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Smart-Grid Renewable Energy Management Using Space Technologies

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Abstract - Smart-grids have now turned into the main focus on renewable energy research areas. Renewable energy systems like solar cells and wind turbines are commonly used on smart-grid due to their easy availability. The major difficulty of using these renewables is the prediction of energy that can be generated due to the unpredictable nature of weather conditions, which in turn results in grid instabilities and voltage fluctuations. Space technologies are found to be an ideal solution for overcoming the grid instabilities caused by the unpredictability of weather conditions responsible for renewable energy generation. Space technologies are responsible for forecasting weather conditions to optimally adjust the smart-grid to generate and store sufficient energy before the renewables fail to meet the energy demand. These technologies also offer quick transmission of the renewable energy generation information produced by the sensors to the grid energy management system. MATLAB/Simulink software is used for designing and simulating the stand-alone and grid-connected smart-grid system consisting of solar and wind energy systems as the primary renewables. The simulation results analyse the difference in results obtained from the grid-connected and stand-alone smart-grid before and after they are integrated with the space technology networks. System performance indices, including electrification costs, grid stability, and system efficiency, are used to perform energy management analysis. From the results of the grid-connected smart-grid system before and after integration with space technology networks, the electrification cost is reduced by over 75% when analysing the monthly electrification for a 5 kW load at a tariff of R1,85/kWh. The system stability is improved by 18% due to the unreliability of renewables. It can be seen that the optimum combination of the smart-grid is when it's integrated with the space technologies.

1 Introduction

The unpredictability of conventional energy generation results in an unsettled energy supply, which has been a prevalent issue in many nations and regions in recent years. Currently [1], any problem with the distribution of electricity lines that results in a total loss of electrical power paralyzes the entire system, which affects commercial, residential, and industrial productions. Renewable energy is currently in high demand, and this demand is only growing as a result of global environmental changes and rising energy prices. Conventional fossil fuel-based electricity producing units are a major component of the current power grid. In the current electrical grid, there are considerable power losses when electrical energy is transported from these generating units to the consumers via distribution lines. Furthermore, there are risks associated with many traditional fossil fuel-based power producing units, such as nuclear power plant hazards. As a result, there is a global movement to change the way power is generated by switching from plants that rely on fossil fuels to ones that use renewable energy resources (RERs) [2]. An updated electrical network that monitors, automates, and optimizes power production, transmission, and consumption using digital technology, sensors, and two-way communication called a smart-grids are then introduced to overcome the drawbacks of traditional generation. The benefit of introducing smart grid system is automatic rerouting in the event of a distribution line failure. These smart grids serve as a loop between consumers and their utilities and are easy to use, assisting users in controlling their electricity consumption. This further increases transmission line efficiency while lowering the demand and cost of electricity. The smart grid has become a formula for both residential and commercial clients, giving them the ability to receive the ideal energy bill. Only by using a network that is integrated with the energy source control can this be accomplished [3].

This paper provides a summary of current initiatives aimed at incorporating renewable energies into the smart grid. The integration of renewable energy resources with the smart grid and space communication networks discussed in this paper optimizes grid stability, improves renewable integration, and improve the energy management. The current initiatives worldwide to integrate these RERs into the smart grid are also

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discussed, concluding with the potential avenues for further research on renewable energy resources integration into the smart grid. This paper further discusses a review of literature in integration of renewables with smart-grid systems, managing renewable energy using space technology, smart-grid system modelling, simulation and results discussion.

2 Literature Review

It has long been recognized that relying solely on fossil fuels to generate electricity is unsustainable because of resource shortages, unstable geopolitics, and environmental degradation. The International Energy Agency (IEA) projected that by 2023, renewable energy sources will generate around 30% of the world's electricity; by 2030, this percentage is anticipated to increase further. Declining costs, technological advancements, and regulatory frameworks that encourage the deployment of clean energy are driving the expanding use of RES [4]. However, as RES's proportion grows as presented in Fig. 1, so do the challenges associated with integrating them into conventional electrical systems.

