Future trends and strategies for sustainable energy management

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Abstract
The need for effective and sustainable energy solutions has grown since the early 20th century due to a steady increase in both global energy production and consumption. The production and demand for renewable energy have increased significantly, while India's consumption of coal and lignite has increased recently as a result of economic expansion and rising natural gas prices. In order to combat climate change and lower carbon emissions, several industrialized nations are simultaneously investing more in renewable energy. In this regard, computer-based modeling is crucial for assessing solar photovoltaic (PV) technology's effectiveness under practical operating settings, as it has become a major clean energy choice. This paper proposes a physics-guided synthetic-data approach to examine inter-annual fluctuations in PV performance using minor perturbations in irradiance and temperature, using 2015 meteorological data used as the baseline for the JAP6-72-320/4BB module. The findings demonstrate that realistic PV operational circumstances can be accurately represented by controlled disturbances. Furthermore, a comparison of Li-ion batteries for PV-based systems shows that Li-ion storage performs better, but electrolyzer cost is still the most important element influencing system efficiency.

Keywords: Renewable energy, Photovoltaic systems, Synthetic data approach, Irradiance and temperature perturbation, Li-Ion Battery, Sustainable Development, Solar PV Modeling.

1. Introduction
Energy sets all aspects of life and matter in the universe into motion, and it can be defined as the ability to do work; energy is the basic force behind all activity. In the olden day's energy was used in mainly three forms. They are human power, animal power and heat. Slavery was a product of a long-standing need for human power. Over time, machines (mainly powered by fossil fuels (coal, oil, gas) and nuclear energy) replaced muscle labour, and the demand for energy increased sharply. This growth has led to increased consumption of fossil and nuclear resources and environmental degradation, resulting in global climate change and its associated disasters such as heavy rains and floods, deforestation, and melting glaciers. Thus, the focus is moving toward the transition to renewable and sustainable energy sources, including solar, wind, biomass, hydropower, and geothermal as shown in Fig. 1 and Table 1.

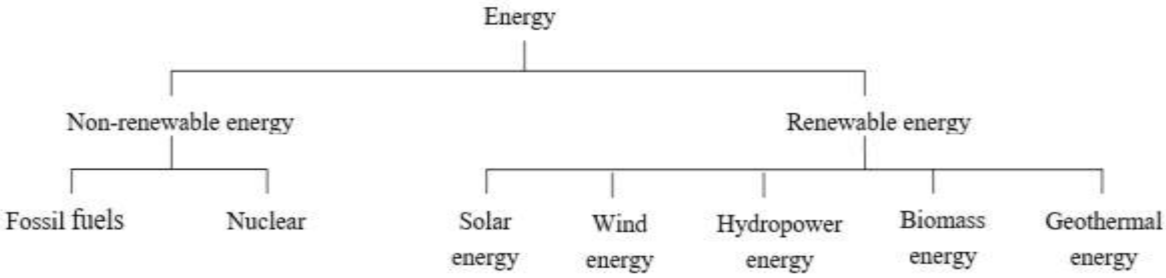

Fig. 1: Classification of energy resources

Renewable energy sources are natural resources which can be replenished naturally over time, providing a sustainable and environmentally friendly alternative to traditional fossil fuels. These sources are helping to diversify our energy mix and cut greenhouse gas emissions. They give us energy in the form of electricity, heat and fuels. These renewable sources offer a number of advantages such as a lower environmental impact, long-term sustainability and the creation of jobs, all of which will help to build a more resilient and environmentally friendly energy future. Research and development in this sector is focused on improving efficiency, sustainability, affordability, energy economics, and product quality.
Such differences in the proportion of renewable energy in the installed capacity and its actual electricity generation can be attributed to variables such as variations in sunshine hours and wind patterns. These variables directly influence the degree of utilization of the installed capacity. The United Kingdom government pledged US$ 1.2 billion in September 2021 for green projects and initiatives in India around renewable energy. The commitment is aimed at helping India reach its ambitious target of 450 GW of renewable energy capacity by 2030. Besides, the

development and exploration of renewable energy is basically dependent on the offshore wind technology and the generation of green hydrogen.

Table 1: Historical development of renewable energy

Invention / Milestone	Year
Early hydroelectric power use	200 BC
Windmills used for wind energy	1590
Hydrogen fuel discovered	1838
Solar energy / photovoltaic foundations	1839
First solar energy system	1860
Solar cells to generate energy	1876
First practical wind turbines	1887
Photoelectric effect	1905
Wind turbines used commercially	1927
Modern dam technology	1935
Solar goes to space	1958
Lithium-ion battery	1970
One whole village goes to solar	1978
Large-scale solar project	1996
Ivanpah Solar Power Facility	2013
Chandrayaan-3 lands at Moon's south pole	2023

The Indian government has announced several key initiatives to promote sustainable energy practices in the Union Budget for the financial year 2022-23. These included the issuance of sovereign green bonds and the provision of infrastructure status to energy storage systems, including grid-scale battery systems. The power consumption was estimated to be around 1895 TWh in the year 2022. The government has allocated 19500 crores for Production Linked Incentive (PLI) Scheme to promote the manufacturing of high efficiency solar modules. Additionally, Energy Efficiency Services Limited (EES) is working with private-sector energy service companies to scale up its Building Energy Efficiency Programme (BEEP).

2. Generation and consumption of energy

Agriculture, building, industrial production, and economic expansion all depend on energy, with per capita consumption serving as a gauge of country development. Among major economies, India has seen the highest growth in renewable energy capacity addition over the past nine years, with solar energy rising by more than eighteen times and renewable energy capacity growing by 2.9 times. It makes sense to incorporate energy planning into economic planning since the energy sector has received about 30% of the entire expenditure of the Indian economy's five-year plan.

Energy planning takes into account a number of variables, including organizational, technological, social, economic, environmental, and demographic considerations. Planning, which can be divided into three stages: technology evaluation, the creation of a mathematical framework for the energy economy system and its implementation and management, and the provision of feedback for action on both the energy supply and demand sectors, requires a system analytic approach and modeling techniques.

Fig. 2 illustrates the variation in renewable energy production and consumption worldwide starting in 2009 (source: https://www.statista.com). Because renewable energy has lower carbon emissions than fossil fuels, developed nations are spending more in it to help ameliorate the climate catastrophe. As a result, after 2010, the proportion of renewable energy to non-renewable energy in the world's electricity output grew significantly, as Fig. 3 illustrates. The information was extracted from the "Energy Statistics Pocketbook 2022."

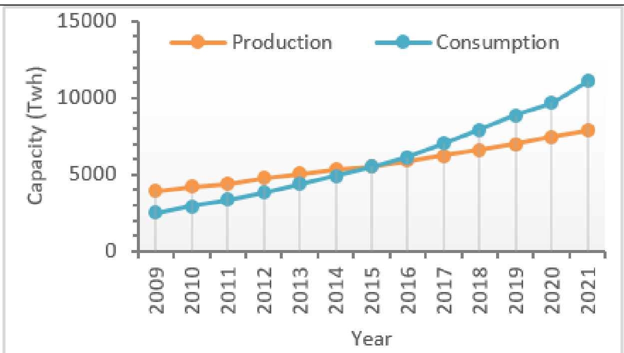

Fig. 2: Global production & consumption of renewable energy

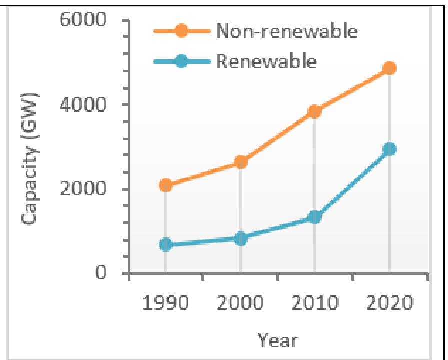

Fig. 3: Global electricity generation

According to the source https://www.yearbook.enerdata.net, domestic coal and lignite consumption in India has increased since 2020 as a result of the country's economic recovery, rising natural gas prices, strong demand, and low average quality of coal and lignite, as shown in Fig. 4. According to the source https://www.powermin.gov.in, India's total energy generation rose from 2009–10 to 2019–20, but it fell in 2020–21 as a result of the COVID-19 epidemic. From 2021–2022, however, it rapidly increased due to an increase in consumption following the release from lockdown, as Fig. 5 illustrates.

