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Renewable Energy Re-Distribution via Multi-scale IoT for 6G-Oriented Green Highway Management

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Abstract—While recent works on investigating renewable energy sources for powering the highway offer promising solutions for sustainable environments, they are often impeded by unequal distribution of sources across the region due to variations in solar exposure and road intensity that electromagnetically and mechanically generate the energy. By exploiting viable gathering of massive renewable energy data using the Internet of Things (IoT), this paper proposes a framework for improved highway-energy management based on the unmanned aerial vehicle-assisted wireless energy re-distribution of the harvested renewable energy. Combining both massive low-rate sensing with high-speed 6G-envisioned transmission for data aggregation, the IoT architecture is of multi-scale, consisting of : i) global data exchange and analytics for energy mapping, re-distribution planning and forecasting, and ii) local data sensing and processing at individual highway lampposts for micro-energy management. The feasibility of the networked energy system is analyzed via analytical cost-reliability analyses. The cost analysis demonstrates the cost-effectiveness through the lowest Requirement of Energy and Cost of Energy for the setup and maintenance. The reliability analysis reveals the energy plus (E+) feature of the system in certain conditions with enhanced reliability in adverse weathers that impact energy generation. With multi-scale data connectivity to intelligently manage standalone renewable energy, this work puts forward a viable idea of 6G use cases with massively networked energy sensors with a vision of achieving super-connected and intelligence-equipped highways.

Index Terms—Energy distribution, energy management, highway, multi-scale IoT, renewable energy, UAV, 6G direction.

I. INTRODUCTION

HIGHWAY lighting system (HLS) is a critical element in modern society and known to ensure the safety of the highway at night, eliminating the poor visibility of potential hazards and enhancing the aesthetics of the road. However,

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the operation of such systems accounts for immense electricity consumption from the national grid, placing a massive demand on the budget for the public highway. A report by EIA showed that the USA spent 141 billion KWh for lighting purposes in its commercial building and public lighting services [1]. The developing or underdeveloped countries struggle most in the highway lighting operation, having a little budget to safeguard their highways.

Given these worldwide concerns on fossil fuel-based energy sources in terms of availability [2] and greenhouse gas (GHG) impact [3], renewable energy sources emerge as a promising alternative with numerous possibilities. The implementation of renewable energy-based HLS provides a profitable replacement of extended grid-based HLS in rural or remote areas. Although many large-scale renewable energy projects like ‘Solar Roadway’ collapsed worldwide [4], small-scale application of renewable energies offers vast energy-saving potential [5], [6], [7], [8]. Extensive initial set-up cost and lack of reliability in case of unforeseeable climatic conditions, i.e., cloudy and overcast days, are two primary performance constraints for large-scale solar-based HLS [9], [10], [11].

Emerging research depicted a departure from sole reliance on the solar-based source to other renewable energy sources that can be harnessed within the highway environment. This includes the provision of a horizontal axis wind turbine (HAWT) [12] to utilize natural wind energy or especially a vertical axis wind turbine (VAWT) [13], to harvest energy from the vehicle’s movement on the road. Driven by varying levels of energy generated by these multiple sources, micro-scale Internet of Things (IoT) platforms have recently been introduced in [8] to manage energy generation and storage in a given lamppost. Integration of diverse multiple energy sources would mean there is an opportunity to extend the lifetime of the renewable energy supplies, which are desirable for environmental sustainability.

The main problem associated with this renewable energy system is driven by the condition that energy sources are not uniformly distributed across different segments of the highway. Solar exposure in different segments of the highway vary, depending on the geography and topology of the environment, vegetation profile, and building density [14]. Mechanically generated sources from wind turbine based mechanism strongly rely on the road traffic intensity, which often fluctuates across urban, suburban and rural settings. Technically speaking, this issue can be solved using a cable-based solution to transfer energy from one lamppost, as a primary energy harvesting point, to other lampposts. However, the required

infrastructure associated with the cable-based solution is often prohibitive in terms of investment and maintenance costs. Wireless-based solutions could therefore be desirable due to their ad hoc characteristics, flexibility and infrastructure-less.

Building upon a new paradigm of the next generation super-connected 6G connectivity [15], this work considers a multi-scale IoT framework to address unequal renewable energy distribution over the highway segments. It will primarily leverage wireless networking technologies that are the backbone of data transmission for energy sensing devices. Within the framework, we partition the the energy system into two high-level building blocks, namely: i) Large-scale global energy data platform, and ii) Small-scale local energy management. By gathering data from a massive number of sensors across the lampposts on the highway, the large-scale global platform acts as a provider of renewable energy mapping and can inform re-distribution planning, forecasting, and decision making. on the other hand, the small-scale local part is responsible for local data sensing and processing to trigger energy generation mechanisms and manage the required energy storage. We refer to a system developed using this framework as a Multi-scale IoT-enabled Hybrid Renewable Energy System (MIoT-HRES). Moving away from the cable-based solution, the renewable energy re-distribution is accomplished using unmanned aerial vehicles (UAVs) that performs electricity charging from lampposts with excessive energy supplies and discharging to lampposts with deficient energy availability. The problem can be casted as collection and distribution where energy parameters are derived through data collected, and subsequently being used to enable evolutionary algorithms to simulate and optimize a UAV route allocation for effective energy distribution.

