# Abstract

Primarily due to climate change and also due to resource depletion a global energy transition is imperative towards a low carbon economy. Increasing renewable share in the power mix is critical for this transition. However, renewable resources have several limitations as a substitute for existing fossil fuels. These renewable resources are generally dilute, intermittent and availability is location specific. Also, availability of these resources is not controllable according to the demand pattern. As a result, system installation for renewable power has to be optimized to assure uninterrupted power at minimum cost and environmental impact. The large-scale (of MW order) storage is not significantly used for such small scale off-grid energy systems. Hybridization of different locally available renewable resources may be an alternative solution to accommodate limitations due to capacity and intermittency of renewable resources.

India has widely varying topography with large variations of renewable resources at different locations both in type and available amount. Also, the socio-economic demography of India is widely varying with a large poor population. Providing reliable power at affordable cost to all Indians is a commitment of the government. Simultaneously, India is committed to net zero emission over a declared time schedule. To accommodate both the energy security of the poor Indians as well as switching over to a low-carbon economy, distributed hybrid renewable energy systems may be a suitable option. In this thesis, a systematic study of sustainability assessment of optimized solutions at different locations of India has been studied. The main objective is to explore sustainable solutions for reliable and clean power to poor populations of specifically remote locations of India. Studies have been carried out to assess an overall sustainability of such distributed renewable energy systems with several criteria like techno-economic, environmental and financial investment risk analysis. As these criteria do not converge to the same solution for a particular location, multi-criteria decision making is performed to decide the practically acceptable optimum solution for these locations. A general framework for Strengths-Weaknesses- Opportunities- Threats (SWOT) analysis of renewable power has been discussed before these studies to explore a sustainable policy guideline for future Indian renewable energy. Selection of the best possible location based on natural resources, social and economic factors using GIS data is also demonstrated. In addition to power several other energy services are also required for different locations of India. Studies are carried out to integrate other energy utilities with power using local renewable resources. India has a long coastline and severe ground water crisis. Desalination is the technology inevitably required for India. For a coastal location with shortage of consumable water,

integrating desalination with renewable power and sustainability assessment of it has also been done. Hydrogen is considered to be a very important energy carrier for the Indian economy. Generation and utilization of hydrogen in integrated energy systems is also explored. To match the gap between demand and supply in renewable energy systems, storage is required. Optimizing storage options including dispatch strategy is explored in one study. The overall study is conducted for seven different locations of India with some typical characteristics for each location. Brief objectives and obtained results for sustainability assessment of distributed hybrid renewable energy systems for rural India are as below:

- A comprehensive SWOT-more improved Hesitant Fuzzy multi-criteria decision-making analysis is required to identify these issues and their priorities for decentralized renewable HESs for Indian villages. The result shows the elimination of demand and supply gap by increasing energy efficiency and imposing taxes on the conventional energy sources are the highest and the lowest priority strategies for India.
- A methodology that integrates GIS with improved and efficient hesitant fuzzy linguistic multi-criteria decision-making to find suitable locations for developing decentralized hybrid energy systems at remote villages of Madhya Pradesh, India is developed. The integrated GIS-MCDM method ensures that Sailana, a remote village of Madhya Pradesh, India located at the western side of the state is the best location to develop the system.
- Techno-economically optimum decentralized hybrid energy system is explored for the remote rural villages of north-eastern hilly region of India, i.e., for the difficult Himalayan terrains of India. The techno-economic optimization shows that the Wind-hydro-DG-Li-ion is the economically optimal (cost of electricity-$0.63/kWh) and the least emitting combination (481 kg/year) to meet the load demand of the area.
- Combined environmental impact assessment by life cycle assessment of energy systems with techno-economic optimization is done to explore better sustainable energy solutions. Study reported that the PV-DG-Li-ion is the best optimal solution with a cost of electricity-$0.067/kWh, excess electricity-14.5% and environmental impact is 40.5–82% lesser for a remote village of the state of Rajasthan.
- Methodology to assess uncertainties in ROI for such systems is also studied. Study shows that the PV-DG-Battery system is the possible optimum solution for remote villages of Gujarat with a cost of electricity- $0.21/kWh, a standard deviation of 0.07 for risk on investment and a moderate environmental impact.

- To improve the techno-economic performance of the energy systems integrated with storage systems, different electrochemical energy storage systems and mechanical storage devices integrated with HESs are compared under different dispatch strategies. Different dispatch and storage module analysis shows that the Zinc-Bromide storage integrated with PV-hydro-DG system is techno-economically optimum (cost of electricity- $0.197/kWh and net present cost- $362384) under 'Load Follow' dispatch strategy for a remote village of Bihar state.
- Comparison between green hydrogen with other conventional storage systems in terms of techno-economic performance factors and risk in ROI is studied for a remote village of Sunderban, West Bengal. The PV-Wind-DG-Li-ion is optimal (cost of electricity- $0.159/kWh, net present cost- $424568, renewable fraction- 96.5% and standard deviation- 0.45%).
- Techno-economic feasibility of different desalination units powered by decentralized hybrid energy systems are also explored. The decentralized hybrid energy system integrated RO-desalination unit is most cost effective (cost of water- $4.57/L) and least emitting for a village of Tamilnadu.