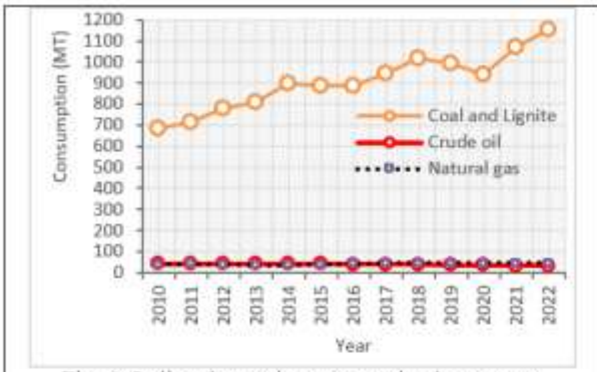

Fig. 4: Indian domestic consumption by sources

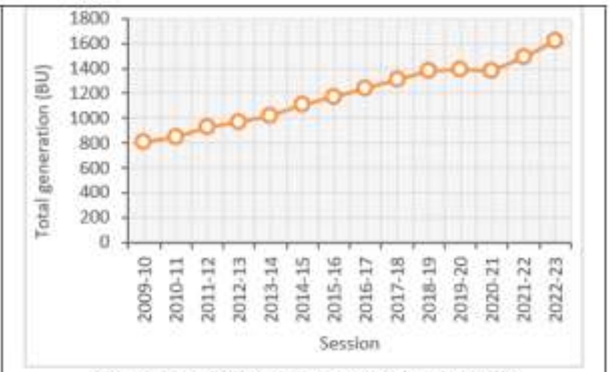

Fig. 5: Total electricity generation in India

According to Fig. 6 (source: https://www.powermin.gov.in), India has made significant progress in closing the gap between energy supply and demand between 2009–10 and 2021–2022.

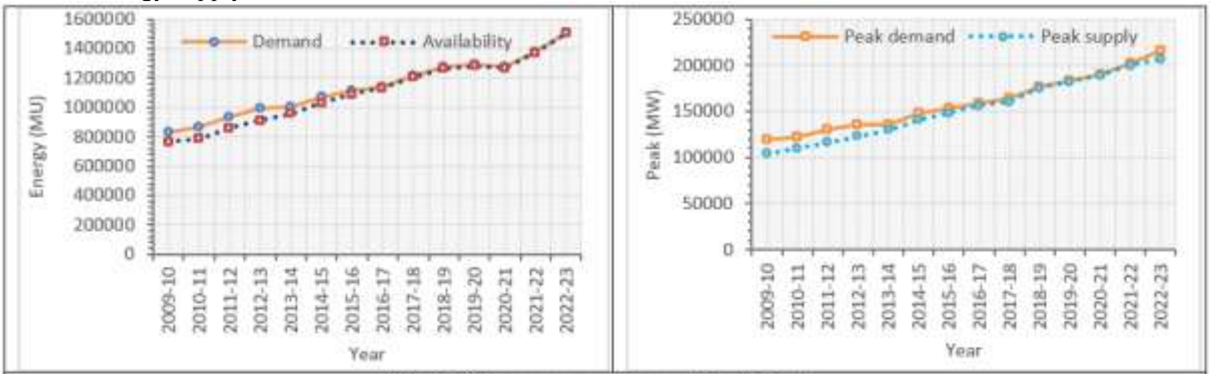

Fig. 6: The power supply position in India

3. Innovation in power generation

Photovoltaic systems, hydrogen, and lithium have the potential to power homes and businesses. These sources reduce the need for finite fossil fuels, which both increases energy security and allays environmental worries. Energy systems are becoming more and more crucial to international efforts to combat climate change and guarantee a sustainable energy future as a result of ongoing technological breakthroughs that increase their price and efficiency. The most popular renewable energy source for producing electricity is solar photovoltaic energy. (Electricity – Global Energy Review 2025) The photovoltaic phenomenon, first noticed by Becquerel in 1839, allows solar energy to be converted into electricity. (Photovoltaic effect, 2024) In order to address the mismatch between production and load, this industry is expanding quickly on a global scale. The most popular storage technique to address the aforementioned mismatch is battery storage, which includes: (Energy storage - IEA, 2021).

3.1 Solar PV systems

Significant progress has been made in areas including material selection, energy efficiency in manufacturing processes, device design, production methods, and innovative ideas to increase the system's overall efficiency in order to maintain this pace. In order to produce the necessary terminal voltage and current ratings, solar photovoltaic arrays are networks of several electrical generators, or solar cells. The explicit mathematical analysis based on randomly produced parameters of solar cell characteristics has been explored in accordance with N.K. Gautam and N.D. Kaushika [1]. For a single diode solar cell, the current-voltage relationship is as follows:

$$I - I_{scc} + I_{scc}\left(\frac{1-\gamma}{e^{P}-1}\right)\left[e^{P\left(\frac{V+IR_s}{V_0}\right)}-1\right] + \gamma I_{scc}\left(\frac{V+IR_s}{V_0}\right) = 0;\ P = \frac{eV_0}{NkT},\ \gamma = \frac{V_0}{R_{sh}I_{scc}} \quad (1)$$

Similarly, for cell(m, n),

$$I_{mn} = (I_{scc})_{mn} - (I_{scc})_{mn}\left(\frac{1-\sigma_{mn}}{e^{P_{mn}}-1}\right)\left[e^{P_{mn}\left(\frac{V_{mn}+I_{mn}R_s}{(V_0)_{mn}}\right)}-1\right] + \sigma_{mn}((I_{scc})_{mn})_{mn}\left(\frac{V_{mn}+I_{mn}R_s}{(V_0)_{mn}}\right) \quad (2)$$

The mathematical network analysis method can be used to examine the electrical properties of series-parallel, total-cross-tied, and bridge-linked arrays. The current I_{mn} for given voltage V_{mn}, the iterative formula for Newton-Raphson method is given as follows:

$$(I_{mn})_{i+1} = (I_{mn})_i - \frac{f(V_{mn}, I_{mn})}{\frac{\partial f(V_{mn}, I_{mn})}{\partial I_{mn}}} \quad (3)$$

According to computational research, bridge-linked type solar cell interconnecting networks are better at handling the consequences of electrical mismatches than series-parallel and total-crossed-tied networks. According to the source https://www.statista.com, the cost of installing solar PV systems steadily dropped globally between 2010 and 2021. The greater availability of materials, which in turn reduced production costs, was the main cause of this cost reduction. According to Fig. 7a, the average installation cost of a solar PV system reached about 857 U.S. dollars per kilowatt by 2021. The number of these installations has surged since 2010 due to the sharp drop in the average installed cost of solar PV systems worldwide. This has resulted in a sharp rise in solar power output in a net zero scenario, as illustrated in Fig. 7b. According to the source https://www.statista.com, after 2015, rising retail electricity costs and expanding legislative support to assist customers in lowering their electricity bills led to an increase in the demand for solar PV worldwide, as illustrated in Fig. 7c.

Based on information from the International Energy Agency (IEA), Fig. 8 shows the global distribution of cumulative power capacity across various technologies. Notably, the percentage of solar PV cells has been rising significantly since 2010. The previous year, it increased significantly to account for 45% of all global investments in energy production. Because of legislative support and growing competition in the solar PV industry, this is three times larger than the investment made in fossil fuel technology. In 2021, increasing solar PV capacity was a top objective for both developed and developing nations. Growing environmental awareness of the depletion of non-renewable resources and pollution emissions, as shown graphically in Fig. 9, was the driving force behind this choice.

According to data from the Ministry of New and Renewable Energy (MNRE) at https://www.mnre.gov.in, India's off-grid solar PV applications program was concentrated on offering solar PV-based solutions in regions lacking dependable grid power between 2013–14 and 2017–18. Figure 10 shows this initiative.