While the previous studies predominantly contemplated on the micro-perspective (i.e., the provision at the individual lamppost level) of devising and managing renewable energy sources to power the highway, this paper takes a step forward by integrating both the micro- and macro-perspectives of energy supplies and demands on the highway to achieve sustainable energy management. This is reflected by specifically applying the concept of multi-scale IoT in the off-grid green energy-based HLS. In particular, our main contributions over state of the art and our previous works [8], [16] include the following.

- We propose and design the multi-scale IoT-based framework to manage renewable energy generation and consumption suitable for highway operation. We provide comprehensive descriptions of the principles, building elements and services integral to the framework.
- We investigate the feasibility of UAVs to perform energy re-distribution via charging and discharging mechanisms across the lampposts. The operation of UAVs is data-driven based on the information gathered and transmitted by a massive number of networked sensors.
- We propose an Inter-lamppost network design to be applied to the MIoT-HRES based on the standalone HLS employing renewable energy harvesting from multiple sources.
- We perform a cost analysis to highlight the least initial

investment and maintenance costs, which can reveal the potential commercial success of the proposed MIoT-HRES.

- We perform a reliability analysis to compare the strengths of the multi-scale IoT-enabled hybrid energy sources with the pure solar-based HLS.

Taking together the data exchange from a massive number of networked sensors via multi-scale IoT and computational intelligence mechanism both at the global and local platform levels, this work envisions a step forward of harnessing a 6G paradigm [15] to enable super-connected green highway energy management.

The rest of the paper is structured as follows. Section II outlines the present status of green energy-based highway lighting solutions and identifies the challenges to meet for commercial success. Section III discusses the proposed IoT based green HLS, system architecture, and special features. The cost and reliability analysis of four test scenarios is presented in section IV. Section V simulates two popular wireless technology for minimum cost and maximum performance. Section VI closes the paper with a conclusion and future work.

II. LITERATURE REVIEW

In this section, the existing works will be discussed and analyzed. For ensuring energy efficient on lighting, many papers work on Photovoltaic based standalone lighting solutions [17], [18], [19], [20]. Several studies focus on investigating economic feasibility with positive outcomes [21], [22], [18]. However, most of these works emphasized the overall performance, life-cycle assessment, improving internal characteristics of the solar charge controller, and battery performance, all of which indeed support the application of the solar system for road lighting. However, the constraint to attain a commercial success of solar-based HLS remains unsolved as the challenges of high initial capital expenditure or unreliability under adverse weather conditions remains unanswered.

Upgrading the basic solar-based standalone lighting system in terms of improved efficiency and performance is related to the cut down of initial set-up cost, which includes refinement of solar panel to reduce solar dependency and real-time controlling of load to minimise energy wastage [8], [23]. Hybrid Renewable Energy System (HRES) based supply system promises higher reliability and stability through intermittent power generation from several energy sources [24]. However, these types of lighting systems still demand huge cost without the adoption of latest cloud-based technologies like IoT.

HRES based HLS has encouraged the researchers with uncountable possibilities, mostly claiming to have better economic feasibility than the conventional diesel-based systems. Recent advances in HRES has come out with many ideas like analysing the potential of a Hybrid system [5], [25], exploiting HRES in rural/remote roadways [5], and proposing the concept of a microgrid by contributing the excess energy to the main grid [26]. Different works suggest different choices of renewable energy sources [12] and different control strategies for a supervisory controller [27] to run the system for HLS. Although HRES promises many attractive features like its

strong reliability compared to pure solar and higher potential of energy plus microgrid concept, the acceptance of HRES in the commercial sector is significantly impaired by its extensive initial cost.

Eventually, standalone lighting solutions for HLS are not limited to the development of the supply system only. Few works considered enabling IoT enabled technology to enhance the efficiency of the standalone system and cut down the initial set up cost. IoT enabled solar lighting came into the interest of a considerable number of researchers featuring energy efficiency and cost-saving in terms of controlling light precisely [28], [29], [30]. For instance, Fabio et al. [31] proposed to establish a PV based Intelligent light controlling system with attractive features of a monitoring station and base control station built on the ZigBee network. In references [28] and [29], the authors deployed a smart light controlling method in pure solar-based lighting system to reduce energy consumption. Abhishek et al. [30] also propose a traffic flow-based solar powered street light control system for energy saving. This study considers solar as the only energy source having only 2days of power back up and relies on the grid for the rainy or winter season. Although exploiting IoT in pure solar-based HLS can boost the energy saving twofold; however, these systems are subjected to one single point of failure as they solely rely on solar power. Provided that solar system fails to generate adequate power around the year due to change of season, especially owing to cloud or rain that persists for a long duration, raising the issue of unreliability.

Throughout the literature, a variety of sensing and managing strategies has been reported for light controlling in solar or grid-based public lighting systems. Nonetheless, the integrated approach of HRES and IoT for HLS has not been much reported. In particular, Farah et al. [24] simulated an optimisation model keeping in mind the design of hybrid energy supply and light controlling method. The authors exploited a predictive model of traffic density using traffic density records in a particular highway and estimated the load consumption for one year through MATLAB simulation. The simulation yields a demand for lower energy costs for optimum supply design. However, considering the need for real-time sensing and monitoring, their work lacks proper information from the perspective of appropriate technology selection for light control. This gap of information also raises other challenges like the cost for smart controlling, faster maintenance response, and acceptable lighting performance for user safety.