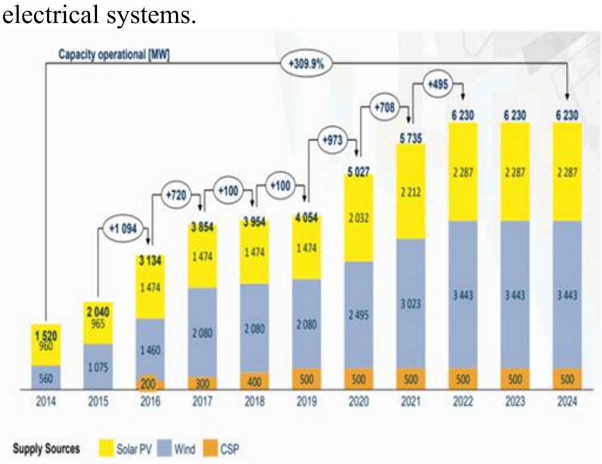

Fig. 1. Renewable energy capacity growth [5]

In contrast to thermal plants that generate output that is dispatchable and predictable, solar and wind are inherently intermittent, resulting in power supply fluctuations that, if not effectively controlled, might compromise grid stability.

2.1 Renewable Energy Resources

In contemporary power engineering, integrating renewable energy sources (RES) into electrical power systems continues to be one of the most significant issues. Transportation electrification, global carbon neutrality goals, and the growing use of distributed energy resources (DERs) are forcing conventional electrical grids to change [6]. To handle these changes, the smart grid paradigm, Fig. 2 depicts some of the relevant characters of renewable energy system which enables the infrastructure that will guarantee that the integration of renewable energy will contribute to system resiliency, affordability, and reliability, in addition to sustainability.

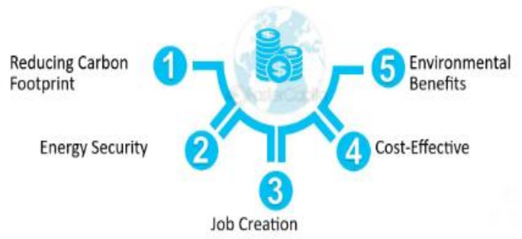

Fig. 2. Renewable energy system characters [7]

At the local level, the integration of renewable energy is very context-dependent. Urban locations typically face problems with load congestion, rooftop solar proliferation, and voltage control, whereas rural areas suffer from insufficient or non-existent grid infrastructure [8]. Therefore, in order to adapt to different operating conditions, smart grids need to integrate distributed intelligence with centralized coordination. The most fundamental technological challenge for integration is the RES's irregularity and intermittency. Cloud cover causes short-term, diurnal, and seasonal fluctuations in solar production. Wind power output fluctuates across periods of seconds to days and is also affected by regional weather patterns.

2.2 Smart-Grid

Modern electricity systems are undergoing a fundamental transformation because to the smart grid concept. The combination of power engineering and information and communication technologies (ICT) permits a flexible, interactive, and efficient grid that can accommodate significant amounts of renewable energy sources (RES) while increasing system reliability and resilience [9]. The unidirectional principle that supported the design of conventional electrical grids states that electricity flows from centralized power plants to passive consumers. Decentralized generation, bidirectional flows, active customer participation, and increasing complexity are characteristics of power networks that render this approach increasingly unsuitable. The conceptual model of a smart grid is presented in Fig. 3 showing the interconnection of energy and communication flows.

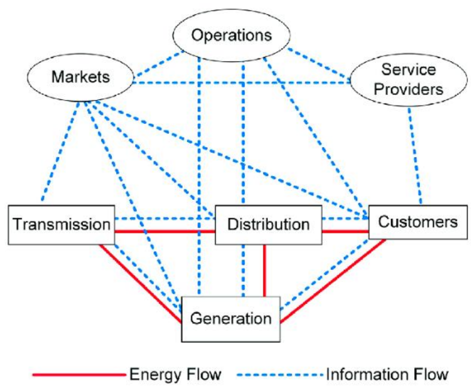

Fig. 3. Smart grid conceptual model [10]

2.3 Smart-grid Communication Networks

Communication networks serve as the smart grid's brains, facilitating data flow between sensors, control centres, and end users so that decisions may be made instantly. Cost, coverage, latency, and bandwidth are all trade-offs in communication technologies. For example, although satellite and wireless systems provide wide coverage, they may encounter interference or delay. According to literature, no single technology is sufficient to manage these trade-offs, necessitating the deployment of hybrid communication infrastructure. Satellites can provide coverage in areas lacking fibre or cellular networks, ensuring that remote renewable facilities and rural micro-grids remain a part of the larger smart grid [11]. The multiple domains of smart grid communication networks is presented in Fig. 4. The figure shows the distance ranges for wide area network (WAN), field area network (FAN), and home area networks (HAN) with their corresponding response speed. For smart grid systems, WAN is suggested due to its high speed and for the fact that it can be discoverable over a long distance.

