# Recent Development of Integrated renewable energy system in India and around the world.

**ABSTRACT:**

Integrated renewable energy systems have evolved by combining some renewable energy sources, especially solar and wind, hydro and biomass together with a variety of storage and control technologies. Worldwide reviews indicate that advanced control strategies and a wide range of storage media (chemical, electrochemical, mechanical, and thermal) are currently implemented in hybrid systems.

Papers on several applications for rural electrification, grid integration are featured in India. Additional studies focus on state level analyses of wind-solar hybrid systems and the policy changes and local constraints such as land use and transmission infrastructure.

India has become one of the busiest testbeds for "dispatchable renewables" with multi-GW tenders mandating firm around-the-clock supply from storage hybrids, scaling incentives for batteries and green-hydrogen. Meanwhile, China continues to combine massive desert wind-solar farms with UHV transmission and local storage; the EU is reengineering markets for flexibility and two-way CfDs; the US is reforming interconnection standards as hybrid plants take over queues; and Australia is expanding VPPs, big batteries, and transmission to unlock high VRE shares.

**Keywords:** integrated renewable energy systems, India, smart grids, hybrid energy, energy storage, microgrids, sustainable energy

1. **Introduction**

The world's energy system is undergoing a fundamental reconfiguration, as it takes the needs to meet increasing electricity demand while simultaneously mitigating climate change. The International Energy Agency (IEA, 2023) has predicted a more than 60% growth in world electricity demand till 2050, which requires a comprehensive and urgent deployment of low-carbon electrification solutions. While renewables such as solar and wind are at the heart of this transition, these sources are subject to the inherent variability, which represents a key challenge to grid stability and security. This has encouraged the paradigm shift from the single-project of renewables to the more complex multi-faceted systems called Integrated Renewable Energy Systems (IRES).

An IRES is more than just generation and co-optimises a suite of technologies. It intelligently combines several renewable sources-often co-located/aggregated across a portfolio-with energy storage, grid flexibility assets (e.g. demand response and virtual power plants), and enhanced transmission infrastructure. The general objective is to deliver firm, dispatchable, time-profiled power products (e.g. round-the-clock supply, blocks of peak power) rather than intermittent megawatt-hours. Model projects for this scenario include hybrid plants (solar-wind-battery storage), virtual power plants for portfolios, the combination of renewables with long-term storage or green hydrogen as seasonal storage, and projects in conjunction with high-voltage transmission axes for the smoothing out of spatial fluctuations.

This transformation is driven by fast cost reductions in variable renewable energy (VRE), ambitious global decarbonisation goals, and enabling policy and market instruments such as tailored tenders, Contracts for Difference (CfD) and storage subsidy. As a result, characteristics such as firmness, flexibility, and deliverability are becoming more important to the market.



Figure 1 Schematic of a typical Integrated Renewable Energy System (IRES)

India, with its rich and varied renewable resources (high solar insolation in states like Rajasthan and Gujarat, and high wind potential along our coasts) is a geography strategic for deployment of IRES. Furthermore, in its remote and rural communities IRES provides an enticing solution to the energy access challenges by way of decentralized hybrid microgrids. The world's leading countries in pioneering IRES are Germany, Denmark, and the United States, which have learned and achieved high renewable penetration and grid stability through the pioneering implementation of IRES, and have set good examples for others.

The objective of this paper is to give a thorough review of recent developments in IRES with particular emphasis on India within the global context. It explores the technological developments, changing policy and regulatory frameworks, implementation arrangements, and continuing issues that characterize the present status of IRES. The report combines findings from peer-reviewed research, government reports, and industry publications to provide a comprehensive, updated view of the road map forward to a more resilient, integrated, and sustainable energy future.

**2.Technological Advancements in Integrated Renewable Energy Systems**

The performance and viability of Integrated Renewable Energy Systems (IRES) is intrinsically dependent on a whole new world of fast-changing technologies. These technologies interact to smooth the intermittency of renewable sources, optimize dispatch and improve grid stability, making variable generation firm and dispatchable. This part focuses on the technological pillars that allow for this change to happen: hybrid energy systems, smart grid technologies, energy storage systems, and microgrids.

**2.1 Hybrid Energy Systems**

A central part of IRES are hybrid energy systems - two or more renewable generation sources, such as wind and solar, with storage, which can be used to create a more reliable and efficient system. These systems reduce the intermittency and the energy curtailment by optimally exploiting the complementary generation profiles of generation resources such as solar and wind generation, to produce a more stable power output (Chowdhury et al., 2022).