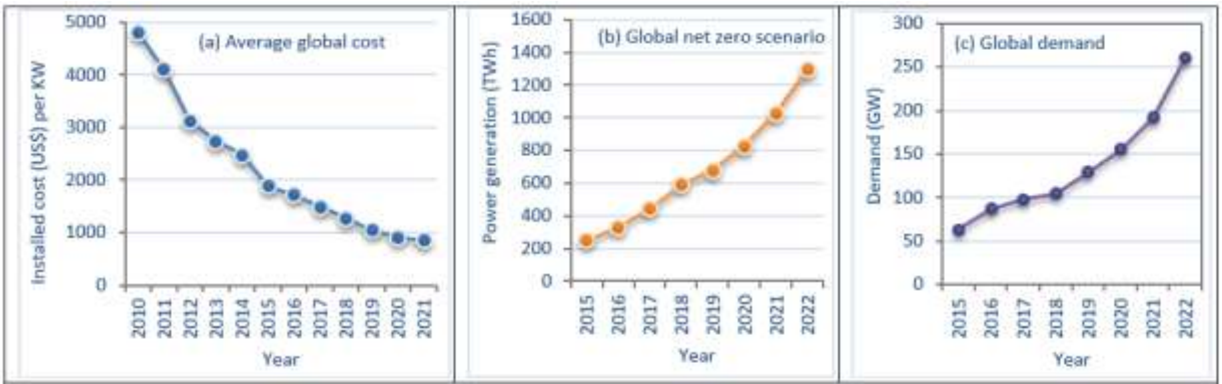

Fig. 7: For solar PV systems

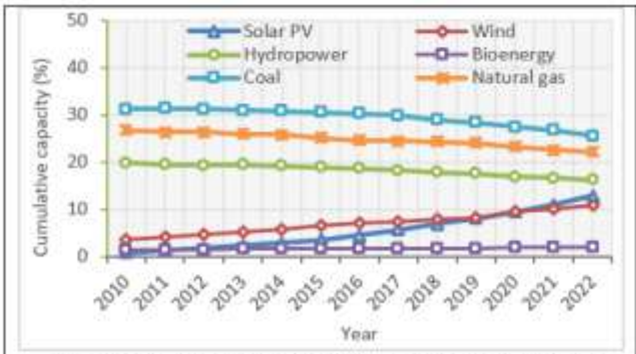

Fig. 8: Global energy collection with different sectors

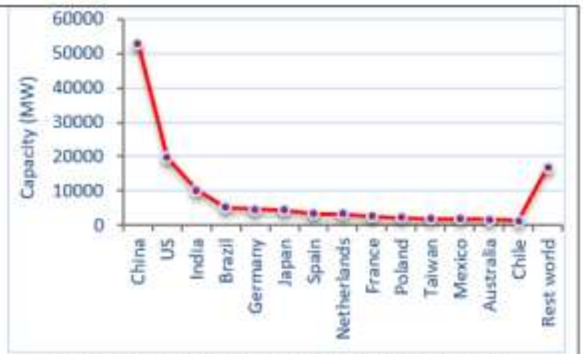

Fig. 9: Solar PV generation capacity in 2021

3.2 Physics-Guided Synthetic Data Modeling of Inter-Annual PV Performance

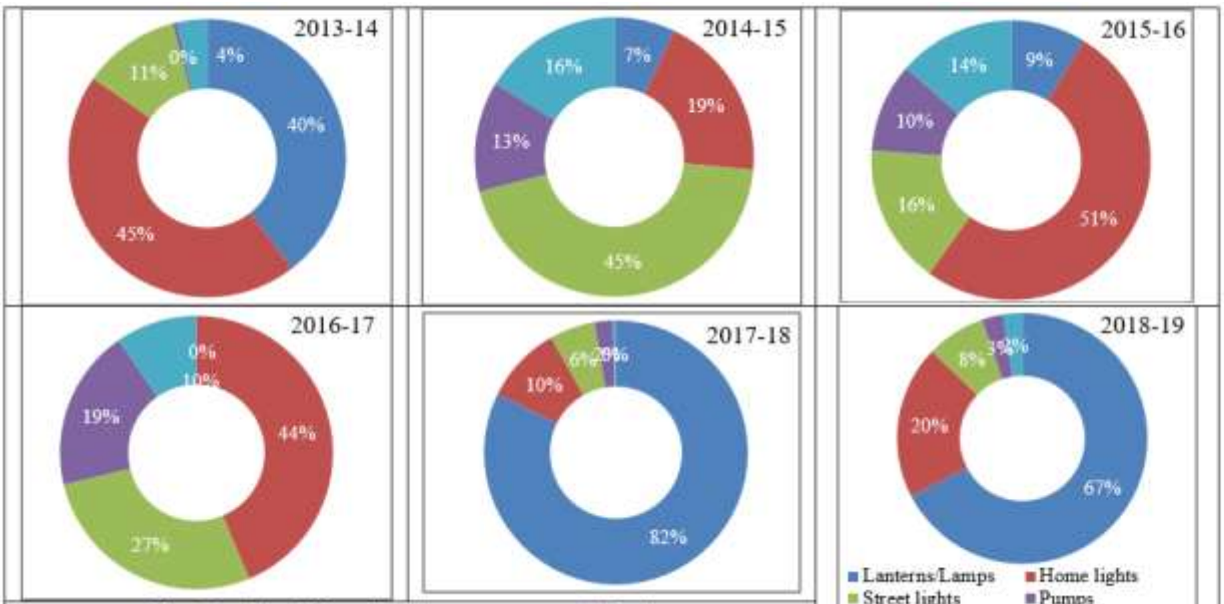

Fig. 10: Solar PV applications programme in India

With solar capacity and cell efficiency increasing quickly, photovoltaic devices are a key component of the clean energy revolution. The goal of cutting-edge ideas like thin-film materials, passivated-contact silicon cells, and perovskite-silicon tandems is to surpass 30% efficiency while still being manufacturable. In order to reduce expensive experimental trial-and-error, computer modeling is now crucial for virtual prototyping, parameter optimization, and yield prediction. Contemporary models include compact one-diode and two-diode equations for device- and system-level analysis, as well as intricate drift-diffusion and Poisson simulations. Improved calibration and sensitivity analysis are made possible by new simulators and ML-based extraction techniques, which strengthen the connection between simulation and industrial R&D and production. In general, PV modeling speeds up the development of next-generation solar cells and connects basic physics with large-scale manufacturing [15-28].

The current generated by a perfect solar cell with neither shunt nor series resistance can be written as

$$\boldsymbol{I} = \boldsymbol{I_l} - \boldsymbol{I_0}.\left[\boldsymbol{e}^{((V+IR_s)/nV_T)} - \boldsymbol{1}\right], \boldsymbol{V_T} = \boldsymbol{kT/q} \tag{4}$$

The total current I in an open circuit is zero. As a result, the voltage at open circuit is

$$\boldsymbol{V}_{oc} = \left[\boldsymbol{log_e}\big((\boldsymbol{I_l}/\boldsymbol{I_0}) + \boldsymbol{1}\big)\right].\boldsymbol{n}(\boldsymbol{kT/q}) \tag{5}$$

The photocurrent that is affected by temperature and incident irradiance levels is:

$$\boldsymbol{I_l} = \big(\boldsymbol{I}_{sc,ref}\,\boldsymbol{s}/\boldsymbol{s}_{ref}\big).\left[\boldsymbol{1} + \boldsymbol{a_I}(\boldsymbol{T} - \boldsymbol{T}_{ref})\right] \tag{6}$$

The voltage V is almost zero in a short circuit. As a result, the short-circuit current $\boldsymbol{I}_{sc}$ is commonly calculated as follows:

$$\boldsymbol{I}_{sc} \approx \boldsymbol{I_l} \tag{7}$$

Irradiance is the power per unit area that strikes the photovoltaic surface at any particular time:

$$\boldsymbol{s}(\boldsymbol{t}) = \boldsymbol{p}_{in}(\boldsymbol{t})/\boldsymbol{A} \tag{8}$$

where $\boldsymbol{p}_{in}(\boldsymbol{t})$, A: the power of sunlight striking the surface (W), the photovoltaic surface area (m^2).

The average monthly irradiance for the given dataset is computed as follows:

$$\boldsymbol{s}_{avg,\boldsymbol{m}} = \frac{\boldsymbol{1}}{\boldsymbol{m_n}} \sum_{t=1}^{m_n} \boldsymbol{s}(\boldsymbol{t}) \tag{9}$$

where the number of valid irradiance measurements for the month is represented by $\boldsymbol{m_n}$.

The reported air temperature is precisely equal to the surrounding temperature $\boldsymbol{T}_{am}(\boldsymbol{t})$ (°C) at any given time:

$$\boldsymbol{T}_{am}(\boldsymbol{t}) = \boldsymbol{T}_{sens}(\boldsymbol{t}), \tag{10}$$

captured by a weather station close to the PV array that has been calibrated.

