

# ABSTRACT

The growing demand for energy, the need to reduce greenhouse gas emissions and the pursuit of achieving the sustainable development goal of ensuring affordable and clean energy to everyone have necessitated the development of energy management systems. These energy management system models seek to provide the best ways to ensure the comfort of the consumers, reduce energy cost, ensure peak load reduction and explore the avenues to integrate renewable energy sources in the present energy mix. Forecasting the future load demand and renewable energy availability is a very important part of any energy management system. The forecasting methods should be robust, computationally efficient and hardware friendly to ensure the best possible energy management operation. Thus, artificial intelligence-based techniques have gained importance in designing forecasting models. However, the real-world data acquisition is plagued with the problems of missing, redundant and insufficient data and requires pre-processing to ensure optimum operation of the forecasting models. Also, the relationships between the electrical load demand of any region and the numerous factors that affect it such as weather, economy and demography are highly non-linear showing various trends which vary in the range of days, weeks and seasons. The above factors somewhat limit the otherwise impressive abilities of artificial intelligence-based forecasting. One of the main challenges of energy management systems is to tackle the variation in the electrical load demand which is significantly large across different regions due to factors such as population density, industrial activity, climate, and access to energy resources. These regions using electricity as their main source of power can be classified as urban, semi urban and rural. The electricity demand of the urban regions is characterized by the highest electricity load due to dense populations, high-rise buildings, commercial centers, and industrial activities, spikes occurring in electricity demand during certain periods, especially during work hours (daytime for commercial and industrial users) and evenings (for residential users) and also during extreme weather conditions, such as summer cooling and winter heating. The contributing factors to the urban energy consumption are extensive use of heating, ventilation and air conditioning systems, high demand from commercial establishments like offices, shopping centers, and hospitals, public infrastructure, data centers and other tech-based industries. The semi-urban regions generally experience moderate electricity demand, with a mix of residential and small commercial loads. The demand pattern here follows both urban and rural characteristics with spikes occurring during early mornings and evenings, when people are home after work and schools. The main contributors to the energy consumption are large residential areas with electric heating, cooling, and household appliances, growing reliance on electric vehicles (EV) leading to increased demand for charging infrastructure, localized small-to-medium scale businesses, schools, and healthcare facilities and seasonal demand variations, especially for cooling in summer and heating in winter. The rural regions typically have lower electricity demand due to sparse population and fewer industries. However, demand can be higher in agricultural areas with irrigation systems or in regions with mining or other resource-based industries. Peaks are often tied to farming or industrial cycles, with demand increasing during certain times of the year, such as the harvesting season when irrigation and machinery use is high. Thus, it is evident that each demographic region has very distinct factors affecting their electricity consumption. The robustness of an energy management system can be measured by its ability to provide the best results irrespective of such demographic variations. A robust energy management system should be able to handle the demographic variations in

energy consumption separately as well as the combined energy demand of a mixed demographic region. It should be able to ensure the best possible outcome for each individual region and the combined regional power demand. With the increasing push towards clean energy, the integration of renewable energy sources in the primary energy mix of the society has become of paramount importance. Energy management systems face significant challenges in handling the complex nature of renewable energy integration in the already highly complex problem of efficient energy management. For urban regions, load balancing is critical due to constant high demand. Integrating renewable sources such as rooftop solar photovoltaic (PV), urban wind turbines, and energy storage helps manage peaks and reduce strain on the grid. For rural regions, there is more potential for decentralized renewable energy systems, including small-scale solar, wind, and bioenergy. Microgrids and local energy storage play a key role in balancing variable demand and improving energy access in these regions. The sub-urban regions can benefit from both centralized grid power and localized renewable sources like community solar projects and home energy storage systems, allowing for a flexible response to changing load demands. Understanding these variations is crucial for designing energy management systems that can efficiently distribute electricity, especially as the share of renewables in the energy mix grows. Energy cost also plays a vital role in determining the efficiency of the energy management systems. Proper tariff system can be leveraged to encourage the consumers in aligning their demand with the generation from the renewable sources. Any power demand profile can be differentiated into peak, valley and flat periods which are different for urban, semi urban and rural regions. So, a common tariff system will not be able to capture the demographic differences and will be inefficient in demand management. Thus, the present research work proposes a properly designed time of use tariff plan to capture the regional variation in demand allowing better demand generation alignment. The present research work proposes an efficient method of load and renewable energy forecasting, monitoring and management system for peak load reduction and renewable energy integration. An artificial neural network-based model has been proposed in this work for electrical load demand forecasting. It makes use of different input factors such as historical load demand data and weather parameters. The set of historical data used as input has been determined through correlation analysis selecting the values which show the highest correlation to the day for which the forecasting has to be done. The different parameters of the weather were investigated to find the parameter which exerts the highest influence in determining the efficiency of the forecasting method. It was found that while temperature shows significant impact, humidity does not play a crucial role in increasing the efficiency of the forecasting model. Further improvement in the efficiency of the forecasting model was achieved by incorporating wavelet transform in the artificial neural network model. The wavelet neural network so formed showed satisfactory performance in short and medium term forecasting with the mean absolute percentage error remaining within 4%. This work further investigates the design and optimization of an energy management system that caters to urban, semi urban and rural regions, addressing the distinct challenges and opportunities of each. It explores the integration of renewable energy, such as solar and wind into local and regional energy systems, with a focus on balancing supply-demand dynamics, reducing energy wastage, and enhancing grid resilience. A model is presented where several regions are combined together based on the demand profile of the regions segregated as urban, semi urban and rural along with the flexibility to schedule loads on the basis of availability of renewable energy sources within the area of the regions. The main focus is on a detailed forecasting based on neural network and

then developing a load management system to manage load during peak hours and off-peak period based on availability of distributed generation capacity and available tariff system. The major contribution of this work is providing a detailed model in which the loads are mapped to their probable supplies based on the region wise classification of Urban, Semi-Urban and Rural. The model is capable of identifying the type of region and consumer category to be addressed from the load demand profile of the region. The output of the model provides an hourly percentage of the total load demand which can be supplied by the available renewable energy. This data was incorporated in increasing the efficiency of the energy management system proposed by this work. A robust and sustainable demography driven energy management system was developed which is capable of optimizing the energy consumption of each region individually as well as in a combined energy community mode. The urban regions are considered to be both grid connected and having available photovoltaic power sources whereas the rural regions are considered to be mostly relying on distributed energy resources and a centralized storage system with uncertain grid connection. The grid connection available to rural region participants is considered to be unreliable and prone to power cuts. The output of the fuzzy logic based source load mapping was used to determine the potential contribution of renewable energy by the participants in the community. The battery system was used to supply power during the non-solar hours and in case of power cuts to the rural area. The participants are free to sell their excess renewable energy to the grid or to the community as required for maximization of social welfare and minimization of their energy costs. Mixed integer linear programming was used to implement the energy management system with automatic rescheduling of flexible loads as required for achieving the optimization goals and incorporating the inequality and equality constraints as required to ensure the logical operation of the system. The efficiency of the proposed regional energy management system has been measured against the sustainable development goals of universal energy access, eco-sustainability through greenhouse gas reduction and improvement of grid health. A demography load clustering-based tariff system was also implemented to exploit the energy usage pattern difference among urban and rural areas to increase the efficiency of the model. The payback period of the infrastructure was done and was found to be in satisfactory range.