The use of hybrid systems has become successful all around the world. India: Gujarat has created large-scale hybrid solar-wind parks of over 1,500 MW with battery storage which is optimized using predictive modeling for reliable supply (Times of India, 2024). n Germany, on the other hand, offshore wind is used together with biomass and hydroelectricity to compensate for the seasonal fluctuations (Schmidt et al., 2023).

These complex systems are designed and operated by exploiting the most modern optimization techniques like mixed-integer linear programming and genetic algorithm for optimal sizing of the components and scheduling the operations taking into account resource availability, load demand, and economic constraints (Basha et al., 2022). The integration of hybrid vehicles into the EV charging infrastructure has brought forward a trend of vehicle-to-grid (V2G) applications to make the EV batteries available as a distributed network of mobile energy storage resources with unprecedented demand elasticity (Li et al., 2023).

**2.2 Smart Grid Technologies**

The digital backbone of smart grids is responsible for physical integration of hybrid systems.which is critical for decentralized generation systems. These grids incorporate real-time monitoring, automated control and communication technologies in order to facilitate integration of variable renewables (IEA, 2023). Key elements are Advanced Metering Infrastructure (AMI) to provide real-time information, Demand Response (DR) to optimize the consumption in peak periods and automatic control systems for optimized dispatch.

Examples of the value of such technologies have been demonstrated in pilot projects in Indian states including Maharashtra, Karnataka and Tamil Nadu, where improved monitoring and control have been estimated to have reduced technical and commercial losses by as much as 15% (MNRE, 2024). Denmark, for instance, has a world-leading degree of integration of wind energy and much of this is enabled by a very sophisticated smart grid. These grids are becoming increasingly operationalized with artificial intelligence (AI) and machine learning (ML) algorithms that predict generation and consumption behavior in such a way that storage and dispatch decisions can be made fully automatically and also in advance (Li et al., 2023).

**2.3 Energy Storage Solutions**

IRES are the key enabler for decoupling production from consumption, and the most important feature of the transition is storage, which allows the IRES to provide power on demand. A variety of storage technologies are being activated, from short-duration lithium-ion batteries to long-duration systems such as pumped hydro storage, flow batteries and new green hydrogen systems (IRENA, 2024).

In India, Battery Energy Storage Systems (BESS) are being installed along with solar farms in states like Rajasthan and Karnataka to discharge solar energy in the evening peak hours, whereas pumped hydro still stands as an important large-scale balancing resource.The huge value of grid scale batteries has been realised internationally, where plants like the Hornsdale Power Reserve in Australia become critical in the provision of inertia and frequency regulation services to the national grid (Tesla, 2023).Solid-state batteries and green hydrogen are the next generation of storage technologies with the potential of higher energy densities and seasonal shifting capabilities. When they are coupled with predictive analytics, these storage solutions require less fossil-fueled backup power, thus, the energy system is much greener (Kumar et al., 2023).

**2.4 Microgrids and Distributed Generation**

Microgrids are the local scaling of the IRES principles. These stand-alone networks are possible in both grid-connected and islanded modes, while incorporating distributed renewable generation, storage, and intelligent controls to offer highly reliable power to localized communities or campuses (Chowdhury et al., 2022).

In India, they are playing a crucial role in tackling energy access issues in remote areas such as Ladakh and the Andaman & Nicobar Islands, where they are blending solar, wind and small hydro to cut reliance on diesel and empower local communities. Beyond rural electrification, microgrids are being implemented worldwide in university campuses and industrial parks, forming resilient and low-carbon energy hubs seamlessly integrating renewable generation and storage capabilities as well as EV charging infrastructure (Li et al. 2023).

The convergence of these technologies - hybrid generation, storage, smart grids, and microgrids at scale - is the technological enabler of the modern IRES that allows us to have a reliable and decarbonized energy future.

**3. Policy and Regulatory Developments**

The transformation from the conceptual models of Integrated Renewable Energy Systems (IRES) to their realisation is critically dependent on a supportive and enabling policy and regulatory environment. Beyond government incentives that only encourage the generation addition of individual assets, governments and international organizations are increasingly developing frameworks that combine incentives for the integration of renewable sources, storage, and smart grid technologies.