The monthly average ambient temperature for the given dataset is:

$$\boldsymbol{T}_{am,avg,\boldsymbol{m}} = \frac{\boldsymbol{1}}{\boldsymbol{m_n}} \sum_{t=1}^{m_n} \boldsymbol{T}_{am}(\boldsymbol{t}) \tag{11}$$

For given dataset, the monthly-average MPP current is:

$$\boldsymbol{I}_{mpp,\boldsymbol{m}} = \frac{\boldsymbol{1}}{\boldsymbol{m_n}} \sum_{t=1}^{m_n} \boldsymbol{I}_{mpp}(\boldsymbol{t}) \tag{12}$$

This is the monthly average operating current under MPPT management.

The average monthly MPP voltage for the given dataset is:

$$\boldsymbol{V}_{mpp,\boldsymbol{m}} = \frac{\boldsymbol{1}}{\boldsymbol{m_n}} \sum_{t=1}^{m_n} \boldsymbol{V}_{mpp}(\boldsymbol{t}) \tag{13}$$

At each instant, the maximum power $\boldsymbol{p}_{max}$ (W) is:

$$\boldsymbol{p}_{max}(\boldsymbol{t}) = \boldsymbol{I}_{mpp}(\boldsymbol{t})\boldsymbol{V}_{mpp}(\boldsymbol{t}) \tag{14}$$

For given dataset, the monthly-average maximum power is:

$$\boldsymbol{p}_{max,\boldsymbol{m}} = \frac{\boldsymbol{1}}{\boldsymbol{m_n}} \sum_{t=1}^{m_n} \boldsymbol{p}_{max}(\boldsymbol{t}) = \frac{\boldsymbol{1}}{\boldsymbol{m_n}} \sum_{t=1}^{m_n} \left[\boldsymbol{I}_{mpp}(\boldsymbol{t})\boldsymbol{V}_{mpp}(\boldsymbol{t})\right] \tag{15}$$

Table A: Specific values constants to construct datasets

Year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
$\delta_{G,Y}$	-0.042	+0.028	-0.018	+0.053	+0.015	-0.024	+0.031	-0.027	+0.035	-0.012	+0.018
$\delta_{T,Y}$	-0.9	1.1	0.2	-1	0.5	-0.8	0.7	-0.4	0.3	0.6	+0.2

