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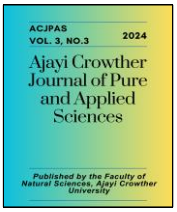
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Article

Development of Power Models for the Integration of Multiple Renewable Energy Resources for Ajayi Crowther University's Power System Flexibility

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Abstract

The global energy landscape is rapidly evolving, driven by the pressing need to reduce greenhouse gas emissions and transition towards sustainable, renewable energy sources. In this context, Ajayi Crowther University (ACU), like many institutions and utilities worldwide, is faced with the challenge of integrating multiple renewable energy resources into its power system while maintaining grid reliability and flexibility. This research focuses on the development of comprehensive power models tailored to the specific needs of ACU's power system to facilitate the efficient integration of various renewable energy sources. The study begins by identifying the existing renewable energy resources available at ACU, including solar photovoltaic (PV), wind and mini-hydro systems, and potential biomass sources. Detailed data collection and monitoring are undertaken to gain insights into the intermittent nature of these resources and their respective energy generation profiles. To address the challenges associated with the intermittent nature of renewable energy sources, the proposed Renewable Energy Hybrid Distribution Generation (REHDG) modelling approach is based on a probabilistic framework, which captures the inherent uncertainty and stochastic nature of solar irradiance and temperature, wind speed, water flow, and bio-waste estimation. The power output of solar, wind, hydro, and bio-waste is treated as random variables and modelled with appropriate probability distribution functions (PDFs). These models enable the assessment of system performance allowing ACU to better anticipate energy generation fluctuations. Ultimately, this research aims to provide ACU with a tailored, data-driven approach to optimize its power system's integration of multiple renewable energy resources. The developed power models and control strategies will serve as valuable tools for achieving grid reliability, reducing greenhouse gas emissions, and enhancing sustainability in line with ACU's commitment to a greener energy future.

Keywords: Renewable Energy Sources; Grid Reliability; Power Models; Intermittent Nature; probability distribution functions (PDFs); Distributed Generations.

1. Introduction

The integration of multiple renewable energy resources into power systems has gained significant attention in recent years due to the growing need for sustainable and clean energy solutions. The ACU power system, like many others, is faced with the challenge of incorporating renewable energy resources while maintaining system flexibility and reliability. Developing power models for the integration of multiple renewable energy resources for power system flexibility at ACU is of paramount importance to explore potential solutions and strategies for renewable energy utilization and ensure a stable power supply.

Renewable energy resources, such as solar, wind, biomass, and hydroelectric power, offer numerous advantages including environmental sustainability, fuel diversification, and reduced greenhouse gas emissions. The goal of the clean energy transition is decarbonization. Carbon dioxide emissions reached 11.2 gigatonnes (Gt) in 2022 from oil alone, whereas renewable energy generation emits little to no carbon emissions to power homes, cars and businesses [1]. However, their integration into power systems presents several challenges that need to be addressed. One critical aspect is the need to ensure power system flexibility to accommodate the intermittent nature of renewable energy generation [2]. Solar and wind energy generation, for instance, is dependent on weather conditions and can exhibit significant variability and uncertainty [3]. This intermittency introduces challenges to grid stability and requires advanced strategies for balancing supply and demand, such as energy storage systems and backup power sources [4]. Furthermore, the integration of multiple renewable energy resources necessitates careful consideration of land use and infrastructure requirements. Wind turbines and solar panels require significant land area, which can have implications for the environment, land use planning, and ecosystem conservation [5].Upgrading the existing power grid infrastructure to accommodate the distributed and intermittent nature of renewable energy resources is also crucial [6].This may involve grid modernization, grid reinforcement, and the implementation of smart grid technologies to enhance system flexibility and control [7].

The cost aspects of renewable energy integration are another significant factor to consider. While the costs of renewable energy technologies have been decreasing over time, they still require substantial investments in infrastructure and equipment [8]. With the push to decarbonize economies, the installed capacity of renewable energy is expected to show significant growth to 2050. *Power* grids will need to expand to meet the increasing demand for electricity and *renewable energy*: to achieve net-zero emissions by 2050 [9] The transition to RES, coupled with economic growth, will cause electricity demand to soar—increasing by 40 percent from 2020 to 2030, and doubling by 2050 [10]. Therefore, assessing the economic feasibility, cost-effectiveness, and potential financial implications of integrating multiple renewable energy resources at ACU is an essential component of the investigation.

To address the aforementioned challenges and optimize the integration of multiple renewable energy resources, various research studies have been conducted in the field. These studies have explored different methods and strategies for enhancing power system flexibility, such as advanced forecasting techniques, energy storage systems, demand response programs, and optimal dispatch algorithms [11]. Additionally, they have investigated the environmental impacts, economic viability, and social acceptance of renewable energy integration [12], [13].

The findings of this review will contribute to the development of a comprehensive framework for enhancing power system flexibility and optimizing renewable energy utilization at ACU.