In the previous work [8], an HRES based smart, single lamppost for standalone lighting operation in highways was proposed. Furthermore, there have been numerous studies (e.g., [16], [28], [29], [30]) investigating efficient control of highway lighting. In this paper, we aim to combine the perspectives of hybrid renewable energy generation and consumption, and add a new dimension of energy distribution. More specifically, we propose an IoT enabled HRES based HLS, i.e., (IoT-HRES). Here the objective of this research is to design an inter lamppost communication network to reduce the initial set-up cost with higher reliability of the overall system. Moreover, this work proposes the smart feature of HLS, including automated maintenance and seamless lighting

criteria.

III. OVERVIEW OF MIIOT BASED FRAMEWORK FOR GHM

The Multi-scale IoT (MIIOT) based Framework for Green Highway Management (GHM) consists of several factors, such as, the concept of MIIOT, MIIOT-HRES enabled Single Lamppost, MIIOT-HRES enabled Lamppost Networks, Global Data Exchange and Services, and GHM. The Framework is depicted in Fig 1 and all the factors are discussed in the following:

A. Multi-scale IoT

A key principle within this MIIOT-based framework is multi-scalability. This is to account for data-driven tasks' requirement at various processing levels from sensors to clouds, and convergence of communication and networking technologies within the 6G paradigm [15]. The MIIOT unit consists of Five components as follows.

- *Data Acquisition and Processing.* The multi-scalability is captured into two data-driven platform categories, namely: i) local data sensing and processing, and ii) global data exchange and services. A task at the local level includes gathering front-end energy data intensity via solar-related sensors and vehicle-mobility-related sensors that are linked to the road traffic intensity. Data processing at the local level may involve size reduction for efficient data representation and transmission.
 - *Intelligence Unit.* Data collected and processed at the sensing front end can be used both locally and globally. In the local context, the data are used to manage charging and discharging mechanisms by an IoT-enabled controller [8] to ensure the reliability and longevity of the battery as an energy storage. In the global context, the sensing data along with the energy storage characteristics data are sent to a computing cloud for global energy planning and management.
- Given the multi-scale nature of the IoT architecture, a variety of adaptive distributed algorithms would make sense to equip intelligence in the system. The algorithms are run across various nodes with each having different processing power and resources. Resource and context awareness is a key for efficient deployment of such algorithms. Time-varying adaptability is required since parameters of interest that govern battery level, battery capacity, charging and discharging rates are time-, weather-, and environmental-dependent, and to be captured through continuous sensing.
- *Physical Networks.* Seamless collaboration between physical networks and intelligence capability is a key feature within future 6G super-connectivity vision [15] to achieve timely energy re-distribution within GHM. To preserve backward compatibility, we propose integration of evolving IoT digital infrastructure with future cellular networking technology. More specifically, sensor data transmission is facilitated using multiple radio access technologies (multi-RATs) combining LoRa, NB-IoT, LTE-M, LTE, and 5G/6G femtocell connectivity [32] as

the front-end physical networks that allow for lamppost-to-lamppost data exchange for enabling seamless highway lighting services [16] and enable lampposts-to-cloud massive remote data transmission.

Whilst evolving IoT technologies such as LoRa, NB-IoT, and LTE-M can purposely be used to transmit low-rate sensing data, high-speed cellular connectivity such as LTE, 5G and 6G (depending on their availability) can be leveraged to transmit aggregated sensor readings at intermediate access points/stations. LTE and 5G can achieve approximate latency in the order of ms, whilst 6G is anticipated to achieve μs latency [15]. Such latency is critical for efficient energy re-distribution since battery charging and discharging are continuous and any significant delay in decision making could impact the efficiency and effectiveness of the distribution techniques.

- *Network Virtualization.* The multi-RATs are managed by the Network Virtualization functionality that adaptively allocates radio resources according to the transmission demand and QoS. Upon reading the cloud, global data processing and services take place. This includes energy mapping, energy re-distribution planning that triggers the activity of UAV to find the high-energy spots and transfer the power to the low-energy spots, and energy forecasting. All these tasks can employ intelligence algorithms for appropriate computation.
- *Security Platform.* Energy networks are often classified as critical infrastructure. It is therefore imperative to protect the networks for the purpose of energy re-distribution within GHM. Authentication is required to any nodes to connect to the networks. End-to-end encryption is applied to protect the data from eavesdropping. In view of the constraints of computational and battery power across nodes, lightweight authentication and encryption would be preferable. To perform continuous monitoring of the networks, distributed intrusion detection system [33], [34] could be leveraged for identifying anomalous events and blocking such anomaly to propagate.

B. MIoT-HRES based Single Lamppost

In response to the above goals, the single unit of a MIoT-HRES based HLS minimizes the solar dependency, improves the system reliability, and provides energy plus (E+) feature under certain atmospheric conditions. This unit has a smart energy management system consisting of a VAWT and Photovoltaic (PV) Panel for energy generation, microcontroller for appropriate data analysis and control, batteries for energy storage, and as well as other necessary types of equipment. A MIoT enabled intra-lamppost communication is presented here. The single unit lamppost consists of several unit such as, battery-unit (BU), wind-turbine-unit (WTU), load Unit (LU) solar-unit (SU), and hybrid-charge-controller unit (HCCU).