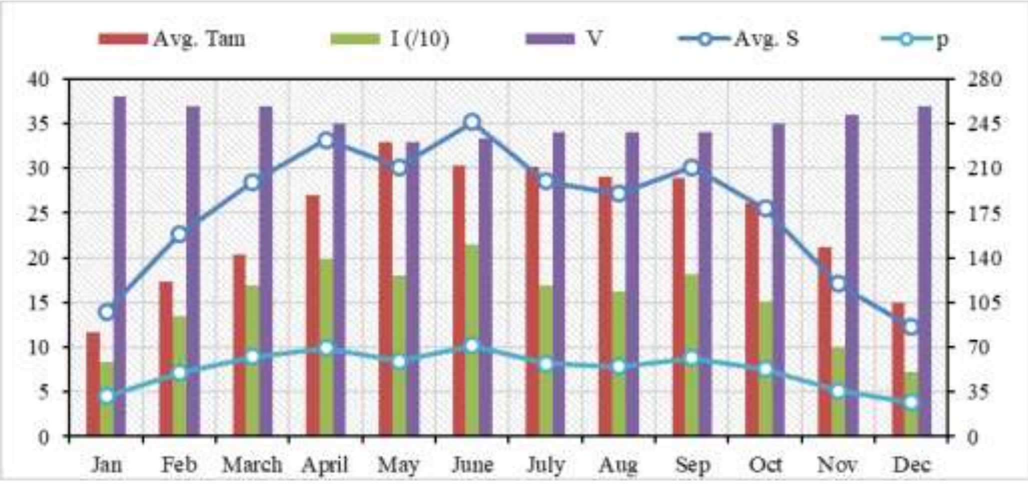

Fig. i: Synthetic monthly dataset for the year 2015

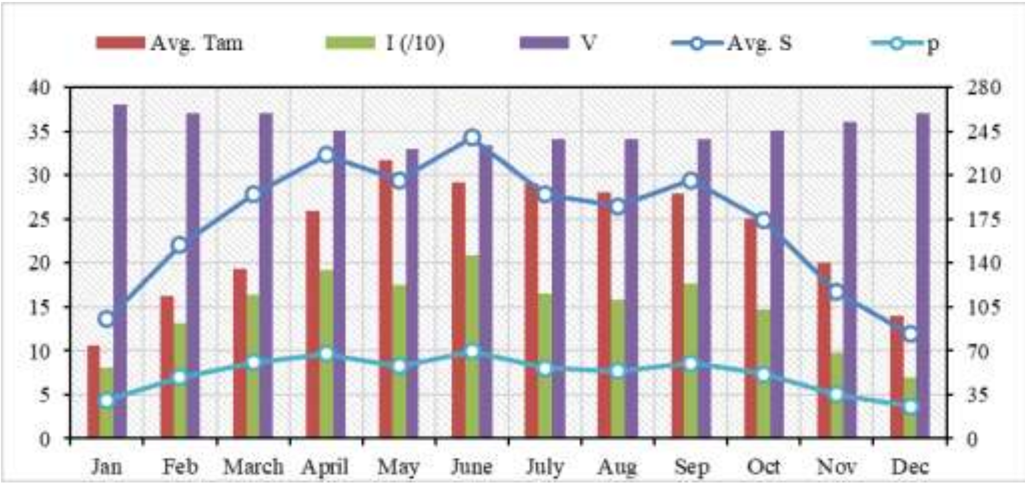

Fig. ii: Synthetic monthly dataset for the year 2016

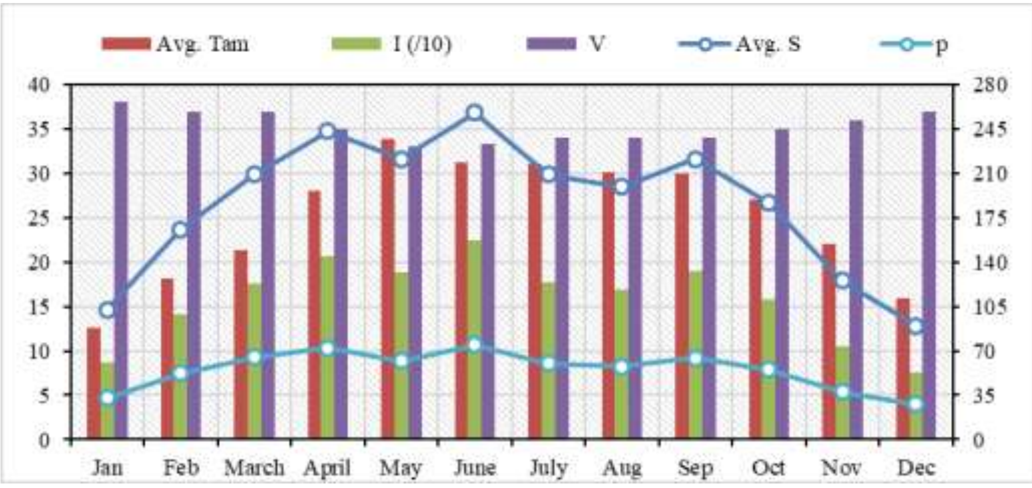

Fig. iii: Synthetic monthly dataset for the year 2017

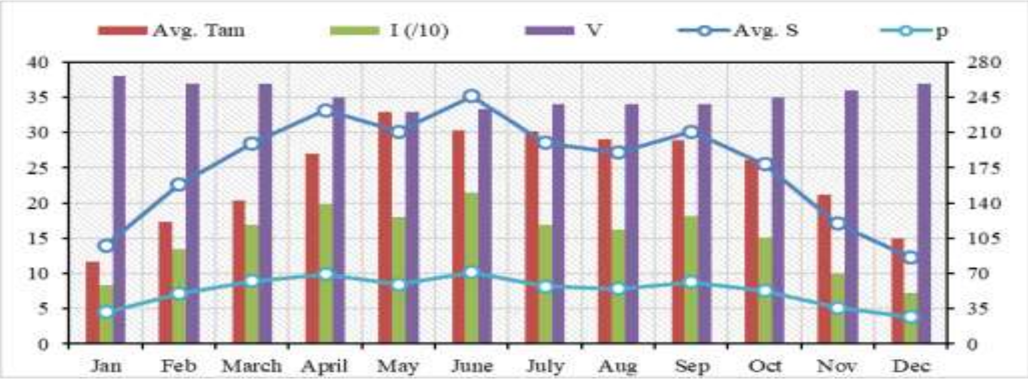

Fig. iv: Synthetic monthly dataset for the year 2018

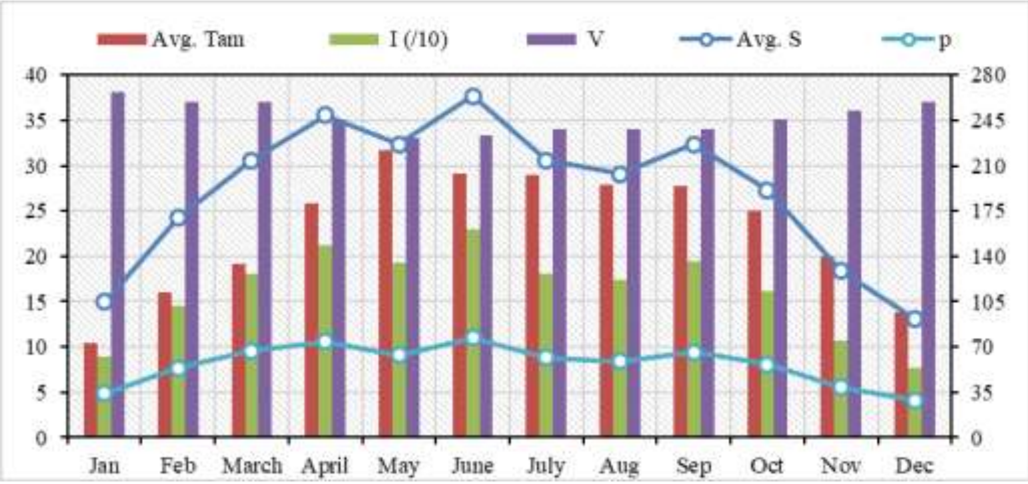

Fig. v: Synthetic monthly dataset for the year 2019

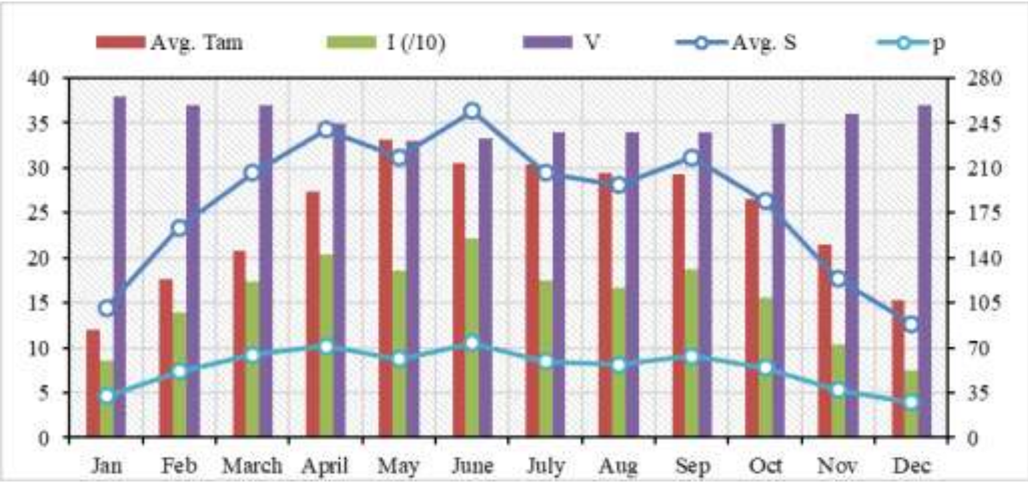

Fig. vi: Synthetic monthly dataset for the year 2020

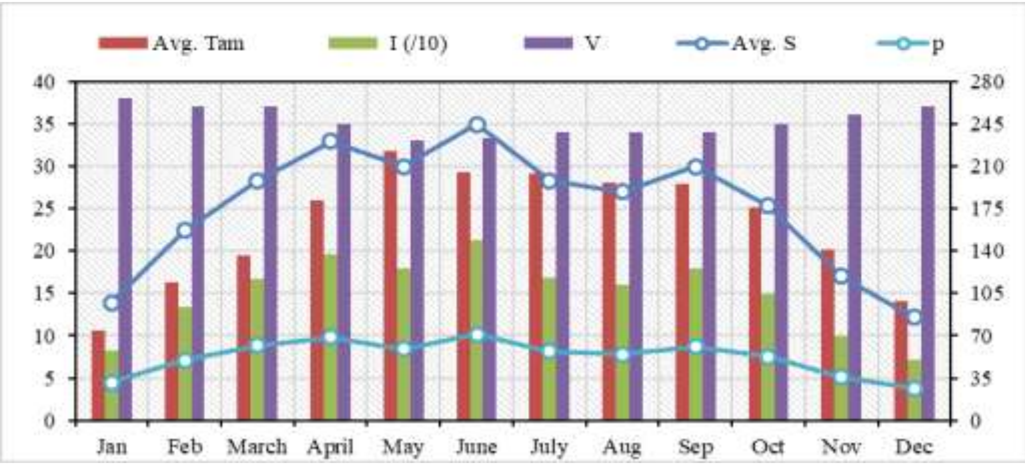

Fig. vii: Synthetic monthly dataset for the year 2021

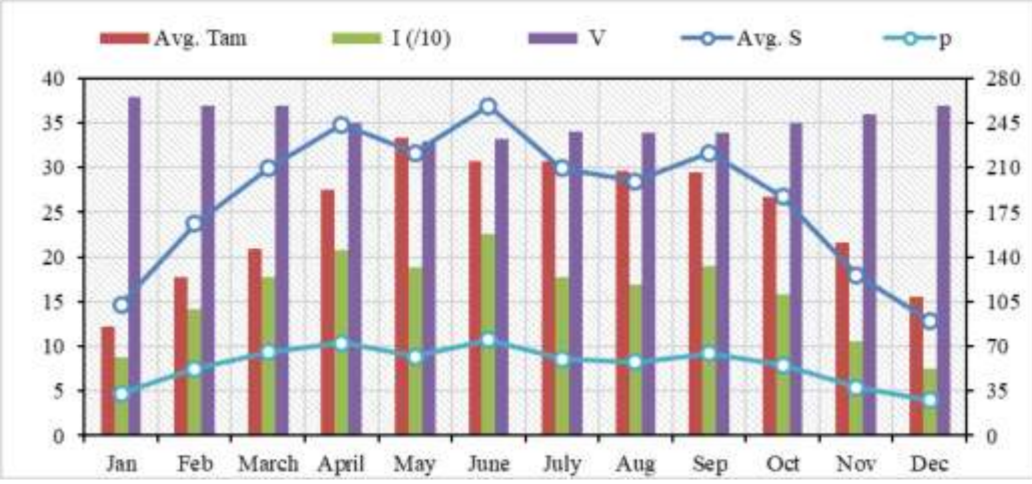

Fig. viii: Synthetic monthly dataset for the year 2022

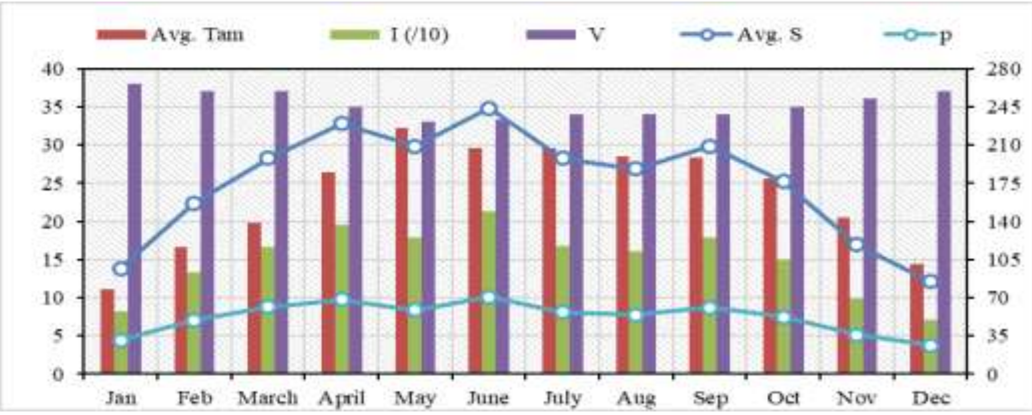

Fig. ix: Synthetic monthly dataset for the year 2023

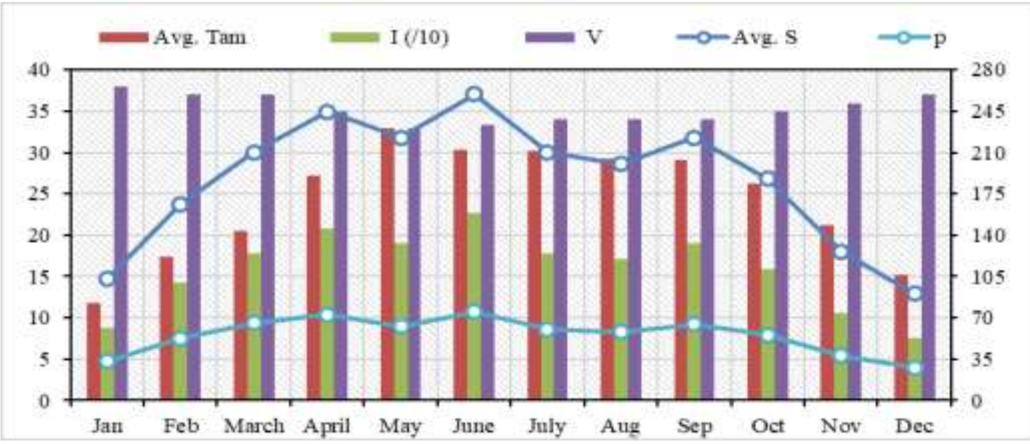

Fig. x: Synthetic monthly dataset for the year 2024

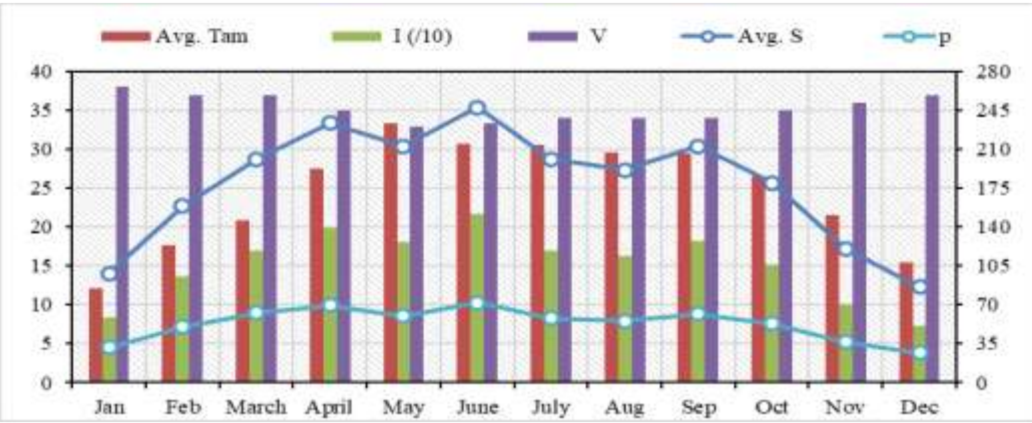

Fig. xi: Synthetic monthly dataset for the year 2025

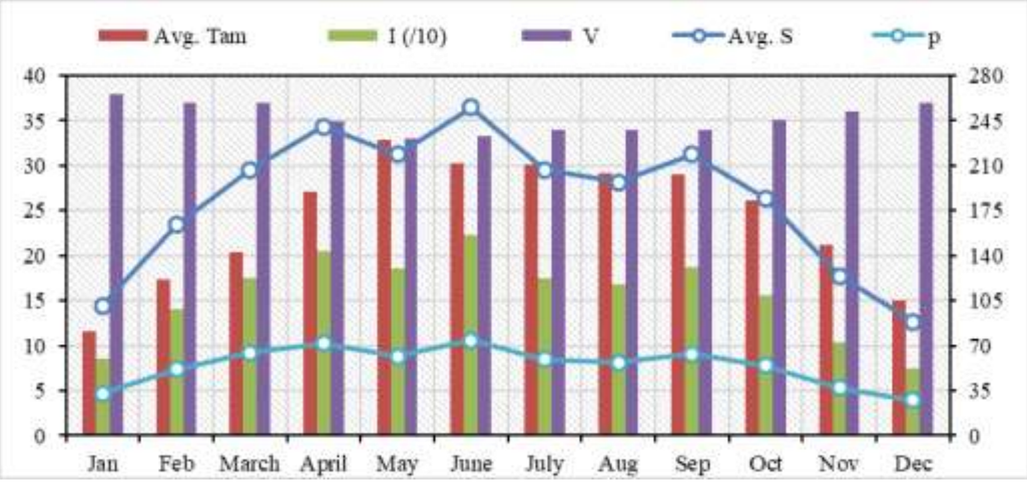

Fig. xii: Synthetic monthly dataset for the year 2026

All changes stay within the predetermined bounds, according to the synthetic PV datasets for 2016–2026 that were generated from the 2015 baseline using a physics-based scaling model developed in MATLAB. Monthly parametric performance for each year is shown in Fig. i–xii. The temperature offsets vary from −1.0 °C (2019) to +1.1 °C (2017), with typical excursions within ±1.1 °C, and the irradiance bias ranges from −0.042 (−4.2%) in 2016 to +0.053 (+5.3%) in 2019; these bounds validate the validity of the synthetic-data creation process.
The statistics reveal a recurring cycle for both temperature and irradiance when looking year over year. Between 2016 and 2019, there were very slight variations in irradiance (−0.042 in 2016, +0.028 in 2017, −0.018 in 2018, and +0.053 in 2019). There are moderate to substantial positive peaks between 2019 and 2024 (most notably +0.053 in 2019 and +0.035 in 2024). There are greater negative variances between 2021 and 2025 (−0.024 in 2021, −0.027 in 2023, and −0.012 in 2025). A positive irradiance change of +0.018 (+1.8%) is recorded in the last year, 2026. Between 2016 and 2026, there was an average increase in irradiance of ≈+0.5% and temperature fluctuations of ≈−0.05 °C.