1.1 The Concept of Flexibility in Power System

Flexibility in power systems refers to the ability of the system to efficiently and effectively respond to changes in electricity supply and demand_[8]. It enables the system to accommodate variations in renewable energy generation, manage fluctuations in electricity consumption, and maintain a reliable and stable supply of electricity. The concept of flexibility encompasses various aspects, including the ability to adjust generation and consumption patterns, optimize system operation, integrate diverse energy resources, and incorporate energy storage technologies.

One key aspect of power system flexibility is the ability to balance electricity supply and demand in real-time [14]. This involves the capability to ramp up or down generation capacity to match the fluctuating demand. According to [15], power system flexibility is crucial for maintaining grid stability and ensuring the reliable delivery of electricity. It allows for efficient utilization of renewable energy resources, which are inherently intermittent and dependent on weather conditions.

The integration of multiple renewable energy resources into a power system requires flexibility to accommodate their inherent variability. As highlighted by [16], the intermittent nature of renewable resources such as solar and wind necessitates mechanisms that can quickly respond to changes in generation output. Effective minimization of emission in remote sites with renewable energy potential may be increased up to 95 percent of load demand. Solar irradiation has direct impact on enhancement of PV efficiency but temperature has inverse impact on the PV efficiency. The operational analysis of optimal energy storage mix to maximize the exergy efficiency, environmental and sustainable benefits for regional and national power grid is an ongoing research goal. This requires grid flexibility to balance the supply-demand equation and minimize the need for conventional backup power plants.

Furthermore, power system flexibility can be enhanced through advanced control and optimization techniques. The authors in [17]emphasize the importance of flexible operation strategies, such as demand response, smart grid technologies, and advanced energy management systems. These approaches enable the effective integration of renewable energy resources and facilitate the dynamic adjustment of power generation and consumption patterns.

Energy storage systems play a crucial role in enhancing power system flexibility. Rugolo and the authors in [18]highlight that energy storage technologies, such as batteries and pumped hydro storage, can store excess renewable energy during periods of high generation and release it during times of low generation or high demand. This enables the system to balance supply and demand, smooth out intermittent generation, and provide ancillary services to support grid stability.

1.2 Integration of Renewable Energy Resources

Zinaman *et al*. [19] explains why renewable energy integration field has witnessed a significant surge in research in recent years, with a particular emphasis on various dimensions of this transition within the power sector. This growth in literature has been notably rapid and continues to gain momentum. While a substantial portion of this literature delves into technical and engineering aspects, an increasingly significant portion focuses on the strategic aspects such as planning, market dynamics, institutional frameworks, regulatory policies, economic considerations, and innovative business models that are integral to the shift towards greater adoption of renewable energy sources. The penetration of Renewable Energy Sources (RESs) to national grids is increasing in many countries. For instance, [20] predicted that, in future, wind power will cover and exceeds a load of Denmark in some low-demand hours throughout the year. Achieving a high level of renewable energy integration in the power grid entails several essential prerequisites, notably accurate forecasting and effective load management. These elements play a pivotal role in the context of smart grids, as they are crucial for facilitating demand response mechanisms. Incorporating intermittent energy sources like RESs and Electric Vehicles (EVs) poses significant challenges to the system due to their inherent variability and unpredictability during operation. While predictable power fluctuations can be managed through advanced scheduling techniques, the element of uncertainty necessitates the presence of backup solutions, such as energy storage systems or grid connections. These backup options are essential to maintain the necessary balance between electricity generation and consumer demand [21].

1.3 Challenges of Large Integration of Renewable Energy Resources

The main challenging issues faced by the grid as a consequence of the increased integration of RES include operational, forecasting, scheduling, interconnection standards transmission, and distribution [22]. Optimal locations for wind or solar power generation, based on weather conditions, may often be situated far from existing transmission lines or consumers. To fully leverage these renewable sources in ideal circumstances, the establishment of new transmission infrastructure becomes imperative. However, it's worth noting that the development of transmission infrastructure is a time-consuming process with lengthy planning and implementation phases, in addition to being a costly endeavor.

Conversely, the distribution side of the energy equation faces several formidable challenges, including the requirement for enhanced protection, control, automation, Micro-grid (MG) capabilities, and effective management. To ensure the seamless integration of intermittent energy sources through interconnection, a heightened level of standardization becomes essential. An illustrative example of operational challenges arises in situations of high wind speeds, which can lead to over-generation conditions or necessitate turbine controllers to curtail generation in order to prevent damage to the turbine blades. This curtailment, in turn, results in a shortage of electricity generation, which must be compensated for, in order to maintain frequency regulation [22]. Energy systems vary from country to country and region to region. Both centralized and decentralized approaches must be used to facilitate the integration of renewable energy sources. Before implementing any changes to energy supply systems that involve greater integration of renewables, a detailed assessment of the availability of renewable energy resources must be made. The sustainability of existing technologies, institutional, economic, and social constraints, potential risks, and the need for new skills and capabilities must be assessed [23]. For the successful implementation of renewable energy sources in each infrastructure (transport, housing and communal services, industry and agriculture), it is necessary to take into account technological, socio-organizational, and economic conditions [23]. Applying an integrated approach to the energy system can be a prerequisite for an efficient and flexible process of renewable integration. The integrated approach involves mutual support in the energy system, intelligent planning and management, and unified long-term planning. The application of the integrated approach will allow for more closely interconnected provision of electricity [24]. Renewable energy technologies are undergoing development and implementation across various sectors, including transportation, residential, communal, industrial, and agricultural domains. Addressing both technical and non-technical challenges associated with renewable energy sources has the potential to expand their utilization across all segments of industrial production. Within each sector, disparities exist related to the current state of renewable energy adoption, the diverse range of energy system configurations, the infrastructure in use, opportunities for enhancing renewable energy integration, unresolved transformation issues, and prevailing trends influencing national and local preferences and cultures.