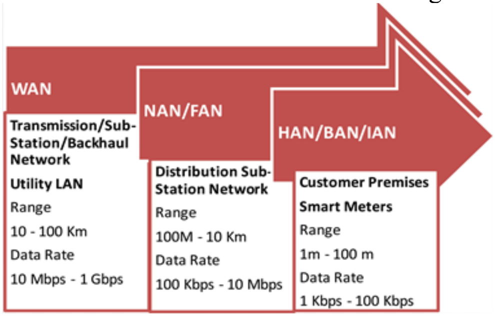

Fig. 4. Smart grid multiple domains [12]

2.4 Space Technologies in RE Management

Information and communication technology advancements are inextricably linked to power system modernization. As smart-grids grow into more complex, decentralized, and data-driven networks. A dependable communication infrastructure becomes equally as important as the physical infrastructure of cables and transformers. Space technologies are then used for monitoring, forecasting, and effective communication in order to maintain remote infrastructure, optimize production, and stabilize grids while managing renewable energy (RE). Important strategies include utilizing satellite Internet of Things (IoT) to link remote assets and merging Earth Observation (EO) data for resource mapping are also used. A dependable and abundant energy supply that is unaffected by location or weather is one advantage of space technologies for managing renewable energies.

In the modern information society, space systems are also quite important and have an impact on all aspects of our daily lives. Every time you use an ATM, watch a satellite TV show, make a phone call, or surf the internet, space technology is being used. Space technology contributes to sustainable development in several ways, including improved agricultural output, better management of our natural resources, and the supply of valuable information for peacekeeping and disaster relief operations. By offering wide-area communication, accurate geolocation, and sophisticated monitoring, space technology integration into grid-connected smart grids improves the energy management of renewables, energy system dependability, efficiency, and sustainability, especially for remote, distributed energy resources (DERs). Coverages of satellite communication system includes a quick response in urban, rural and remote areas as presented in Fig. 5.

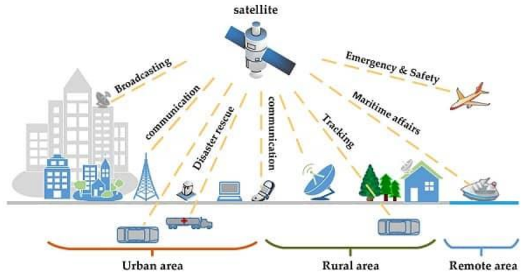

Fig. 5. Satellite communication coverage [13]

3 Modelling and Simulation

3.1 Solar Energy System Modelling

A solar energy system, also known as a photovoltaic system, uses panels, inverters, and battery storage to turn sunlight into electricity that powers homes or businesses. These systems cut carbon emissions, enable energy independence during outages, and lower utility bills by producing renewable electricity on-site. The energy requirements of the load influence the size of the solar panel that has to be installed. The location-dependent factors of temperature and solar radiation, as well as the season in which the energy system is situated, all affect the PV system's size. The PV cell's equivalent circuit is presented on Fig. 6.

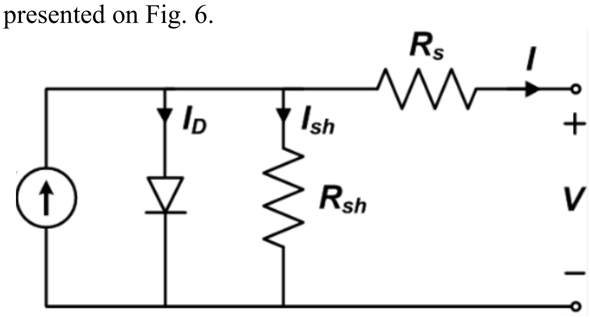

Fig. 6. PV Cell equivalent circuit [14]

The amount of power that a single PV panel can produced can be mathematically estimated using equation (1):

$$I_d = I_o(e^{38.9V_d} - 1) \quad (1)$$

Where I_d and I_o are the diode and reverse saturation current respectively, V_d is the diode terminal voltage. This equation is used at a standard test condition with a temperature of 25°C. The amount of current supplied to the load from a single cell is then calculated using equation (2).

$$I = I_{sc} - I_o(e^{38.9V_d} - 1) \quad (2)$$

Where I is the load current and I_{sc} is the current produced by the cell.