The SU produces energy from the PV panel, which has a MPPT based solar charge controller to pick up the maximum combination of voltage and current from the PV panel. Being the primary energy source, it forwards the energy to the BU through the MPPT to keep the battery safe from being

overcharged. The WTU has a VAWT that extracts energy from aerodynamics losses produced by vehicles on the highway. Using a 3-phase AC generator, it produces the AC energy and then forwards it to the DC battery in BU through a rectifier. In the presence of sunlight, the battery will be charged by PV panel whereas VAWT will charge the battery with the business of the road. A HCCU, comprised of a micro-controller and a wind charge controlling unit, monitors and controls the hybrid energy production and battery energy distribution. It decides the battery charging transition between the PV panel and VAWT and dumps the excess energy in a given path. A Lead Acid battery bank is sized for every single lamppost to support the highway lighting demand with a fixed amount of maximum excess energy for wireless power distribution. A DC to AC inverter is exploited in BU to support the AC LED light in the LU. Finally, LU operates the light whenever it is decided from the HCCU.

Ensuring maximum energy output is a challenge in renewable energy-driven HLS. The energy generation units, the SU and WTU, operate together to feed the demand for lighting load. In the proposed system, the SU and WTU operate together to ensure the load-demand on LU. The battery is charged by the generated power when both energy sources are substantially accessible. For ensuring battery fitness, battery state of charge (SOC) 90% and 30% are denoted as th_{\max} and th_{\min} , respectively. A battery SOC of less than 30% can wither the battery as well as compress battery life. The battery discharges until its SOC is greater than or equals to th_{\min} . There is a UAV docking point, as depicted in Figure 1, where the UAV will be landed and recharged the battery if required. Charging will be done using the wireless battery charging technology [35].

C. MIoT based Lamppost Networks

To minimize the initial set-up cost in an enhanced manner and to ensure user comfort in night-time driving, this paper proposes an inter-lamppost network solution underpinned by relay networks in an MIoT-HRES based HLS. The enhanced efficiency through the installment of IoT reduces the energy demand, results in a reasonable investment cost, and offers energy-efficient services such as seamless lighting and automated maintenance. The proposed relay network incorporates four distinct components, namely Introductory Lamppost (IL), Leader Lamppost (LL), and Associate Lamppost (AL). They work together as a unit, which is described as follows.

Typically facilitated by multiple sensors, micro-controllers, and transceivers, IL is the first lamppost of the targeted highway segment, which is located right after the highway toll plaza. This allows the lampposts to have a small delay in sensing incoming vehicles and making decisions thereby. The motion and light sensor data for detecting any vehicle are forwarded to the following lamppost for switching on the light. The forwarding nature of information is automated in which the driver does not notice the changing behavior of lampposts. This ensures the safety and comfort of the highway users. Consequently, the lampposts are turned on only whenever necessary, and the energy demand for entire night lighting can significantly be reduced.

To further minimize energy consumption, we assign the highway into small sectors. The first lamppost of every sector is acknowledged as a Leader Lamppost (LL), which plays the role of an anchoring node and a divider between sectors. This concept saves a lot of energy since without designating sectors, the entire lamps of the highway would be turned on unnecessarily. The length of each sector is represented by a distance, which is K multiples of human eye vision range to offer uninterrupted lighting coverage. The LL is similar to the IL except with an extra role of communicating with the control centre in the case of an emergency. For instance, the LL informs the control centre whenever it detects any malfunctioning lamppost via appropriate long-range connectivity.

In the proposed network, AL acts as a relay node, and all the lampposts work as a relay node exempting the LL. This AL turns on its light using its sensing unit or according to the propagated information from the previous lamppost. Whenever an AL receives the data of car arrival, it propagates this information to the following lamppost. The functionality of the AL is unlike the LL. To save electrical energy, the AL goes dim when no vehicle is detected by the system (i.e., when the road is less crowded).

The highway maintenance department is regarded as the GMS of the proposed system. The GMS responds to the call for maintenance from the LL as they collect the information of faulty lamppost under their surveillance. Using MIIoT network platform, the LL initiates the call for maintenance to GMS.

The proposed network architecture of the MIIoT for GHM is depicted in Figure 1. Each lamppost has a transceiver capability and appears as a network node in the system. The identity of each node can be acknowledged using the NodeID. Five key building blocks constitute the internal architecture of the proposed system, i.e., Vehicle Sensing unit (VSU), Micro-controller Unit (MCU), Communication Unit (CMU), and Lighting Uni (LU), Battery Status Unit (BSU). Typically, VSUs are the sensory units (e.g., Light intensity and Proximity Sensor) used to identify the presence of vehicles and forwards this information to the controller or MCU after the detection is done. The MCU serves as a key decision maker for lighting fluctuations and the LU acts accordingly. The CMU forwards the information of the incoming vehicle to the CMU of the subsequent lamppost. BSU will forward the battery status of the individual lamppost. This information forwarding is done with an assumption that all the intermediary hops will carry the data until it reaches the cloud. The GMS manages all the elements and executes an emergency maintenance operation when any faulty notification is received. The communication between LL and GMS is enabled by the MIIoT network platform.