It is important to note that intermittent power sources, like renewables, require storage systems to balance the grid load alongside conventional energy sources and uphold grid reliability. One approach involves diversifying co-located renewable resources for power generation, while another entails utilizing geographically dispersed renewable utilities. The aggregation of either of these strategies contributes to mitigating the intermittency impact on the grid.

To guide the prioritization of renewable energy technologies concerning commissioning, research and development (R&D), and policy setting, national renewable energy roadmaps are essential. Multi-Criteria Decision Making (MCDM) Models, as commonly advocated in the literature, serve as valuable tools for the decision-making process. This research intends to develop power models for the integration of multiple renewable energy resources for ACU power system flexibility taking into consideration the available renewable resources within the campus.

2. Materials and Methods

2.1 Developed Algorithm

To effectively plan the integration of renewable energy resources into a REHDG (Renewable Energy Hybrid Distributed Generation) scheme, the development of renewable resources power models for the purpose of quantifying the resources of the site is very important [25]. These required two levels of synergy. Firstly, appropriate models are needed to describe the characteristics of solar, wind, hydro, and bio-waste potential at a given site. Secondly, models must be developed to estimate the potential power that can be harnessed from these resources. A typical REHDG for the site will use photovoltaic, wind, biomass and micro-hydro models that use solar irradiance, wind speed and bio-waste and water flow data.

There are two main approaches to modeling: deterministic and stochastic. Deterministic models use chronological time series, but they can be memory- and time-consuming. If a particular year selected to characterize a site happens to be unusually good or poor, the optimization may not reflect the actual resource profile accurately. To address this issue, the proposed REHDG modeling approach is based on a probabilistic framework, which captures the inherent uncertainty and stochastic nature of solar irradiance and temperature, wind speed, water flow, and bio-waste estimation. The power output of solar, wind, hydro, and bio-waste is treated as random variables and modeled with appropriate probability density functions (PDFs). These models enable the assessment of system performance.

A REHDG system typically consists of multiple solar photovoltaic generators (solar park), wind generators (wind farm), hydraulic turbines, and bio-waste power generators (biomass power system). Effective minimization of emission in remote sites with renewable energy potential may be increased up to 95 percent of load demand. Solar irradiation has direct impact on enhancement of PV efficiency but temperature has inverse impact on the PV efficiency. The operational analysis of optimal energy storage mix to maximize the exergy efficiency, environmental and sustainable benefits for regional and national power grid is an ongoing research goal [26]. The performance of such a system is evaluated using appropriate probabilistic models. Solar irradiance is typically modeled using a Beta distribution function, wind speed with a Weibull distribution function, hydropower with a Gamma distribution function, and bio-waste resource data with a Log-normal distribution function. Actual measured data is used to model these four distribution functions, and the model parameters are estimated using the Maximum Likelihood Estimation (MLE) technique. Multiple distribution functions are fitted to the data clusters to capture seasonal, monthly, daily, and hourly variations in solar irradiance, wind speed, bio-waste, and average annual rainfall. This study uses actual field-measured data in computing solar (α_t, β_t) and wind (c_t, k_t), rainfall (ϑ_t, v_t), and bio-waste (μ_t, σ_t) probability density functions (PDFs) using Maximum Likelihood Estimation (MLE) technique.

The likelihood equations to obtain likelihood values of the parameters α_t, β_t, c_t, k_t, ϑ_t, v_t, μ_t, and σ_t are given as:

$$F = [F_1(\alpha_t, \beta_t), F_2(\alpha_t, \beta_t), F_3(c_t, k_t), F_4(c_t, k_t), F_5(\vartheta_t, v_t), F_6(\vartheta_t, v_t), F_7(\mu_t, \sigma_t), F_8(\mu_t, \sigma_t)]^T$$

The procedure for obtaining the Beta, Weibull, Gamma and Log-normal distribution function parameters is described with the following steps:

1. Load the historical data of S_i, V_i, R_i and B_i for $i = 1 \ldots n$.

2. Initialise with appropriate values of $\alpha_t^{(0)}$, $\beta_t^{(0)}$, $c_t^{(0)}$, $k_t^{(0)}$, $v_t^{(0)}$, $\vartheta_t^{(0)}$, $\mu_t^{(0)}$, *and* $\sigma_t^{(0)}$.