 **3.1 National Policies**

National governments are the main stimulators of IRES development through direct specific policies, financial incentives and strategic actions. These measures are aimed at de-risking investment, establishing market certainty and overcoming technical and regulatory barriers to integration.

In India, the Ministry of New and Renewable Energy (MNRE) has played a catalytic role in developing an ecosystem for IRES. Key initiatives include:

The National Solar Mission, which puts the foundations of large-scale renewable adoption.

* Roof-top solar based programs such as PM Surya Ghar: Muft Bijli Yojana which encourages rooftop solar and distributed generation.
* Design of hybrid renewable energy parks dedicated to colocation of solar, wind and storage projects making it easier to acquire sites and transmission infrastructure (MNRE, 2024).
* The programs offer a combination of capital subsidies, technical assistance, and research assistance that encourage utility-scale and decentralized projects alike.

Worldwide, policy mechanisms have developed to appreciate the dispatchable power that IRES supply. Germany's Renewable Energy Sources Act (EEG) has been an important instrument in setting priorities for renewable grid access and market-based incentives. The Energy Agreement for Denmark is a cross-party political agreement which gives a long-term political framework that gives policy stability for investors. In the United States, stand-alone storage and hybrid systems have been added to the Investment Tax Credit (ITC), making them much more cost-effective (Schmidt et al., 2023; DOE, 2023). These frameworks together lower investment risk and provide the long-term visibility needed to drive deployment of large-scale IRES:

3.2 International Agreements

At the global level, international climate treaties have provided an impetus for nations to hasten their energy transition and IRES is one of the principal tools to achieve binding targets. Under the UNFCCC (United Nations Framework Convention on Climate Change), the Paris Agreement has promised that signatory countries will provide Nationally Determined Contributions (NDCs) with many explicitly containing targets for RE capacity and grid modernization (UNFCCC, 2023).

This global ambition is strengthened with formal international cooperation. Research organisations like the International Renewable Energy Agency (IRENA) enable knowledge exchange, policy benchmarking and analysis on the integration of high shares of renewables. The Clean Energy Ministerial (CEM) and the International Energy Agency (IEA) were key mechanisms for technology transfer, finance mobilization, and multi-disciplinary coordination of R&D. These partnerships enable the codification of best practice, the reduction of technology costs by sharing innovation, and further the development of a global marketplace for integrated renewable energy technologies so that lessons learned in one location can be applied and implemented in another.

A synergy between strong national policies and integrated international action, therefore, is generating a fertile environment for the emergence and quick growth of IRES technologies and their worldwide diffusion.

**4. Case Studies**

 For instance, one paper presented hybrid energy storage systems which contained batteries, supercapacitors, flywheels, compressed air, pumped hydro, and fuel cells. These systems reported a record low power loss of 36% with an increase in cycle life of 70% and a decrease in capacity loss of 60%. Other reviews present demand-side management schemes and multi-agent control strategies developed to enhance the cost effectiveness and reliability of the system.

Large-scale systems of renewable energy are being tested and refined in real-world settings around the world, in order to test and refine their theoretical and policy frameworks for Integrated Renewable Energy Systems (IRES). This section delves into the practical implementations across India and the world, scrutinizing the varying strategies, contractual frameworks, and technological integrations that are shaping the future of renewable energy.

**4.1 Integrated Renewable Energy Systems in India**

In India, the evolution of the IRES landscape is moving swiftly from isolated renewable projects to coordinated and sophisticated systems that are optimized around firm dispatchable power (driven by new policy and falling cost of technology).

**4.1.1 Pioneering Projects and Configurations**

 Gujarat Hybrid Energy Parks: The flagship example, these parks pair over 1,500 MW of co-located solar and wind with battery storage. Large-scale hybridization has been shown to be technically feasible by employing predictive modeling for curtailment reduction and reliability improvement optimization of generation and dispatch (Times of India, 2024).

Rooftop Solar and Net Metering: Decentralized generation via rooftop solar installations is increasing in many urban areas like Mumbai, Bangalore, and Pune. Under the net metering scheme, prosumers can help stabilize the grid and the democratization of energy production by feeding excess electricity into the grid (MNRE, 2024).



Figure 2 Geographical distribution of India's key renewable energy projects and supporting infrastructure

Remote Microgrids: Solar-, wind- and small-scale hydro-based microgrids are able to provide clean reliable energy in remote areas like Ladakh and Andaman & Nicobar Islands, displace expensive and polluting diesel generators and improve energy access (Chowdhury et al., 2022).

