable energy governance in India: challenges and prospects for achieving the 2022 energy goals. *Journal of Resources, Energy and Development*, 14(1):13-22, 2017.

[29] Bhattacharya, S., Banerjee, R., Ramadesigan, V., Liebman, A., and Dargaville, R. Bending the emission curve—The role of renewables and nuclear power in achieving a net-zero power system in India. *Renewable and Sustainable Energy Reviews*, 189:113954, 2024.

[30] Vishwanathan, S.S., Fragkos, P., Fragkiadakis, K., and Garg, A. Assessing enhanced NDC and climate compatible development pathways for India. *Energy Strategy Reviews*, 49:101152, 2023.

[31] Abhyankar, N., Mohanty, P., Deorah, S., Karali, N., Paliwal, U., Kersey, J., and Phadke, A. India's path towards energy independence and a clean future: Harnessing india's renewable edge for cost-effective energy independence by 2047. *The Electricity Journal*, 36(5):107273, 2023.

[32] Ministry of New and Renewable Energy. State-wise (Location based) installed capacity of Renewable Power as on 31.01.2025. Retrieved on January 10, 2025, from https://mnre.gov.in/en/physical-progress/.

[33] Panme, F.A., and Sethi, L.N. Hydropower potential in assam: assessment and analysis, 2021.

[34] Gohain, M., Mahanta, D.K., and Baishya, K. June. Micro-Hydro and Solar Synergy: A Review of Hybrid Power Solutions for Assam's Energy Challenges. In *2024 6th International Conference on Energy, Power and Environment,* (ICEPE), pages 1-5, IEEE, 2024.

[35] Saha, P., Sultana, S.F.S., Saha, A., and Das, M. Sustainable Development Goals and Assam—A Roadmap to a Better Future. In *Sustainable Development Goals in Northeast India: Challenges and Achievements*, pages 317-341, Singapore: Springer Nature Singapore, 2023.

[36] Nayar, R. Enforcing renewable purchase obligations. *Economic & Political Weekly*, 51(40):21-23, 2016.

[37] Chaturvedi, V., Koti, P.N., and Chordia, A.R. Pathways towards India's nationally determined contribution and mid-century strategy. *Energy and Climate Change*, 2:100031, 2021.

[38] Narula, K. Renewable energy certificates (RECs) in India–a performance analysis and future outlook. *Renewable and Sustainable Energy Reviews*, 27:654-663, 2013.

[39] Statista. *Global cumulative installed solar PV capacity 2000-2023*. Retrieved on February 13, 2025 https://www.statista.com/statistics/280220/global-cumulative-installed-solar-pv-capacity/, 2024.

[40] Jäger-Waldau, A. Snapshot of photovoltaics− February 2024. *EPJ photovoltaics*, 15:21, 2024.

[41] Hossain, M.S., Wadi Al-Fatlawi, A., Kumar, L., Fang, Y.R., and Assad, M.E.H. Solar PV high-penetration scenario: an overview of the global PV power status and future growth. *Energy Systems*, 1-57, 2024.

[42] Sahu, B.K. A study on global solar PV energy developments and policies with special focus on the top ten solar PV power producing countries. *Renewable and Sustainable Energy Reviews*, 43:621-634, 2015.

[43] Benghanem, M., Haddad, S., Alzahrani, A., Mellit, A., Almohamadi, H., Khushaim, M., and Aida, M.S. Evaluation of the performance of polycrystalline and monocrystalline PV technologies in a hot and arid region: an experimental analysis. *Sustainability*, 15(20):14831, 2023.

[44] Dambhare, M.V., Butey, B., and Moharil, S.V. Solar photovoltaic technology: A review of different types of solar cells and its future trends. In *Journal of Physics: Conference Series,* 1913(1):012053, 2021.

[45] Sahu, B.K. A study on global solar PV energy developments and policies with special focus on the top ten solar PV power producing countries. *Renewable and Sustainable Energy Reviews*, 43:621-634, 2015.