3.2 Wind Energy System Modelling

In order to generate clean, renewable electricity, wind energy systems use rotors with blades to capture the kinetic energy of the air. These systems, which range in size from modest residential turbines to massive offshore wind farms, harness mechanical energy from wind to generate electricity. Important parts include the gearbox, nacelle, blades, and tower; yaw devices are frequently used to maximize wind capture. The necessity for accurate wind modelling and turbine performance assessment justifies the use of real wind

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data, as wind speed is a critical factor in power generation. Equation 3 can be used to mathematically model the quantity of electrical power that a wind turbine can produce.

$$P = 0.5 \times \rho \times A \times V^3 \quad (3)$$

In which P is the power generate, ρ is the air density, A is the swept area of the rotor blade and V is the wind speed.

The main components of a wind energy system are shown in Fig. 7, where the gear system is responsible for transmitting rotary energy from the turbine to the generator, and a generator converts mechanical energy into electrical energy and supply power to the load/grid

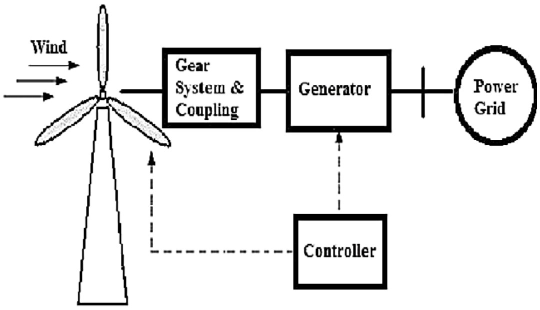

Fig. 7. Wind energy system [15]

3.3 Hybrid Energy System Simulation

The appropriate blocks are arranged using the Simulink libraries configurable block libraries to construct a schematic model, which is then joined into a system diagram for solar and wind energy modelling using MATLAB/Simulink. The solar and wind energy systems' schematic diagrams, which were created and simulated using MATLAB/Simulink, are shown in Fig. 8 and Fig. 9, respectively.

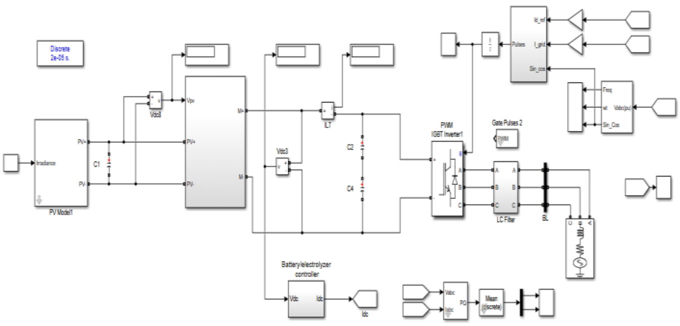

Fig. 8. Grid-connected solar energy system schematic

Blocks can be added by dragging them from the library browser or using the rapid insert option. The integration of solar and wind energy system with the utility grid results in a smart-grid system shown in Fig. 10, which is integrated with space technology network to assess the generated energy and model the renewable energy management to verify the benefits of space technology integration. The general behaviour of the system is then ascertained by measuring tools like voltmeters and oscilloscopes, which are used to measure the output and examine the waveform.