**4.1.2 Innovative Contracting Models and Market Evolution**

 Another important development in the IRES journey in India is that the tender design has changed from energy-only auctions to auctions procuring firm capacity.

Firm & Dispatchable Renewable Energy (FDRE): The recent finding of tariffs of the order of Rs.4.98-4.99/kWh in the 630MW FDRE tender is a landmark achievement that establishes that demand following renewable power, backed by storage, can be sourced at competitive prices (ETEnergyWorld.com[1], 2024).

Round-the-Clock (RTC) Power: Similarly, the RTC auctioning capacity at ~Rs5.06/KWh shows the market's preference for 24/7 assured renewable supply, which in turn is encouraging innovation from developers in technology blending and scheduling (pv magazine India [5], 2025). The evolution has led to a healthy discussion on cost optimization and risk allocation between pure RTC/FDRE and others (solar-plus-storage, for example) [The Times of India][8].

**4.1.3 Enabling Infrastructure: Storage, Hydrogen, and Transmission**

Scaling enabling technologies is a key foundation for enabling these new contracting models. Storage Scale-Up: India is aggressively stimulating battery energy storage systems (BESS) by way of a central viability gap funding (VGF) scheme aimed at 30 GWh of capacity. This is supplemented by tariff-based bidding and large-scale state-level commitments (e.g. Rajasthan's 4,000 MWh plan), indicating a maturing market for standalone storage (Energy Storage, 2025).

Green Hydrogen Integration: The National Green Hydrogen Mission (NGHM) is developing a strong ecosystem for sector coupling. Hydrogen can serve as a new integration lever for IRES (by combining multi-GW RE with pumped storage), and large-scale offtake deals for green ammonia (e.g., multi-GW RE with electrolyser manufacturing) are already in the process of being developed, demonstrating that hydrogen also works as a long-duration storage solution.

Transmission Expansion: The evolution of the Inter-State Transmission System (ISTS) and green energy corridors is at the heart of evacuating power from high potential renewable areas to enable co-located and virtual hybrids across various regions.

**Key Takeaway for India:** The market is firmly moving away from the "cheapest solar", to one that values firm power and power that can be scheduled. This is being catalysed by a synergetic policy drive towards contracted firmness (RTC/FDRE), subsidised storage, green hydrogen and grid expansion, enabling integrated portfolios to deliver the reliability of traditional resources at ever more competitive prices.

**4.1.4 Transmission for high-VRE and integrated portfolios**

Transmission infrastructure development is the pivotal strategic enabler that links the rich but often remote renewable resource centers in India with the major load centers and provides the backbone to a truly integrated national energy system. As Figure shows, which maps India's top renewable energy projects, the country's renewable wealth is geographically concentrated: huge solar parks in sunny states Rajasthan (Bhadla, Rewa) and Karnataka, wind farms in the windy corridors of Tamil Nadu (Vankusawade) and Jaisalmer, and world-class geothermal potential in Ladakh (Puga). This spatial mismatch between generation and demand creates a need for a strong inter-state transmission system to avoid curtailment and to fully exploit such resource. India is making a concerted effort to do so via the Green Energy Corridors (GEC) project, and the more general connectivity of ISTS (Inter-State Transmission System) for evacuation of power from these high-potential areas, to aid the government's ambitious goal of 500 GW of non-fossil capacity by 2030. This infrastructure is needed not only for co-located hybrid plants, but also to create "virtual hybrids" by aggregating renewable assets across the region and dispatch them as a single firm product to smooth the variability of local assets and improve overall grid reliability.



Figure 3 Geographical Distribution of India's Flagship Renewable Energy Projects.

 **4.2 Global Case Studies**

Germany - Energiewende: Germany's transition policy combines solar, wind, and biomass with energy storage and smart grids, and generates more than 50 percent renewable electricity. With the help of economic modelling and grid management, curtailment has been minimised and system reliability increased (Schmidt et al. 2023).

Denmark - Wind Energy Integration: Denmark gets 45% of its electricity from wind (and biomass and district heating). Smart grid technologies enable the real-time management of the supply-demand imbalances and the grid stability with the presence of volatile wind power (Petersen et al., 2022).