[46] Vyas, B.K., Adhwaryu, A., and Bhaskar, K. Planning and developing large solar power plants: A case study of 750 MW Rewa Solar Park in India. *Cleaner Engineering and Technology*, 6:100396, 2022.

[47] Rathore, P.K.S., Chauhan, D.S., and Singh, R.P. Decentralized solar rooftop photovoltaic in India: On the path of sustainable energy security. *Renewable energy*, 131:297-307, 2019.

[48] Enerdata. India surpasses 100 GW of solar capacity. Retrieved February 23, 2025, from https://www.enerdata.net/publications/daily-energy-news/india-surpasses-100-gw-solar-capacity.html#:~:text=As%20of%2031%20January%202025,to%20100%20GW%20in%202025, 2025.

[49] Assam Power Distribution Company Limited, Solar Initiatives. Retrieved on February 19, 2025, from https://www.apdcl.org/website/, 2025.

[50] Das, D., Saikia, S., Saharia, S.J., and Mahapatra, S. Performance analysis of MW-scale grid connected rooftop and ground-mounted solar power plants installed in Assam, India. *Energy for Sustainable Development*, 76:101309, 2023.

[51] Khan, S., Ahmad, A., Ahmad, F., Shafaati Shemami, M., Saad Alam, M. and Khateeb, S. A comprehensive review on solar powered electric vehicle charging system. *Smart Science*, 6(1):54-79, 2018.

[52] Yap, K.Y., Chin, H.H. and Klemeš, J.J., 2022. Solar Energy-Powered Battery Electric Vehicle charging stations: Current development and future prospect review. *Renewable and Sustainable Energy Reviews*, 169, p.112862.

[53] Pati, S. Socio-Technical Drivers for Community Renewable Energy Systems–Analysis of Case Studies from India. *Journal of Sustainable Development*, 10(3):143-143, 2017.

[54] Chattopadhyay, D. Electrification of remote villages in Assam (India): Issues and case studies. In *2013 IEEE Power & Energy Society General Meeting,* 1-5. IEEE, 2013.

[55] Singh, R., and Kumar, P., Solar energy scenario in India: Opportunities and challenges. *Highly Efficient Thermal Renewable Energy Systems*, 56-61.

[56] Mane, P.D., and Khandekar, S.R. Clean Energy Innovations in India: Driving Sustainable Development. *ANVESHAK-International Journal of Management*, 70-88, 2024.

[57] Rathi, G., and Soni, M.K, October. Impact Analysis of PM KUSUM Scheme Individual Pump Solar Component C. In *2024 International Conference on Sustainable Energy: Energy Transition and Net-Zero Climate Future (ICUE),* pages 1-7, IEEE, 2024.

[58] Shankar, A. India's Solar Journey. In *The India Forum,* 2024.

[59] Rohankar, N., Jain, A.K., Nangia, O.P., and Dwivedi, P. A study of existing solar power policy framework in India for viability of the solar projects perspective. *Renewable and Sustainable Energy Reviews*, *56*:510-518, 2016.

[60] Keshavadasu, S.R. Regulatory and policy risks: Analyzing the uncertainties related to changes in government policies, regulations, and incentives affecting solar power project development and operations in Kenya. *Energy Policy*, 182:113760, 2023.

[61] Wandhe, D.P., 2024. An Overview on Production Linked Incentive (PLI) Scheme by The Government of India. *Available at SSRN 4693578*.

[62] Akoijam, A.S., and Krishna, V.V. Exploring the Jawaharlal Nehru national solar mission (JNNSM): Impact on innovation ecosystem in India. *African Journal of Science, Technology, Innovation and Development*, 9(5):573-585, 2017.

[63] Vogt-Schilb, A., and Hallegatte, S. Climate policies and nationally determined contributions: reconciling the needed ambition with the political economy. *Wiley Interdisciplinary Reviews: Energy and Environment*, 6(6):e256, 2017.

[64] Tiwari, G.N., and Dubey, S. *Fundamentals of photovoltaic modules and their applications*. Royal Society of Chemistry, 2009.