3. Put $\alpha_t^{(0)}$, $\beta_t^{(0)}$, $c_t^{(0)}$, $k_t^{(0)}$, $\vartheta_t^{(0)}$, $v_t^{(0)}$, $\mu_t^{(0)}$ and $\sigma_t^{(0)}$ in $F = [F_1(\alpha_t, \beta_t), F_2(\alpha_t, \beta_t), F_3(c_t, k_t), F_4(c_t, k_t), F_5(\vartheta_t, v_t), F_6(\vartheta_t, v_t), F_7(\mu_t, \sigma_t), F_8(\mu_t, \sigma_t)]^T$ to obtain $F1$, $F2$, $F3$, $F4$, $F5$, $F6$, $F7$ and $F8$ and then, obtain $\frac{\partial F(X)}{X}$ (Jacobian Matrix).

4. To solve for $\Delta\alpha_t$, $\Delta\beta_t$, Δc_t, Δk_t, $\Delta\vartheta_t$, Δv_t, $\Delta\mu_t$ and $\Delta\sigma_t$, use the equation

   $$F + \frac{\partial \mathbf{F(X)}}{\mathbf{X}} \Delta\mathbf{X} = 0$$

   Let $X = [\alpha t, \beta_t, c_t, k_t, \vartheta_t, v_t, \mu_t, \sigma_t]^T$.

5. From 4, check for tolerance error as follows:

   $$max\,|\,F_{u(u=1,2)}^{(m)}(\alpha_t, \beta_t), F_{v(v=3,4)}^{(m)}(c_t, k_t), F_{w(w=5,6)}^{(m)}(v_t, \vartheta_t) F_{d(d=7,8)}^{(m)}(\mu_t, \sigma_t)\ | < \varepsilon_1$$

   or $max\,|\,\Delta\alpha_t^{(m)}, \Delta\beta_t^{(m)}, \Delta c_t^{(m)}, \Delta k_t^{(m)}, \Delta v_t^{(m)}, \Delta\vartheta_t^{(m)}, \Delta\mu_t^{(m)}$ *and* $\Delta\sigma_t^{(m)}\ | < \varepsilon_2$.

   Where ε_1 and ε_2 are the maximum allowable error.

6. If step 5 is not satisfied, then

   $$\alpha_t^{(m+1)} = \alpha_t^{(m)} + \Delta\alpha_t^{(m)}$$

   $$\beta_t^{(m+1)} = \beta_t^{(m)} + \Delta\beta_t^{(m)}$$

$$c_t^{(m+1)} = c_t^{(m)} + \Delta c_t^{(m)}$$

$$k_t^{(m+1)} = k_t^{(m)} + \Delta k_t^{(m)}$$

$$v_t^{(m+1)} = v_t^{(m)} + \Delta v_t^{(m)}$$

$$q_t^{(m+1)} = q_t^{(m)} + \Delta \; q_t^{(m)}$$

$$\mu_t^{(m+1)} = \mu_t^{(m)} + \Delta \mu_t^{(m)}$$

$$\sigma_t^{(m+1)} = \sigma_t^{(m)} + \Delta \sigma_t^{(m)}$$

Then go to step 3.

The obtained parameter values that are relevant to power generation embody in them the information concerning the location, terrain, solar, wind, rainfall, and bio-waste profiles of the site under study. The values also define the stochastic models.

ACU aims to evaluate the potential for generating renewable energy at its campus. To achieve this, the development of power models specific to renewable resources is essential as shown in Figure 1. These models will enable the university to assess the amount of power that can be generated from renewable resources such as solar, wind, hydro, and bio-waste. The power output characteristics of each renewable energy source are influenced by various factors. For solar power, the solar irradiance and temperature of the site, as well as the characteristics of the photovoltaic (PV) modules, play a significant role. The main influencing parameter for solar power is solar irradiance.

To estimate the power output of PV modules, a power performance curve is used. This curve represents the relationship between the power output and various factors such as solar irradiance, temperature, and module characteristics. By analyzing this curve, the power output of PV modules during different states or hours can be determined. The power output of PV modules can also be calculated using equations that consider temperature coefficients, ambient temperature, short circuit current, open circuit voltage, and fill factor. These calculations provide a more accurate estimation of the power output based on specific environmental conditions.

In addition to PV systems, other renewable energy resources like wind, hydro, and bio-waste generators should be included in the power models. Each of these resources has its own power output characteristics, which depend on factors such as wind speed, water flow, and moisture content of bio-waste. The development of these renewable resource power models allows for a comprehensive assessment of the potential power generation at ACU. By considering the specific conditions and characteristics of each renewable energy source, the models can estimate the amount of power that can be generated from these resources.