United States - California Hybrid Systems: California uses large-scale hybrid renewable systems with solar PV, wind and storage Demand response and AI-enabled grid management to optimise energy dispatch, less fossil fuel backup and thus lower emissions (DOE 2023).

Australia - Hornsdale Power Reserve: The 150 MW lithium ion battery system has proven the value of storage integration for grid support, frequency regulation and ancillary services, and has set the benchmark for large-scale IRES (Tesla, 2023).



Figure 4 Comparative analysis of the strategic focus areas in IRES deployment across leading countries.

**4.2.1 China: mega-bases + UHV = spatial integration at scale**

Desert base camps (Phase-2) and vacuum lines China is developing multi-GW wind-solar "clean-energy bases" in Gobi/desert areas in conjunction with +-800 kV UHV DC transmission (e.g., Longdong-Shandong to be commissioned in 2025 with some 10.5 GW "new energy" connected). This model incorporates remote VRE with load centers and onsite storage to decrease curtailment. ([China Daily][21])

Acceleration and limitation of grid However, rapid development has once again brought the limitation of the grid to the forefront, which led to fresh investment (State Grid 2024 plans) and policy emphasis on utilization. (Reuters, 22; China Daily, 23; Financial Times, 24)

**4.2.2 European Union: market design reform to value flexibility**

Electricity Market Design (EMD) reform 2024 The EU introduced reforms that opened up the possibility of two-way CfDs and supporting flexibility (storage/DR), which also improve the bankability of hybrid/co-located assets and system services. (See Department of Energy's Energy.gov page 25)

**4.2.3 United States: hybrids dominate interconnection queues; process reform**

FERC Order No. 2023 (2023-2024 compliance) has a transformation in interconnection - cluster studies, ready-to-build requirements - of critical importance as solar+storage hybrids become a large proportion of queues. ([Renewable Watch][17]) (Complementary evidence: share of hybrids in queues is rising (shown in annual Berkeley Lab queue briefings): see Hybrids series 2023-2024.

**4.2.4 Australia: batteries, VPPs, and long lines to integrate RE zones**

Transmission and REZ planning is ongoing (e.g. 2025 Victorian Transmission Plan; HumeLink to link Snowy 2.0 and renewables). ([Energy][26], [The Australian][27])

Hydrogen strategy update (2024) + production tax incentive (from 2027) to enable sector-coupling and firming via power-to-X (DCCEEW [28], Australian Taxation Office [29], Hunter New Energy [30], CSIRO Research [31]).

**5. Challenges in Implementing Integrated Renewable Energy Systems**

Despite this strong technological progress and robust policy drive, the large-scale deployment of Integrated Renewable Energy Systems (IRES) is complicated by a multi-dimensional array of challenges. This will require the progressive and coherent addressing of the identified barriers, including infrastructure, finance, regulation and technology, to enable the full potential of IRES to be realised for a secure, affordable and clean energy transition.

**5.1 Infrastructure Limitations**

* Most countries' electricity grids are a legacy design based on a one-way power flow that is only suitable for large, dispatchable fossil-fueled power plants. Introduction of high penetrations of variable and distributed renewables demands a major evolution of this grid structure.
* Aging and Insufficient Transmission Networks: Most existing grids are not designed to evacuate power from large renewable hubs in remote areas to load centers in far-flung cities, resulting in congestion and curtailment. This is acute especially in countries which are seeing a rapid increase in renewable capacity such as India.
* Need for Bidirectional Power Flow: Distribution grids need to be modernized to handle two-way electricity flow from millions of distributed energy resources (DERs) such as rooftop solar that can lead to voltage sags, protection coordination problems, and reverse power flows.
* Need for Advanced Grid Technologies: High VRE integration requires pervasive deployment of enabling technologies such as smart inverters (for grid-support functionality), phasor measurement units (PMUs) (for real-time visibility of the grid), dynamic line rating systems and advanced transformers for flexibility, reliability and hosting capacity. These capital-intensive upgrades have a long lead time and strategic planning (Li et al. 2023).