D. GDES

The Global Data Exchange and Services (GDES) consists of three parts namely, Backhaul Networks (BNs), Big Transportation Data Analytics (BTDA), and Stakeholders. The BNs, referred to as external networks, are the gateway for Lampposts to communicate with Cloud and transmit their important information for data storage. The IL and all the

LLs will have the capability to communicate with BNs. The rest of the Lampposts are named as Associate Lamppost (AL), who only propagate the information from one AL to another AL. The LL will have additional features compared to the AL, such as high computational capability, communicate with heterogeneous networks, fixed and no resource and energy constrained. All the data will be stored in the Cloud and they will be processed by the BTDA to know the behaviours of the gathered data so that a set of services can be provided, which are requested by the stakeholders (e.g., Government Organizations, NGOs, Social Organizations and so on).

E. Green Highway Management

The outcome of the proposed MIIoT based framework will envision a set of services, which will contribute to stakeholders. Exploiting the concept of MIIoT, a set of services can be offered, namely: Highway Lighting, Lamppost Maintenance and renewable energy distribution. Utilizing this concept lots of additional services can be provided for developing an Automated Transportation System. The effectiveness of the suggested services is validated and discussed in the following section.

Whilst the highway lighting and lamppost maintenance can be accomplished through actuating and notification operations as mentioned in previous subsections, the renewable energy distribution requires algorithms to run across individual lamppost nodes as well as the Control Centre. Figure 2 captures step-by-step executions of the energy re-distribution technique via the aid of UAVs. The first step is to collect the energy status of all lampposts, which may include the battery level, current charging/discharging rates, and renewable energy exposure (e.g., solar intensity or vehicle movement intensity). Once this is done, the second step is to calculate necessary parameters for energy re-distribution. In particular, in this step, the sensed data from the first step will be combined with the lampposts mapping data as well as the UAVs' characteristics such as the speed, manoeuvre capability, and energy carrying capacity. This calculation is done by a Control Centre since energy re-distribution shall be done globally. Once the parameters are calculated, a selected evolutionary algorithm is simulated to undertake optimization of UAVs' route allocation in the third step. This will then be followed by the fourth step where feasibility of energy re-distribution is verified. If the output of the algorithm determines non-feasible distribution, the Control Centre will look for an alternative evolutionary algorithm that improves the optimality of route allocation. Additional resources (e.g., UAVs) or reduction in a set of lamppost to participate in the re-distribution process may be sought until the algorithm converges. Once this is confirmed, then the last step is to dispatch the UAVs to accomplish energy re-distribution according to the route determined by the optimal evolutionary algorithm.

IV. VALIDATION, RESULT, & DISCUSSION

In this section, we consider four types of HLS, namely (i) Pure Solar [36], (ii) HRES [37], (iii) IoT-Solar [16], and (iv) IoT-HRES (the proposed system), and compare their

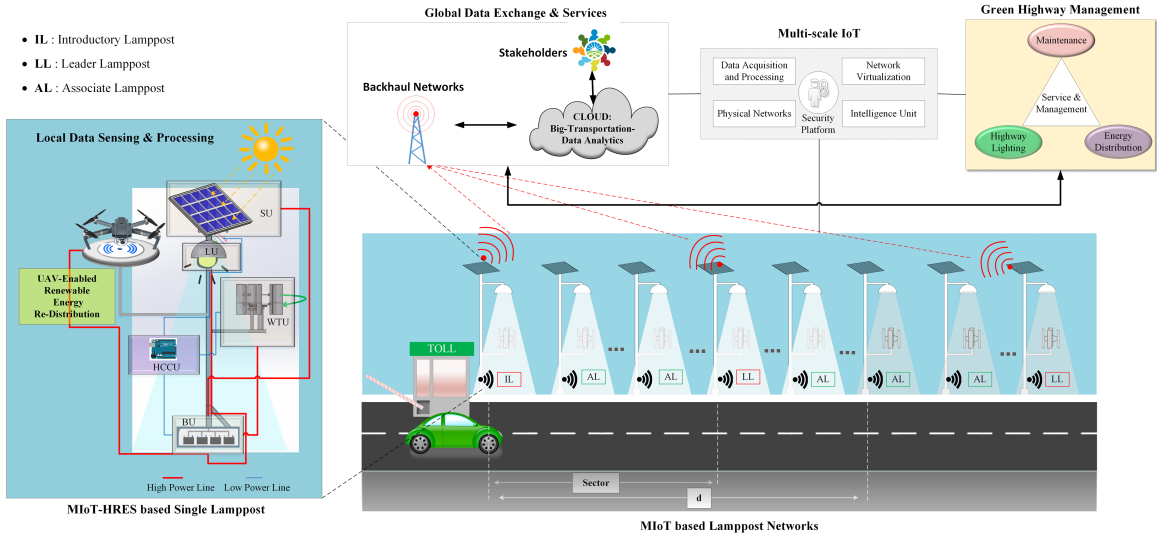


Fig. 1. Proposed MIoT based Framework for GHM

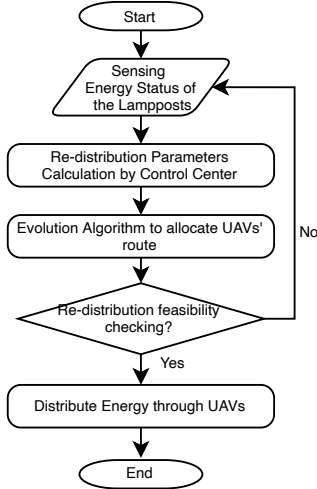


Fig. 2. Flow chart of the Renewable Energy Re-distribution Mechanism.