These models also enable the evaluation of the capacity utilization factor (CUF) for each renewable energy component. The CUF represents the efficiency and energy output capability of the power units. By comparing the average power output to the rated power, the CUF provides insights into the effectiveness of each renewable energy source. The selection of optimal renewable energy components is based on the highest CUF criteria. This means that the components with the highest efficiency and energy output are chosen for implementation. By selecting the most suitable components, ACU can maximize the potential power generation from renewable resources.

Furthermore, the power models assist in integrating and balancing the power generation from intermittent resources like solar and wind with the continuous generation from resources like hydro and bio-waste. This integration ensures a consistent power supply that matches the university's load demand.

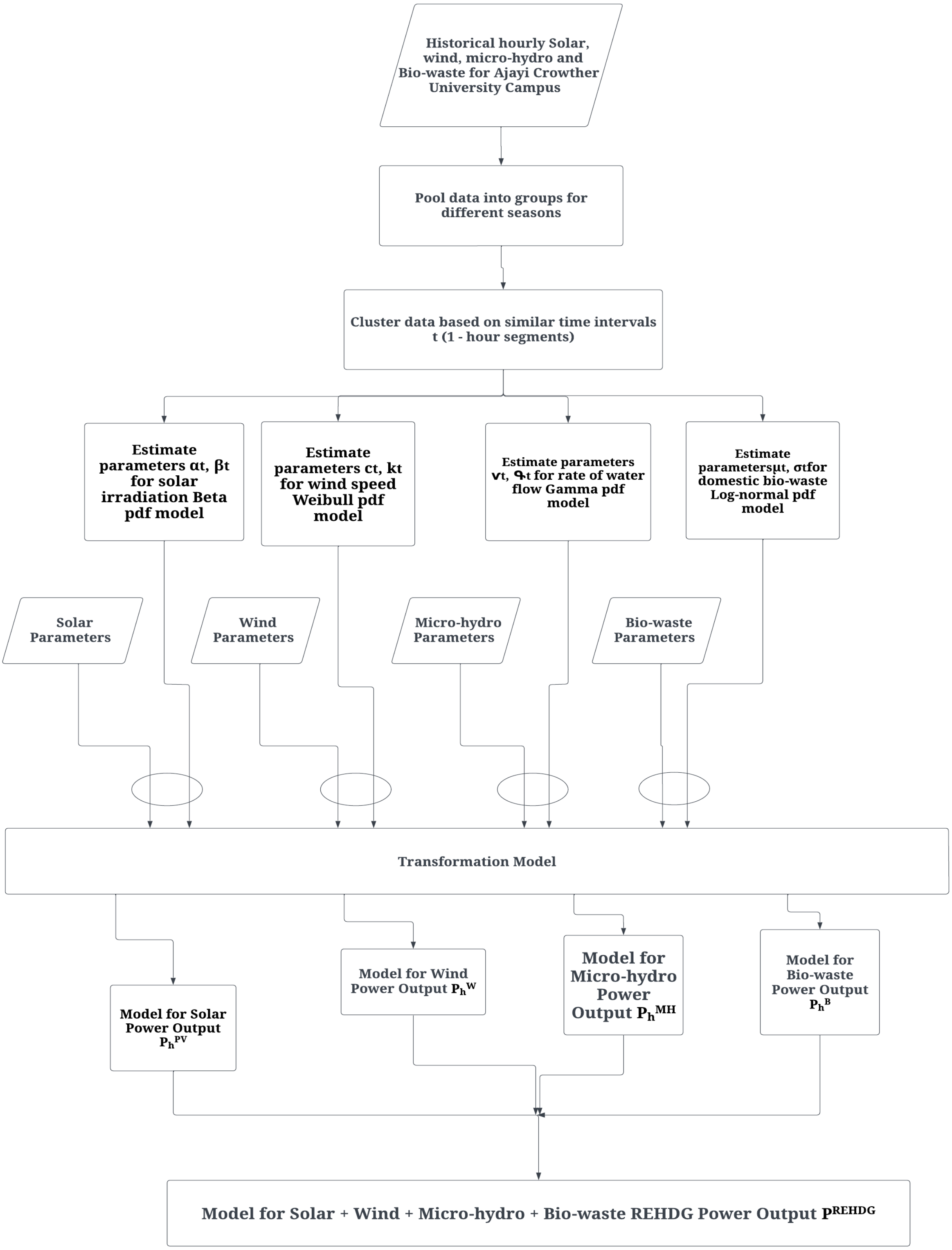

Figure 1: Renewable Energy Resource Power Assessment Model (RERPAM) Steps for a Renewable Energy Hybrid Distribution Generation System (REHDGS)

3. Results and Discussion

For this study, ACU Campus was selected. The data has been analyzed and divided into four seasons which are represented by any day within that season. The day representing each season is further subdivided into 24 1-hour time segments, each referring to a particular hourly interval for the entire season. Hence, there are (24 × 4 = 96) time segments. The available wind speed and solar irradiation data are then utilized to generate typical frequency distributions for each hour in each season. From these data, the maximum likelihood estimated parameters for the Weibull, the Beta, the Gamma and the Log-normal distribution for each of the 24 1-hour segments for 1 day for each of the 4 seasons were computed; thus forming a (24×8) matrix which contains the vectors α_t, β_t,c_t, k_t, v_t, $ϥ_t$, μ_t, and σ_t, where $t \equiv (i, j)$ denotes season i (i = 1 . . . 4) and hour j (j = 1 . . . 24. The seasonal hourly load profile provided hourly peak load as a percentage of the daily peak load. The power output from wind or solar thermal generator unit is determined by the wind speed and solar data at the candidate location respectively.