[65] Murillo-Yarce, D., Alarcón-Alarcón, J., Rivera, M., Restrepo, C., Muñoz, J., Baier, C., and Wheeler, P. A review of control techniques in photovoltaic systems. *Sustainability*, 12(24):10598, 2020.

[66] Xiaoli, X., and Daoe, Q. Remote monitoring and control of photovoltaic system using wireless sensor network. In *2011 International conference on electric information and control engineering,* page 633-638, IEEE, 2011.

[67] Shen, M., and Gao, Q. A review on battery management system from the modeling efforts to its multiapplication and integration. *International Journal of Energy Research*, 43(10):5042-5075, 2019.

[68] Martin, A.D., Cano, J.M., Medina-García, J., Gómez-Galán, J.A., and Vazquez, J.R. Centralized MPPT controller system of PV modules by a wireless sensor network. *IEEE Access*, 8:71694-71707, 2020.

[69] Liu, J., Wu, J., Qiu, J., and Zeng, J. Switched Z-source/quasi-Z-source DC-DC converters with reduced passive components for photovoltaic systems. *IEEE access*, 7:40893-40903, 2019.

[70] Uzum, B., Onen, A., Hasanien, H.M., and Muyeen, S.M. Rooftop solar pv penetration impacts on distribution network and further growth factors—a comprehensive review. *Electronics*, 10(1):55, 2020.

[71] Lutenegger, A.J. Foundation alternatives for ground mount solar panel installations. In *Geotechnical and Structural Engineering Congress,* 1873-1885, 2016.

[72] Sontake, V.C., and Kalamkar, V.R.,. Solar photovoltaic water pumping system-A comprehensive review. *Renewable and Sustainable Energy Reviews*, 59:1038-1067, 2016.

[73] Lulhe, A.M., and Date, T.N. A technology review paper for drives used in electrical vehicle (EV) & hybrid electrical vehicles (HEV). In *2015 International Conference on Control, Instrumentation, Communication and Computational Technologies (ICCICCT)*, 632-636), IEEE, 2015.

[74] Falvo, M.C., Sbordone, D., Bayram, I.S., and Devetsikiotis, M. EV charging stations and modes: International standards. In *2014 international symposium on power electronics, electrical drives, automation and motion*, page 1134-1139, IEEE, 2014.

[75] Reddy, K.S., Aravindhan, S., and Mallick, T.K. Techno-economic investigation of solar powered electric auto-rickshaw for a sustainable transport system. *Energies*, 10(6):754, 2017.

[76] Nadimuthu, L.P.R., and Victor, K. Performance analysis and optimization of solar-powered E-rickshaw for environmental sustainability in rural transportation. *Environmental Science and Pollution Research*, 28:34278-34289, 2021.

[77] Upadhyay, P., and Kumar, R. A ZVS-ZCS quadratic boost converter to utilize the energy of PV irrigation system for electric vehicle charging application. *Solar Energy*, 206:106-119, 2020.

[78] Kumar, S., Miglani, Y., and Tomar, A. September. Solar-Powered EV Charging and Adaptive Irrigation System. In *2024 IEEE Region 10 Symposium (TENSYMP)*, page 1-7, IEEE, 2024.

[79] Nawaz, M.U., Qureshi, M.S., and Umar, S. Integration of solar energy systems with electric vehicle charging infrastructure: challenges and opportunity. *Revista Espanola de Documentacion Cientifica*, 18(02):1-18, 2024.

[80] Ullah, Z., Wang, S., Wu, G., Hasanien, H.M., Rehman, A.U., Turky, R.A., and Elkadeem, M.R. Optimal scheduling and techno-economic analysis of electric vehicles by implementing solar-based grid-tied charging station. *Energy*, 267:126560, 2023.

[81] Bondalapati, S.R., Bhukya, B.N., Anjaneyulu, G.P., Ravindra, M., and Chandra, B.S. Bidirectional Power Flow Between Solar-Integrated Grid To Vehicle, Vehicle To Grid,

And Vehicle To Home. *Journal of Applied Science and Engineering*, 27(5):2571-2581, 2024.