The findings show that the little temperature offsets have less of an impact on predicted PV performance than fluctuations in irradiance. 2019 has the best irradiance bias (+5.3%), whereas 2016 has the worst (−4.2%). All things considered, the synthetic datasets are appropriate for sensitivity analysis, parameter tuning, and performance forecasting for new photovoltaic technologies. They also represent genuine year-to-year variability in PV conditions. Modest temperature offsets (−1.0 °C to +1.1 °C) and controlled irradiance variations (−4.2% to +5.3%) accurately simulate real-world PV system conditions.

3.3Li-ion battery

For environmentally friendly storage and development technologies, lithium is an essential metal. Australia, Chile, China, Argentina, Brazil, Zimbabwe, Portugal, Bolivia, and the United States are just a few of the countries where it can be found. Australia is the world's top producer and largest supplier, according to the source https://www.statista.com/statistics/. Additionally, Bolivia and Argentina have the largest lithium reserves, as seen in Fig. 11. Lithium deposits in Bolivia and Argentina are 21 million tons and 19 million tons, respectively. Lithium is mostly extracted from hard rock mines in Australia.
The Salal-Haiman region of Jammu & Kashmir's Reasi District is where lithium resources were initially found in India. Significant lithium reserves were later discovered in the Nagaur region of Rajasthan, particularly in the Renvat hill in Degana. More specifically, the lithium-bearing property covers 18,913 Kanals and 17 Marlas, including 3,929 Kanals of private land, 269 Kanal and 7 Marla of state-owned land, and 14,715 Kanals and 10 Marlas of forest area, according to statistics from the District Administration Reasi. The Degana region, which has a long history of providing the nation with tungsten materials, has significant lithium reserves, according to the Geological Survey of India (GSI). According to GSI and mining authorities, Rajasthan's lithium reserves might supply almost 80% of India's total need for this vital metal. With enough capability to meet domestic demand, this discovery could make India the seventh-largest lithium deposit in the world and lessen its need on China for lithium.

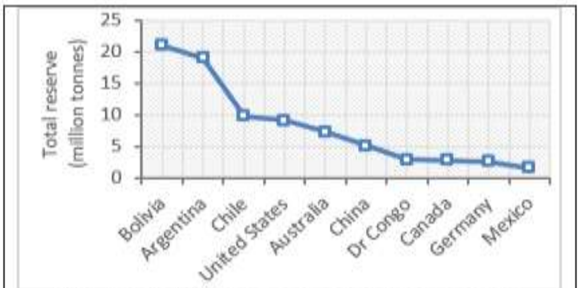

Fig. 11: Lithium reserve of various country

The importance of industrial energy management as a partial solution to the problem of separating GDP growth from rising commercial energy demand is shown by this finding. It also emphasizes how decentralized energy and power systems require technology developments.