performance in terms of cost and reliability. Consequently, we validate the proposed IoT-HRES based HLS over three other HLS through analytical cost and reliability analysis. The cost analysis deals with the energy cost of the overall system from the perspective of the solar panel cost. Furthermore, it approximates the reduced maintenance cost in the automated maintenance procedure. Finally, a reliability analysis is done to measure the resilience of the proposed system in comparison with other test scenarios in adverse weather conditions.

A. Energy Cost Analysis

The energy cost analysis initially focuses on the truncating solar panel cost, which holds the major cost-share in the successful implementation MIoT-HRES. This analysis includes estimating solar panel sizing according to the load demand, i.e., the requirement of energy (ROE) and the cost involved with this sizing process, i.e., the cost of energy (COE).

Some underlying assumptions are considered to calculate the energy consumption with the associated cost.

1) *Comparative study of ROE*: To illuminate the highway, we consider a lamppost having a LED light of 96Watt for one single lamppost. To recognize the least amount of energy required to feed the load for 10 hours of lighting service, we define the least Watt-hour demand of 960Wh. Hence, the energy required for a pure solar based HLS is defined as, $E_{Solar} = E_L = 960Wh$. Here, E_L is the energy required by the load. E_{Solar} and E_L are equal in pure solar based HLS as E_{Solar} is calculated contemplating all the system losses.

However, the factor of road busyness, R_B affects the energy generation in an HRES based HLS as it integrates the energy of solar, E_S with energy from the wind turbine, E_W , which relies on the vehicular aerodynamic loss. Therefore, $E_W = E_R R_B T$. Here, E_R , R_B , and T denote the generator rated power, percentage of road busyness, and operation hour of the wind turbine. Hence, the required Energy from Solar panels in Hybrid System,

$$E_{HRES} = E_L - (E_R R_B T) \quad (1)$$

The third test scenario focuses on the exploitation of IoT in pure solar based HLS, where the lighting is controlled by embedded instructions in the microcontroller. The demand for energy in IoT enabled pure solar system is given by,

$$E_{SIoT} = E_F R_B + E_D (1 - R_B) \quad (2)$$

Where E_{SIoT} , E_F , R_B , and E_D is the requirement of energy for IoT based solar system, the requirement of energy with full light, the percentage of road busyness, and the requirement of energy with dimmed light, respectively. Here, the full light specifies 100% brightness with maximum wattage, and dimmed light specifies the 10% brightness of maximum wattage. The proposed IoT-HRES based lighting system exploits a smart hybrid renewable energy supply. It has a unique controlling mechanism that utilizes the energy as per the

requirement of the highway. The Required energy for IoT enabled Hybrid System,

$$E_{HRES-IoT} = E_{HF}R_B + E_{HD}(1 - R_B) \quad (3)$$

Where E_{HF} = Requirement of energy with Full Light with hybrid supply, and E_{HD} = Requirement of energy with Dim Light with hybrid supply. The ROE for four different lighting systems has been calculated and plotted in Figure 3

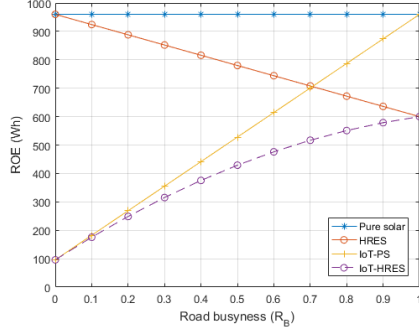


Fig. 3. Requirement of Energy (ROE) for four test scenarios

The solar panel sizing for the required energy in pure solar, HRES, IoT-PS, and IoT-HRES is utterly different as the ROE varies for all the test scenarios. Moreover, with the degrading value of ROE, the system demands lesser solar panels, which proves itself to be an intuitive step to cut down the investment cost.

2) *Comparative study of COE*: We analyze the costs associated with the design of the mentioned four types of lighting systems to sustain the load demand. The sizings of the solar panel for the required energy in pure solar [36] / HRES[37] / IoT-Solar[16] / IoT-HRES are entirely different. As the solar panel contributes to the highest share of investment for a standalone system, reducing the size of the panel would be an intuitive step to cut down the investment cost. In this regard, the cost of energy for solar panels in each scenario is estimated analytically and presented below. The cost of energy (COE) determines the cost of the solar panel to provide the ROE stated by a specific standalone system.