**5.2 Financial Constraints**

* The transition to IRES is capital intensive, in that it transfers costs from fuel (OPEX) for conventional plants to technology upfront (CAPEX) for renewables, storage and grid modernisation.
* High Upfront Capital Costs: Despite the significant reduction in Levelized Cost of Energy (LCOE) for solar and wind, the integrated system cost (generation, storage (BESS, pumped hydro), power electronics, grid connection) is still very high. The economics of long-duration energy storage (LDES) and green hydrogen are still in flux.
* Investment Risk and Cost of Capital: In most developing economies, perceived policy and regulatory risks, currency instabilities, and immature financial markets contribute to higher cost of capital, which has a crushing impact on the economics of large-scale IRES projects.
* Need for Innovative Financing Models: Overcoming these hurdles involves moving beyond traditional project finance. Blended finance (public, private and philanthropic capital), green bonds, yieldcos and de-risking instruments from multilateral development banks are key in mobilising private investment and bankability (Chowdhury et al., 2022).

**5.3 Policy and Regulatory Barriers**

* Technology changes faster than policy and regulatory frameworks can change, which results in a major implementation gap.
* Fragmented and Inconsistent Policies: Inconsistent and fragmented policies between different government departments (e.g. energy, environment, finance) and at the state and national levels create uncertainty for investors. The timing of tenders, the policies for net metering and the obligation to buy renewable energy (RPOs) distort the market.
* Outdated Market Design: The prevailing electricity markets are mostly designed to reward generation (Rs./kWh) and not capacity (Rs./kW) or ancillary reliability services (inertia, frequency regulation, black-start capability). The value proposition of IRES is not properly rewarded for the services it provides;
* Regulatory Lag and Grid Code Limitations: The lack of standardised grid codes that require advanced capabilities (such as voltage and frequency ride-through) from new renewable projects and storage can compromise grid stability. Additional long and complex land acquisition, environmental clearance and grid interconnection processes further delay projects (IRENA, 2024).

**5.4 Technical and Operational Challenges**

* A grid with inverter-based resources (IBRs) is a fundamentally different working paradigm than a synchronous generator-dominated grid, with different technical challenges.
* System Stability and Reliability: IBRs offer limited inertia, which is an important characteristic of traditional generators that stabilizes the grid frequency in case of disturbances. This creates the possibility for cascading failures. Without the natural reactive power support of large spinning turbines, managing the voltage stability is also a crucial challenge.
* Forecast and Scheduling Errors: Solar and wind generation is variable and somewhat unpredictable, and this makes it hard to balance the grid. Even though forecasting is better now, some errors still occur, meaning that expensive (and carbon intensive) balancing reserves are still required.
* Cyber-Security and Data Management: The growing digitization and interconnectedness of IRES (through smart meters, IoT devices, and automation controls) opens up an increasing cyber-attack surface. Both the large amounts of data produced for real-time optimization and the cyber-security risks to critical energy infrastructure are top operational concerns that are complex and difficult to address (Basha et al., 2022).
* Interoperability and System Integration: Interoperability and control of equipment from different manufacturers (solar inverters, BESS controllers, grid management systems) is a non-trivial problem that involves standardization on an industry-wide level.

## **5.5 METHODOLOGY**

To achieve the objectives of the proposed study, a systematic and research-oriented methodology will be followed. The step-by-step approach for conducting the research is outlined below:

Step 1: Identification of the research location/region: Un-electrified villages will be selected based on clustering, the number of households per village, and the distance between villages. Relevant data will be gathered from state nodal agencies and other reliable sources to ensure a representative sample.

Step 2: Demand analysis: The electrical power demand of the research area will be calculated by analyzing the power consumption patterns of different sectors such as households, commercial establishments, street lighting, small businesses, agriculture, and others. This analysis will provide insights into the energy requirements of the region.

Step 3: Evaluation of available resources: The potential of various renewable energy resources in the specified region, including solar, wind, small hydro, biomass, and biogas, will be assessed. This evaluation will provide a comprehensive understanding of the available resources and their suitability for integration into the hybrid energy system.

Step 4: Configuration of the integration: Based on the power consumption analysis and resource assessment, an appropriate configuration for integrating the renewable energy sources will be chosen. Multiple options will be evaluated, considering the power demand and the availability of resources to determine the most suitable configuration.

Step 5: Mathematical modelling of system components: Mathematical models of various components of the Integrated Hybrid Renewable Energy System (IHRES) will be developed. These models will consider the performance characteristics of the components under different operating conditions, enabling a better understanding of their behavior within the system.

Step 6: Development of a system-wide operating plan: An optimized operating plan will be formulated, taking into account factors such as power demand, power generation from renewable sources, resource allocation, operating limitations of the energy generating system, battery bank storage limits, and the desired level of power dependability. This plan will ensure efficient and reliable operation of the IHRES.