Lithium has a variety of uses. It is used as a drug to treat mental disease in the form of lithium carbonate. Additionally, it is utilized in the production of lightweight alloys for the aviation sector. Lithium hypochlorite is utilized as a reagent in some chemical reactions and as a disinfectant in swimming pools. Because lithium can reliably forecast residence duration and closely resembles the mobility of metals in soil solutions and water bodies, it is also utilized as a tracer in studies of soil and water pollution.

Li-ion batteries are a particular subset of lithium batteries that use Li-ion technology to store and release electrical energy, but lithium batteries as a whole comprise a variety of lithium-based chemistries. Li-ion batteries' high energy density and rechargeable nature make them popular in electric cars and portable electronics. Table 2 illustrates the distinction between lithium and Li-ion batteries. The EV market is driving up demand for lithium resources. Lithium is a soft, silvery-white alkali and non-ferrous metal that is essential to many sectors, including batteries for electric vehicles. The imported amounts and prices of lithium and Li-ion for three consecutive sessions are shown in Table 3.

Table 2: Difference between lithium and lithium-ion battery

Factor	Lithium battery	Lithium-ion battery
Rechargeability	Non-rechargeable	Rechargeable
Efficiency	Lower efficiency	Higher efficiency
Energy density	Higher energy density	Lower energy density
Capacity loss	Capacity is lost over use	Less capacity is lost
Size and weight	Smaller and lighter	Larger, with better weight capacity
Electrode material	Metallic lithium is used	Lithium compounds such as lithium cobalt oxide or lithium iron phosphate are used
Applications	Cameras, clocks, and small electronic devices	Smartphones, laptops, electric vehicles, and similar devices

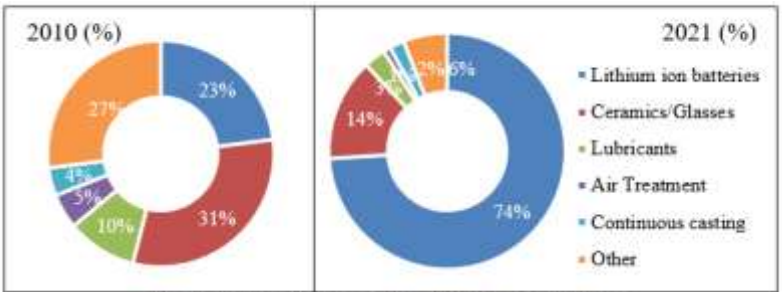

Fig. 12: Global change in Lithium consumption

Table 3: Imported quantities and cost of lithium and Li-ion for three continuous sessions

	2018-19 Quantity (Thousand numbers)	2018-19 Value (Rs. Crores)	2019-20 Quantity (Thousand numbers)	2019-20 Value (Rs. Crores)	2020-21 Quantity (Thousand numbers)	2020-21 Value (Rs. Crores)
Lithium (HS Code: 85065000)	85,224	202	72,376	147	71,392	173
Lithium-ion (HS Code: 85076000)	6,27,353	8,574	5,39,428	8,819	5,16,733	8,811

Imported quantities in these session are decreasing continuously while their costs are fluctuating. Table 4 & 5 represent the factors influencing lithium and inflation/shortages of lithium respectively.

Table 4: Factors influencing lithium

For demand	For supply
Growing EV adoption	Where resources are located
Consumer electronics demand	Available production capacity
Energy storage systems	New technology
Industrial use	Environmental rules
Urban growth and infrastructure needs	Political stability and price changes
Government support and incentives	Trade policies
Recycling efforts	New discoveries

Table 5: Inflation & shortages of lithium

Causes	Impact
More energy storage needs and market growth	Price swings
More gadgets and electronic devices	Higher battery costs
Government policies and regulations	Social and geopolitical effects
Advances in technology	Higher battery costs
Recycling efforts	Price changes
More energy storage needs and market growth	Price swings

Li-ion batteries, EVs, ceramics/glasses, lubricants, pharmaceutical, air treatment, polymers, aluminum-lithium alloys are the main industrial applications of lithium. Lithium consumption increased globally because of the surge in EV adoption and renewable ener gy storage since 2010 to 2021 as shown in Fig. 12.

Fig. 13 represents the variation in average lithium carbonate price for last 13 years, where better growth in price has been seen in 2016-18 and faster growth in 2021. The average Li-ion battery price has decreased due to the increase in worldwide lithium production, decreasing logistics costs, and an increase in the number of units of Li-ion batteries produced by manufacturing industries. But due to increase in demand of volume weighted Li-ion battery and in average production cost of lithium carbonate, the average price of Li-ion battery increased by 7%

in 2022 instead of 2021 as shown in Fig. 14.

3.2.1 Importance of Lithium for India

Lithium is very crucial for Indian economy as renewable energy source to reduce imports, self-reliance, battery manufacturing, clean energy targets and economic benefits for Jammu & Kashmir, digital revolution. But currently, India has to face many challenges to extract lithium as water consumption (approximately 1.9 million liters/metric tonnes), environment degradation, lack of expertise, feasibility study, impact on Himalayas, high investments etc. Currently, less than 1% of lithium is recycled due to the lack of a significant incentive to develop a lithium recycling industry. However, with rising demand for lithium resources, the need to recover lithium before it's wasted in disposal will become crucial.

Following the source https://batteryuniversity.com, the specific energy density of lead acid(Pb-A), nickel-cadmium(Ni-Cd), Li-titanate(LTO), Li-iron phosphate(LFP), nickel-metal hydride(NiMH), Li-ion manganese oxide(LMO), nickel manganese cobalt(NMC), sodium sulphur(NaS), Li-cobalt(LCO) and Li-nickel cobalt aluminium oxide(NCA) has compared as shown in Fig. 15. A Li-aluminum (NCA) stand out for its high capacity, but this advantage is specific to energy storage. In terms of specific power and thermal stability, Li-manganese (LMO) and Li-phosphate (LFP) outperform other systems.

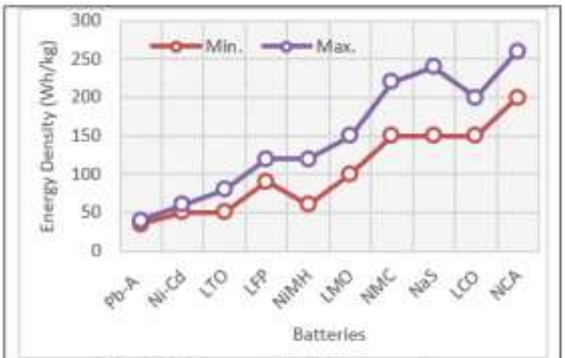

Fig. 15: Energy density comparison

4. Innovation in electric vehicle

Following source https://www.livemint.com/news/india/ev-industry-in-india, India, a rapidly growing economy, aspires to be a manufacturing hub for electric vehicles under the 'Make in India' initiative as shown in Fig. 16. Also, despite the early stage of the Indian EV industry, there's potential for substantial growth, with reported market projections far exceeding recent sales figures. Following the source https://www.statista.com, the highest growth is attained by 2-wheeler sale in 2019 and declined by 18% in 2020 due to economic slowdown and nationwide lockdown as shown in Fig. 17