The selection of a solar PV module depends on many factors, including cost and efficiency. The solar module price varies slightly from manufacturer to manufacturer. To illustrate the cost-effectiveness of our proposed system, we consider establishing the PV sizing and the cost of a PV panel for a pure solar-based highway lighting system. To determine the cost of the solar module in a pure solar-based lighting system, we assume the Full light power is 96W. Total watt-hour ratings of the system is 960Wh (96W x 10 hours). The Actual power output of a PV panel is 15 Watt (Peak power rating = 20 x Operating factor = 0.75). The power used at the end is 12.15 Watts (actual power output of a panel x combined efficiency = 15 x 0.81). The energy produced by one 20Wp panel in a day is 97.2Wh or watt hours (Actual power output x 8hours/day = 12.15 x 8). The number of solar panels required to satisfy the estimated daily need is 10 panels (Total watt-hour rating/ daily energy produced by a panel =

960Wh/97.2Wh = 9.88). The Cost of PV array is 900 RM (No. of PV Module x Cost per module = 10 x 90 (For a 20Wp panel @ 4.5 RM/Wp (Solar Power, 2019)). Hence, The Cost of Energy for a Pure Solar based lighting system is, $COE_{SOLAR} = 900RM$. The comparative study of HRES, IoT-PS and IoT-HRES is exhibited in the Table I, where IoT-HRES significantly outperform than others due to the same reasoning of ROE.

B. Maintenance Cost Analysis

Monitoring the real-time lamppost functioning status offers additional saving to the highway service providers. The proposed IoT based fault detection system for highway lighting systems continuously analyzes and reports in near-real-time, providing a remote monitoring feature. This feature inhibits malfunction & optimizes the fault recovery operations. In this way, the faulty lampposts can be identified on time along with their location, thus providing an organized recovery action with a well-planned and scheduled repair team.

To prove the efficiency of the proposed automated maintenance system over traditionally practised manual maintenance, we perform a brief maintenance cost analysis in this section. As we know, manual maintenance differs from one to another area depending on the willingness and activeness of the highway service providers. Hence we consider the most practised manual maintenance, which is usually done every two years. We consider, the Highway length, $H_L = 50$ km; the sector length, $S_L = 1$ km; Gap between lampposts, $G_L = 37$ meter or 0.037 km. Therefore, the number of lampposts in one sector, $N_S = S_L / G_L = 27$ (rounded). And the number of lampposts in highway, $N_H = H_L / G_L$.

Here, we calculate relevant costs and compare them between traditional and proposed automated maintenance systems. The operational cost for maintenance, C_{OPM} is defined by, $C_{OPM} = C_R + C_L$ Where, the rental cost of equipment (e.g. the sky lift rental) to execute the maintenance service (C_R) added with the labour cost per day (C_L). The maintenance time, (T_M) plays a significant role in the total cost for maintenance. It is represented by the number of lampposts that need to be serviced in the highway, N (can be either N_S or N_H) divided by the maximum number of lampposts that can be serviced per day (N_M). Hence, $T_M = N / N_M$. We refer to (Ramli, Arief, Aziz, 2016) for the reference values of C_{OPM} & N_M . The total cost of Maintenance (C_M) is represented by, $C_M = C_{OPM}T_M$. This derives the total cost for maintenance for a particular stretch of highway, while the cost per lamppost maintenance (CPLM) is calculated as $C_{PLM} = C_M / N$. Figure 4 presents the comparative cost of traditional and automated maintenance with respect to a probability of maximum 50% faulty lamppost throughout the test period.

C. Reliability Analysis

In this section, we analyse the reliability of four test scenarios to check how adverse weather affects solar panel energy generation. We use the global formula [38] in below to estimate the electrical energy generated in the output of a

TABLE I
COMPARISON OF HRES, IoT-PS AND IoT-HRES WITH RESPECT TO COST ANALYSIS

R_b	E_{HERS} [Wh]	E_{IoT-PS} [Wh]	$E_{IoT-HRES}$ [Wh]	N (HERS)	N (IoT-PS)	N (IoT-HRES)	CoE_{HERS} [RM]	CoE_{IoT-PS} [RM]	$CoE_{IoT-HRES}$ [RM]
0%	960	96	96	10	1	1	900	90	90
10%	924	182.4	175.56	10	2	2	900	180	180
20%	888	268.8	248.64	10	3	3	900	270	270
30%	852	355.2	315.24	9	4	4	810	360	360
40%	816	441.6	375.36	9	5	4	810	450	360
50%	780	528	476.16	9	6	5	810	540	450
60%	744	614.4	476.16	8	7	5	720	630	450
70%	708	700.8	516.84	8	8	6	720	720	540
80%	672	787.2	551.04	7	9	6	630	810	540
90%	636	873.6	578.76	7	9	6	630	810	540
100%	600	960	600	7	10	7	630	900	630

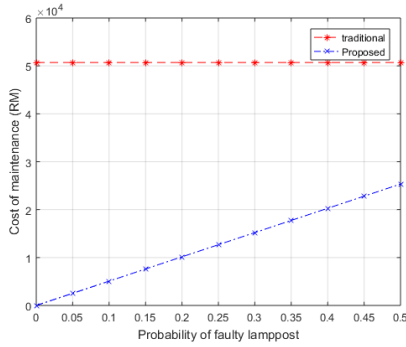


Fig. 4. Comparative maintenance cost of proposed vs. traditional lighting system.

photovoltaic system,

$$E = ArHPR \quad (4)$$

Where E , A , r , H , and PR defines energy (kWh), total solar panel Area (m^2), the solar panel efficiency (%), annual average solar radiation on tilted panels, and the performance ratio coefficient for losses, respectively.