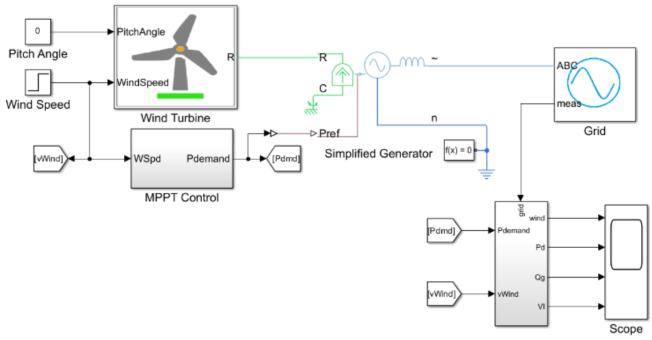

Fig. 9. Grid-connected wind energy system schematic

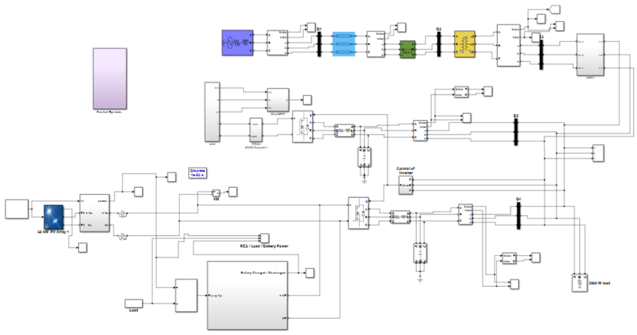

Fig. 10. Grid-connected smart-grid energy system

4 Results Analysis

4.1 Stand-alone Smart-grid System

A smart grid energy system uses real-time feedback to control the flow of energy from various sources. In order to provide intelligent scheduling, real-time monitoring, and automated power system control, the smart grid architecture integrates the power, communications, and IT layers. With features like bidirectional power and information flow, artificial intelligence (AI), deep learning, and complex algorithms are used to guarantee stable, reliable, and high-quality power delivery. When a smart grid system is simulated before it is integrated with the space technology networks, the unstable power generated is presented in Fig. 11. These results are being obtained using the 1000 W/m² of solar irradiance at 25°C with a wind speed running at 5.8 m/s.

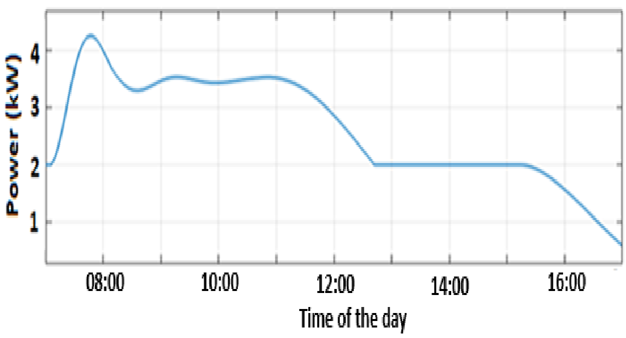

Fig. 11. System generation before space technology is enabled

From these results, there is variation in power due to power system instability and the unpredictable nature of renewable energy resources used to make up a smart grid. Over a period of 0.1 seconds, the initial maximum power produced was 4 kW over 0.01

seconds, then the power drops to 2 kW. This power variation is eliminated by integrating the smart-grid with the utility grid for improved stability and constant power generation even in the absence of renewable energy resource generation.

4.2 Grid-connected Smart-grid System Incorporating Space Technology

A smart-grid's integration with space technology networks aims to increase system stability and efficiency. The communication networks also act as a conduit for alerting the grid of impending instability brought on by renewable energy sources' inability to provide the grid's load demand. This allows the system to automatically switch to the utility and immediately sustain the load demand. In order to meet the load demand and manage the system stability, the system is connected with the utility grid and integrated with space communication technologies, and the simulation is conducted on MATLAB/Simulink. The output power generated following the integration with space technologies is displayed in Fig. 12, where the power system stability is being improved.

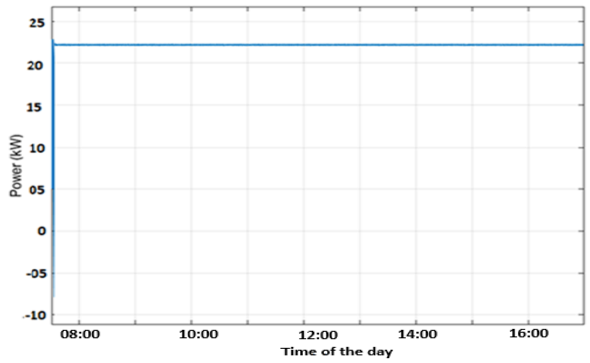

Fig. 12. System generation after space technology is enabled

When compared with the power generation in Fig. 11, Fig. 12 shows the impact contributed by the utility grid integration with smart grid as the power system instability is being eliminated. The smart grid integration with the utility grid also provisions for a three-phase voltage that can be supplied to a 380-volt three-phase load as presented in Fig. 13.