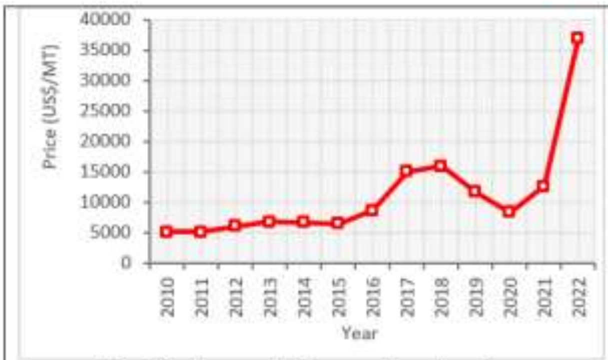

Fig. 13: Average lithium carbonate price

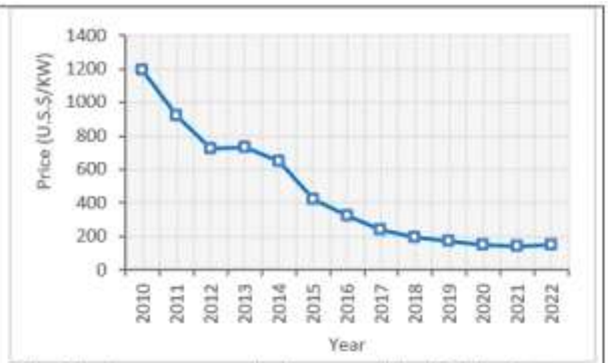

Fig. 14: Average cost of volume weighted Li-ion battery

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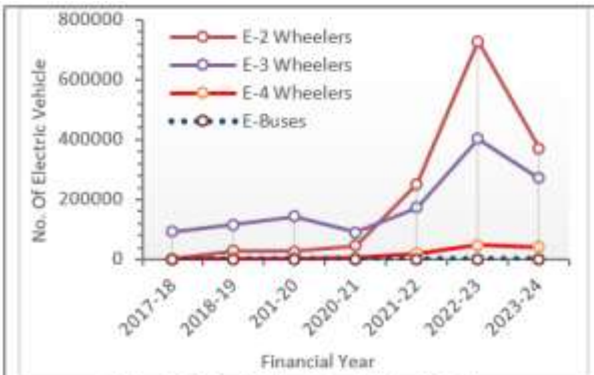

Fig. 16: No. of electric vehicle in India

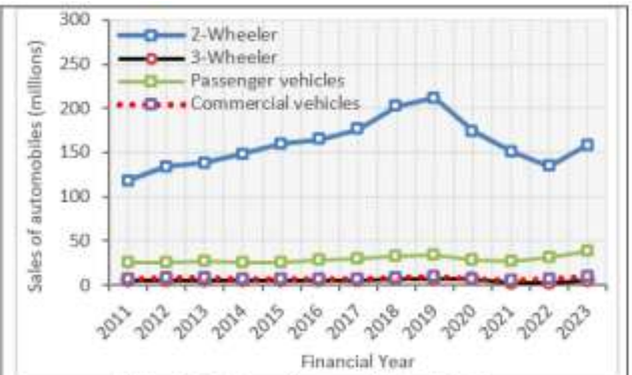

Fig. 17: Sales of automobiles in India

According to the source https://www.statista.com, China has the highest estimated global demand of Li-ion battery

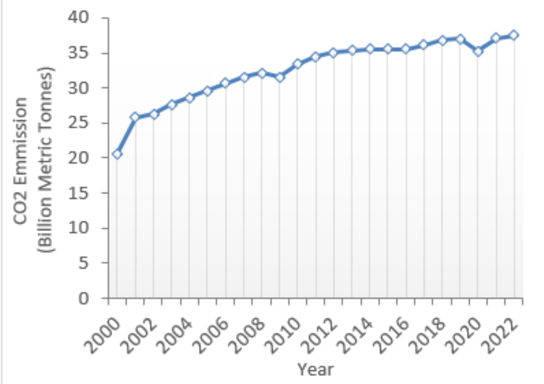

Fig. 19: Annual CO_2 emission worldwide

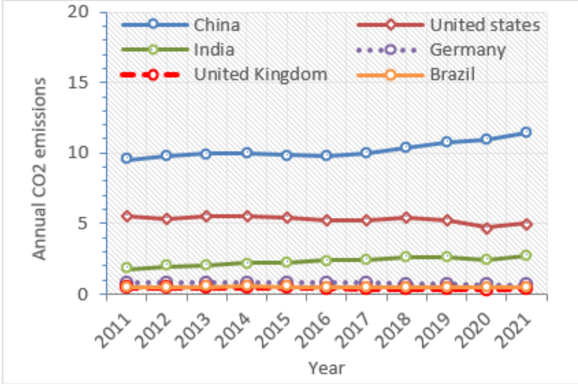

Fig. 20: CO_2 emissions from fossil fuels and industry

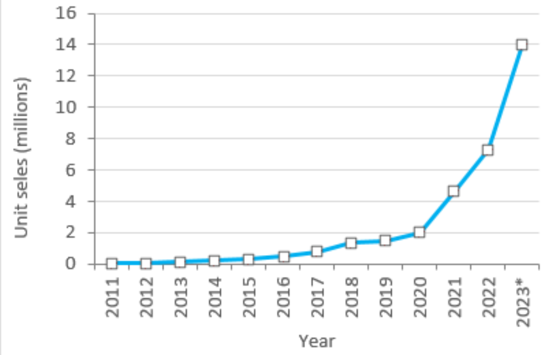

Fig. 21: Global Battery-EVs sales

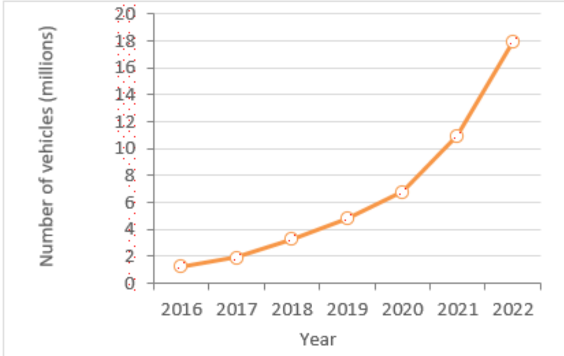

Fig. 22: Global count of used battery-EVs

exhibited in Fig. 18. China's extensive manufacturing capacity and ability to offer lithium products at competitive prices have propelled the nation to a dominant position in global lithium production. China's status as the largest consumer of lithium is attributed to its rapidly growing electronics and EV industries. Following source https://www.statista.com/global -co2-emissions/, Fig. 19 shows that there is increase in the CO_2 emission from 2000-2008 and then decreased in the emission has been noticed due to the rise of renewable in the power sectors in the next two year.

After 2010 the carbon emission increased due to the increased in the demand of automobiles. According to the source www.ourworldindata.org/co2-emissions/, Fig. 20 shows that most CO_2 emission generated by fossil fuels and industry has been made by China as compared to other countries and then followed by United states which pollutes the environment. Following source https://www.statista.com/global-battery-electric-vehicle-sale/, Fig. 21 represents battery-electric vehicle sales are projected to reach 14 million in 2023, up from about 7.3 million in 2022. BEV sales have increased due to several factors, including increasing consumer interest in more sustainable transport and government regulation to curb direct transportation emissions. According to the source https://www.statista.com/, Fig. 22 shows that the use of electric vehicles around the world has been increasing continuously since 2016.

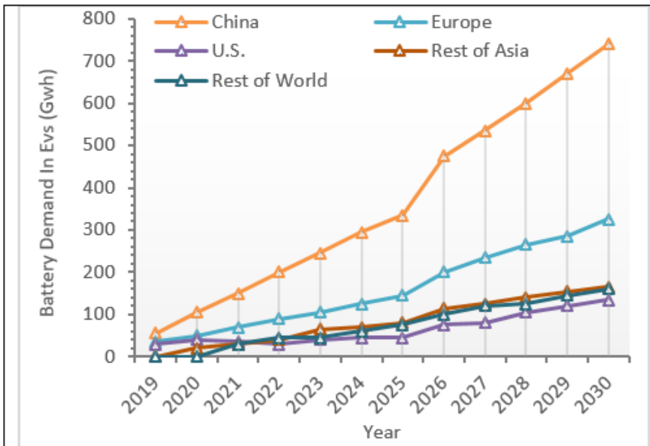

Fig. 18: Estimate global Li-ion battery demand in EVs

Conclusion

The high demand for electricity in India, the growing capacity for renewable energy, and the fast-growing market for lithium-ion batteries all show how important lithium is when it comes to sustainable development. Solar energy potential, increasing PV deployment and the world's growing use of renewable energy are driving the need for lithium-based technologies for clean energy storage, grid reliability and future energy planning. India produced

1,844 TWh power in 2022-2023, 1,618 TWh from utilities, becoming world's third biggest power producer. India's solar potential and long-term solar deployment are supporting the rise of renewables, but thermal power is still the primary source of electricity in the country. Worldwide, renewable electricity continued to be produced and consumed more, reflecting the move to low-carbon energy systems. The Indian lithium ion battery market is growing rapidly with increasing economic importance of lithium in energy storage, electric transportation and sustainable infrastructure. Furthermore, the simulated PV datasets for the period 2016–2026 show that the output is more affected by the irradiance than by the temperature. Therefore, these data can be employed for sensitivity analysis and model validation. In conclusion, PV-based generation and lithium-backed storage are key technologies for India's sustainable energy transition.

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