A reliable solar lighting system produces electricity consistently to meet user demand. However, two main parameters affect the solar panel performance: solar panel efficiency and solar insolation. Apart from the panel efficiency, which is approximately fixed by the manufacturer, the reliability of the solar system predominantly depends on the solar insolation, which represents the hourly average radiation intensity of sunlight. The actual energy generated by the solar panel considering energy loss by varying solar insolation,

$$E_{AS} = E_S - \alpha E_S \quad (5)$$

Here, E_{AS} is the Actual Power we can get from the solar panel, E_S is the rated power expected from a solar panel, and α represents the probability of adverse weather which ranges from 0 to 1. The increased value of α increases the chances of energy deficiency in a pure solar system. In reality, the value of solar radiation H , which depends on α , never becomes exactly zero as the solar panel mostly keep generating energy even if it is cloudy or rainy. However, compared to the sunny days, cloudy/rainy days have 90% less sunlight, and

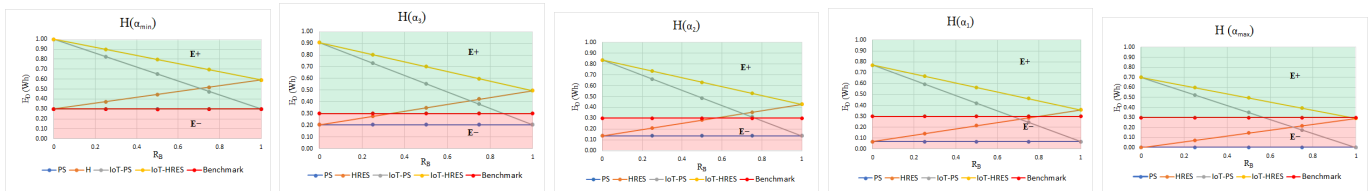
their energy production also reduces thereby. Hence, for our proposed system, we are expecting the solar panel to provide 960Wh per day where the maximum solar radiation is 5.69 (approximated) (SI, 2019) considering the minimum effect of α . Additionally, to calculate the reliability of solar panel, we consider a range of H where $H_{max} = 5.69$ kWh/m² (α_{min}) and $H_{min} = 3.5$ kWh/m² (α_{max}). Here, α has been varied as α_{min} , α_3 , α_2 , α_1 & α_{max} for the decreasing value of solar radiation H .

Below, we compare the four test scenarios according to different road busyness for the evaluation of the reliability for each system. The energy difference between rated energy and actual energy for different solar radiation & road busyness has been calculated, normalized, and plotted in Figure 5.

D. Renewable Energy Re-Distribution

The technical feasibility of solar based energy systems depends on the solar radiation, which is extremely variable and fluctuating. Different parameters of meteorological conditions define the distribution of solar radiation in a site. Typically, solar energy's decentralized application, particularly in HLS, yields a maximum autonomy of 3 to 5 days. The system generates a generous amount of surplus energy when it does not experience any adverse weather. Conversely, some areas might face severe atmospheric conditions requiring emergency attention for additional energy to run the HLS. Herein, a small contribution from a single decentralized lamppost may not prove a significant role in energy sharing between different regions. However, a centralized, interconnected HLS can re-distribute the energy from its local reservoir with additional facilities like charging electric vehicles (EVs) or even feeding the energy to the national grid.

Looking at the reliability analysis of our proposed system in Figure 5, in any given road busyness between (0 to 1), almost all the test scenarios experience energy surplus in some extent depending on the type of HLS. Although the incorporation of wind turbines merged with the concept of IoT helps the proposed system sustain its operation in maximum hostile weather, it also indicates the highest E+ feature in maximum solar radiation. The proposed MIoT based lamppost network can utilize the data regarding its overall energy generation, utilization, and the surplus energy or shortage to constantly



(a) Reliability of four test scenarios at α_{\min} (b) Reliability of four test scenarios at α_3 (c) Reliability of four test scenarios at α_2 (d) Reliability of four test scenarios at α_1 (e) Reliability of four test scenarios at α_{\max}

Fig. 5. Reliability of four test scenarios at five different levels of α

filter and improve the system design with improved efficiency and reliability. Integration of wireless charging with the aid of UAVs can provide prompt charging services, thus upgrading the future green highways to the next level.

V. CONCLUSION

This paper has presented a UAV-enabled renewable energy re-distribution mechanism via a multi-scale IoT paradigm, which is envisioned to pave the way for 6G-oriented green highway energy management. Specifically, we have proposed a multi-scale IoT-based framework to manage renewable energy generation and consumption suitable for highway operation. We have presented intra- and inter-lamppost communications platforms to develop renewable energy harvesting mechanisms exploiting the gathered data from the massive number of networked sensors. We have also explained a data-driven energy re-distribution technique via charging and discharging mechanisms across the lampposts assisted by parametric-oriented energy sensing and distribution route allocation. In order to examine the feasibility of the proposed system, we have conducted the cost and reliability analyses, which reveals favorable performance in terms of ROE, COE, and the energy plus (E+) feature in a variety of conditions. This work envisages a step forward of harnessing a 6G paradigm to enable super-connected green highway energy management.

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