Step 7: Problem formulation: A well-defined problem will be formulated, establishing an objective function and incorporating relevant constraints. This step will provide a clear framework for the subsequent optimization process.

Step 8: IHRES size optimization: Various optimization techniques will be applied to determine the optimal size of system components. Different approaches will be explored, considering the defined objective function, to achieve an optimized configuration of the IHRES.

**5.6 Research Gaps**

Extensive research has been conducted on various aspects of IRES, including hybrid sources design, unit sizing, cost optimization, operation, control, and modelling. However, there are several research gaps that need to be addressed to further enhance the effectiveness and efficiency of IRES.

* Scope to integrate SPV system along with other renewable resources such as wind and biomass.
* Scope for optimization of IRES based on the net present cost (NPC), cost of energy (COE), and power reliability by considering peak power reduction.
* Scope for Transient analysis of the system by step changes in the variable parameters like solar radiation, wind speed, and load demand.

A major research effort should be on the optimal allocation of resources in IRES systems. Very few studies have properly addressed the issue of systematically allocating resources in IRES with the upfront intent to optimize overall system performance. Development of new optimization models and algorithms for a more effective resource allocation will enhance efficient and cost-effective IRES development in the future. Through transient analysis, a first step to overcome stability concerns associated with IRES systems in the literature is to conduct simulations and studies that analyse how an IRES system responds to step changes in variable factors, such as solar radiation, wind speed, or load demand. Overall, there are a variety of research gaps and further research opportunities within the field of IRES. If researchers address these research gaps, it can lead to novel IRES systems that would be robust and efficient, and could be important contributors towards a sustainable energy future.



By following this clear and research-oriented methodology, the study aims to systematically address the research objectives and contribute to the knowledge and understanding of the design and optimization of Integrated Hybrid Renewable Energy Systems.

**6. Future Outlook & Recomendation**

As the converging trends of climate urgency, energy security needs and unstoppable technological innovation combine, the global movement towards Integrated Renewable Energy Systems (IRES) is only going to accelerate. The future energy system will be one of highly connected, intelligent and flexible networks which measure reliability and value rather than volume of generation. This section highlights the expected global evolution and provides specific recommendations for important stakeholders.

**6.1 Emerging trends in IRES include:**

The development of IRES will be influenced by strategic national priorities and by the maturity of core technologies:



Figure 5 Projected timeline for the maturation and deployment of key technologies enabling the future growth of IRES.

India is likely to nearly triple its successful procurement of firm, dispatchable power through FDRE/RTC tenders, while also expanding its battery storage capacity through the VGF scheme. Early commercial scale green ammonia offtake agreements will be the anchors of multi-gigawatt sector coupled IRES portfolios, combining renewables, storage, and hydrogen production (e.g. SolarQuarter [10], The Times of India [20]).

China will keep on developing mega-scale systems combining enormous desert-based wind-solar-storage complexes with its UHV transmission network. As the share of VRE is expected to increase over the years, an increasing emphasis will be on incorporating software-defined optimization and local storage to keep curtailment rates in check, according to a Reuters report (22).

European Union: The Electricity Market Design (EMD) reforms introducing two-way CfDs and new flexibility markets will catalyse investment Doing so will expedite the deployment of co-located storage and demand response in close alignment with the EU's broader renewable hydrogen and industrial decarbonization policies.

United States: FERPA compliance with FERC Order No. 2023 will help simplify the interconnection process for a queue that is dominated by hybrid projects. Together with the ongoing IRA tax credits, this will generate a new wave of complex, portfolio-based renewable products that provide 24/7 clean energy matching and shape power blocks (see Renewable Watch[17]).

Australia is going to use a combination of Renewable Energy Zone (REZ) transmission links, gigawatt-scale batteries, and its hydrogen production incentive to support some of the world's highest instantaneous VRE penetration rates with a distributed network of virtual power plants (VPPs) and firming assets (The Australian 27, DCCEEW 28).

Cross-Cutting Emerging Trends: Emerging trends include the commercialization of next-gen storage (solid-state batteries, flow batteries), the proliferation of AI-optimized hybrid microgrids, the deep integration of EVs as a grid resource (V2G) and greater international cooperation on R&D and standards, all of which will be important for overcoming existing deployment barriers (Kumar et al., 2023).