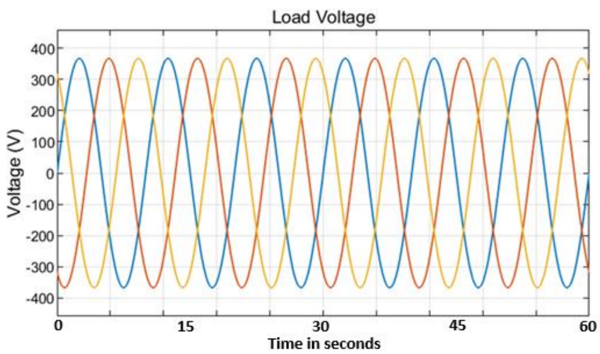

Fig. 13. Three-phase load voltage produced

4.3 Integrated System Results Analysis and Validation

Utilizing the space technology networks, renewable energy management optimizes the generation and supply, storage, and real-time data analytics. Space technology networks are conceptual enablers that cannot be simulated on MATLAB/Simulink software; however, integrating renewable energy sources with the space technology networks to make up a smart-grid makes energy systems more stable, dependable, efficient, and adaptable to changes in supply and demand. Table 1 presents system performance indices of the smart grid system before and after integration with space technology networks for improved renewable energy management.

Table 1. System Performance Indices

Performance Indices	Before Integration	After Integration
Electrification cost @ R1,85/kWh	R6 660 per month	R3 330 per month
Grid Stability	43.5%	61.5%
Grid Efficiency	66%	73.8%
Sustainability	57%	63%
System maintenance	Scheduled maintenance	Proactive maintenance

The presented results were simulated on MATLAB/Simulink with a 5-kW load assumption for both cases, and performance indices were recorded. The electrification cost is calculated based on the assumption that the load is running 24 hours per day for 30 days, using the time of use tariff of R1,85/kWh, using Equation 4.

$$Monthly\ electrification\ cost = \\ no.\ of\ hour\ per\ day \times \\ no.\ of\ days\ per\ month \times ToU \times load\ rating \tag{4}$$

Stability and sustainability of the smart grid system involve combining economic viability, technical reliability, and the environmental impact, as the system consists of renewable energies. The efficiency of the smart grid is determined by equation 5, comparing the renewable energy system sensitivities, i.e., solar and wind systems, with the total electrical power output from the energy system.

$$\eta_{system} = \frac{P_{total}}{P_{solar} + P_{wind}} \tag{5}$$

The power input and output to the grid by the RES is also measured on MATLAB/Simulink to determine the efficiency provided in Table 1.

5 Conclusion

This study introduced a method for managing renewable energy in smart grids by integrating cutting-edge space technology, such as satellite communication, remote sensing, and space-based monitoring systems. The study's findings showed that integrating space-enabled technologies with smart-grid infrastructure increases sustainability by 6%, and the grid efficiency by 7.8% while also lowering the cost of electrification by approximately 50%. Space technologies facilitate improved decision-making and efficient use of energy resources by providing real-time monitoring, predictive analytics, and improved communication capabilities. The suggested paradigm emphasizes how satellite-assisted systems can help with major issues related to integrating renewable energy, like intermittency, grid instability, and restricted accessibility in remote areas. Additionally, reliable forecasting of solar and wind energy resources is made possible by the use of geospatial data and Earth observation technology, which enhances operational planning and lowers energy losses. The results show that combining space technology with smart-grid systems can help achieve global sustainability objectives while hastening the shift to more robust and clean energy networks.

The practicality and scalability of such solutions are anticipated to be improved by ongoing developments in satellite systems, artificial intelligence, and Internet of Things (IoT) technology, despite obstacles relating to implementation costs, cybersecurity, and infrastructure complexity. Future research should concentrate on creating affordable architectures, bolstering data security measures, and investigating the use of cutting-edge technologies like digital twins, machine learning, and next-generation satellite networks for autonomous energy management. All things considered, intelligent, efficient, and sustainable energy ecosystems for future smart cities and remote villages can be achieved through smart-grid renewable energy management enabled by space technology.

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