3.1 Combined Correlation of Wind-Solar-Micro hydro-Domestic Bio-waste Resource with Electricity Load Demand

A per-unit system was used to present the combined availability of the four resources and it was assumed that the wind generation system and the solar generation system have same rated maximum power output. Figure 2 to Figure 5 give values for each season for the correlation coefficient between solar, wind, micro hydro, domestic bio-waste and a combined resource with the electricity load demand and also between wind and solar power profile. For all sites, the wind and load appear somewhat complementary to each other, the solar and load are positively related (this is expected because when solar reaches its peak, the load demand is also high). The combined output has positive correlation throughout.

Using the MLE method of model parameter estimation, the seasonal hourly parameters of wind speed (c, k), solar irradiance (α, β), micro-hydro (v,ϥ) and domestic waste biomass (μ,σ_t) were determined. The maximum likelihood estimated parameters for the Weibull (wind), the Beta (solar), the Gamma (Micro hydro) and the Log-normal distribution (domestic waste biomass) were determined for each of the 24 1-hour segments for 1 day for each of the 4 seasons; thus we get a (24 × 8) matrix which contains the vectors α_t, β_t,c_t, k_t, v_t, $ϥ_t$, μ_t, and σ_t. where $t \equiv (i, j)$ denotes season i (i = 1 . . . 4) and hour j (j = 1 . . . 24) for the site.