**6.2 Recommendations (for policymakers, system operators, and developers)**

To maximize the benefits of IRES, and ensure a timely energy transition, coordinated efforts are needed from policy makers, system operators, and developers.

1. Procure for Value, Not Just Volume: Regulators and utilities should move procurement to shape-based (RTC) and firm (FDRE) contracts that define temporal delivery profiles. India's tender models have been a strong example. Contracts should include penalties and rewards based on system value of reliability to provide developer accountability;
2. De-Risk Technological Bottlenecks: Policymakers should make targeted, time-limited financial support (e.g., VGF for BESS, two-way CfDs for green H2) available to kick-start markets for technologies for which upfront costs are still a major bottleneck. Support mechanisms need to be structured so they ultimately phase out as technology costs drop and markets mature.
3. Prioritize Enabling Infrastructure: Transmission planning can no longer be reactive, but proactive. Advanced transmission [HVDC/UHV, REZ links] and grid modernization software [co-optimized dispatch] are key integration technologies, and should be treated by governments and system operators as critical investments in the same way as generation assets.
4. Modernize Market and Interconnection Rules: Rules for hybrid resources should be codified by regulatory bodies as a matter of urgency. This includes clarifying co-located generation and storage interconnection rights, defining deliverability requirements and determining reasonable capacity accreditation methods. The FERC Order No. 2023 is a practical guide that provides the renewable industry with important regulatory direction.
5. Foster Prudential Sector Coupling: Green hydrogen deployment should be carefully directed where it creates the highest system value: as a feedstock for hard to abate industries (fertilizer, refining, shipping, steel) and for long-duration storage. Policy should ensure that the production of hydrogen is linked to new cheap renewable energy and storage to prevent adding more congestion to the grid ([mnre.gov.in][34]).
6. Build Data and Forecasting Capabilities: Quality data is critical for the efficient operation of complex, multi-asset portfolios. System operators and developers need to invest in advanced meteorological forecasting, market data analytics and robust correlation-risk management models together in order to optimize scheduling and maximize the value of integrated portfolios.

6.3 Future scope of work

Research and development are continuous process.Following are the research ideas in which fyture scope of research work is to be done.

1. Future study should include other renewable energy options or storage devices.Besides resources dependability analysis incorporating some storage devices and dump load is required.
2. It is necessary to investigate effective DC microgrids for IRES by utilising DC equipments on both generation and demand sides
3. Feasibility analysis with Renewable Energy Sources,storage devices and implimentation of DSM strategy.
4. Hydrokinetic technology,pumped hydro storage,hybrid energy storage system,hydrogen energy storage system also can be incorporate with IRES.

 **7. Conclusion**

Integrated Renewable Energy Systems (IRES) play a central role in the shift to a global energy system, as they can successfully mitigate the critical issues of intermittency, reliability, and sustainability of separate renewable technologies. National schemes like India's hybrid parks development, rooftop solar and deployment of microgrids in remote areas can provide powerful examples for scaling up. These initiatives are mirrored around the world by leading examples from Germany, Denmark, the United States and Australia, which show that large-scale integration of a range of renewable technologies is possible and successful.

Despite significant obstacles in terms of infrastructure, finance, policy and operations, innovative solutions in hybrid configurations, energy storage, intelligent grids and AI-enabled management offer a strong way forward to overcome these challenges. The future of IRES relies on continued international cooperation, as well as on enabling policy frameworks which incentivise investment and deliver a risk-deleted deployment. Finally, ongoing research and development of new technologies such as green hydrogen, advanced microgrids, and vehicle-to-grid (V2G) systems will be a critical step to increase the scalability, reliability, and sustainability of IRES and strengthen their contribution towards global energy security and climate targets.**8.**

**Abbreviations:**

IRES (Integrated Renewable Energy System), VRE (Variable Renewable Energy), BESS (Battery Energy Storage System), LDES (Long-Duration Energy Storage), RTC (Round-the-Clock), FDRE (Firm & Dispatchable Renewable Energy), CfD (Contract for Difference), UHV/HVDC (Ultra-/High-Voltage DC), REZ (Renewable Energy Zone), PPA (Power Purchase Agreement), VPP (Virtual Power Plant), NGHM (National Green Hydrogen Mission), SIGHT (Strategic Interventions for Green Hydrogen Transition), CEA (Central Electricity Authority), ISTS (Inter-State Transmission System).

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Details of the AI usage are given below:

1.

2.

3.

**9. Reference:**

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