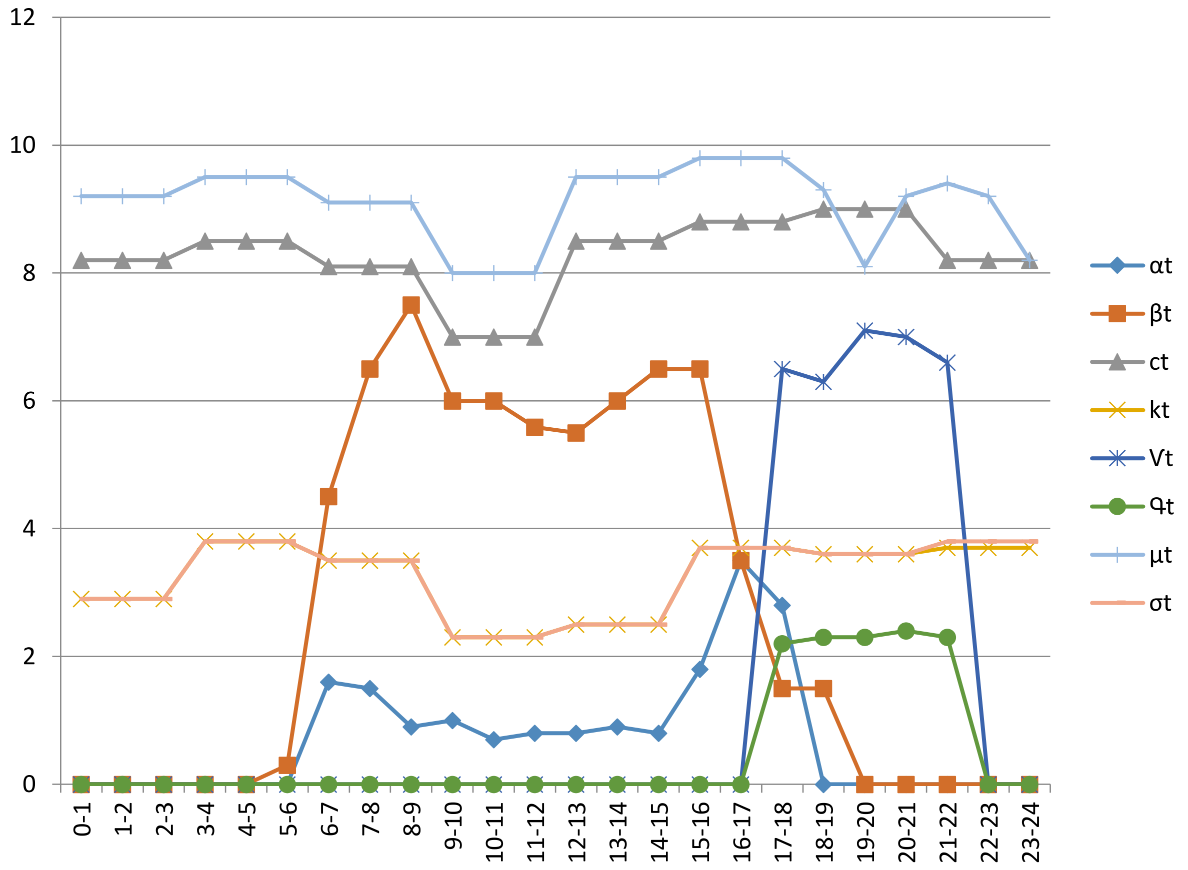

Figure 2. MLE parameters for the Renewable Energy Resources for season 1

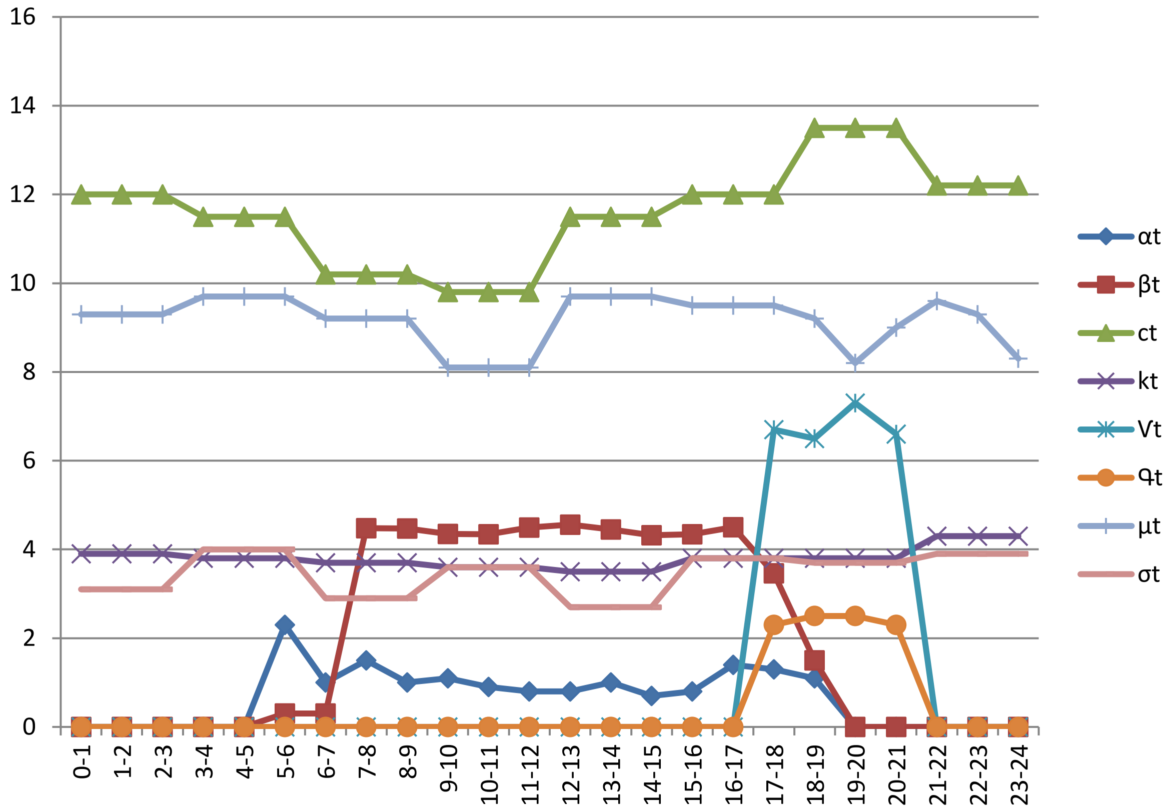

Figure 3: MLE parameters for the Renewable Energy Resources for season 2

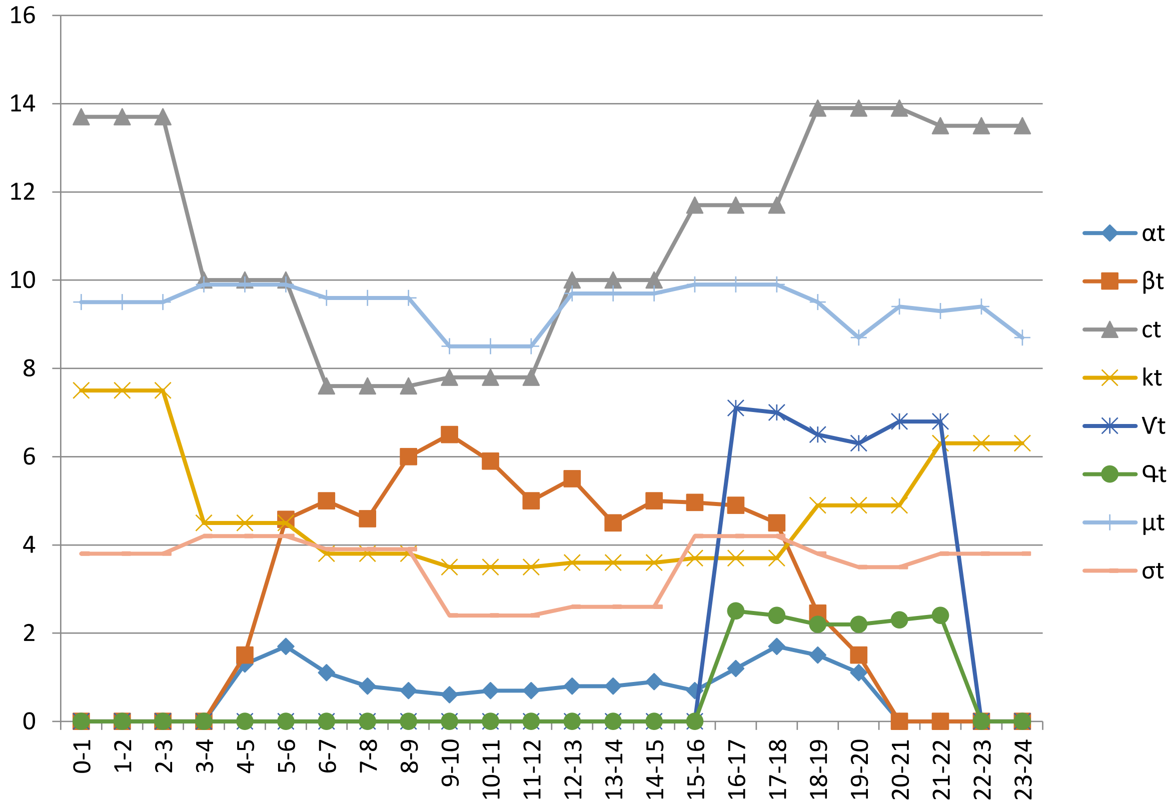

Figure 4: MLE parameters for the Renewable Energy Resources for season 3

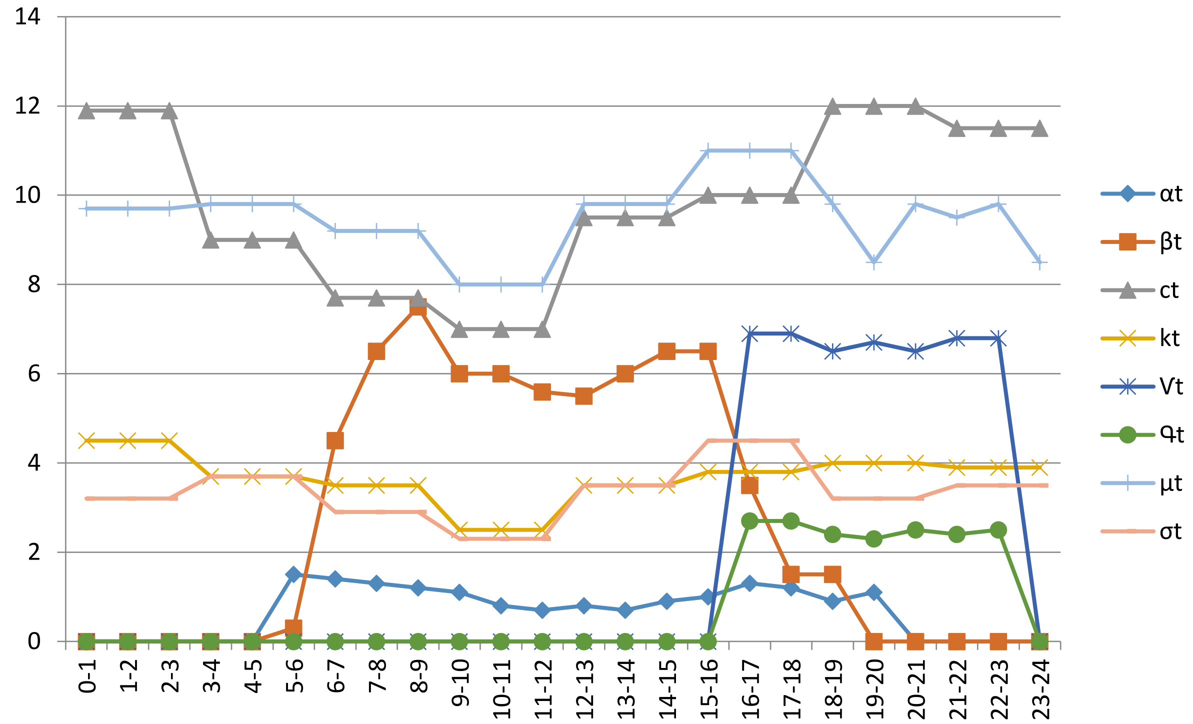

Figure 5: MLE parameters for the Renewable Energy Resources for season 4

The hourly load profile, hourly wind speed patterns; the hourly irradiance, hourly water flow rate and hourly domestic waste conditions are shown in Figure 6(a-d). These time-series data will be used to calculate the available wind power, solar power, micro-hydro power, biomass power and the insufficient or surplus power at each time instant.

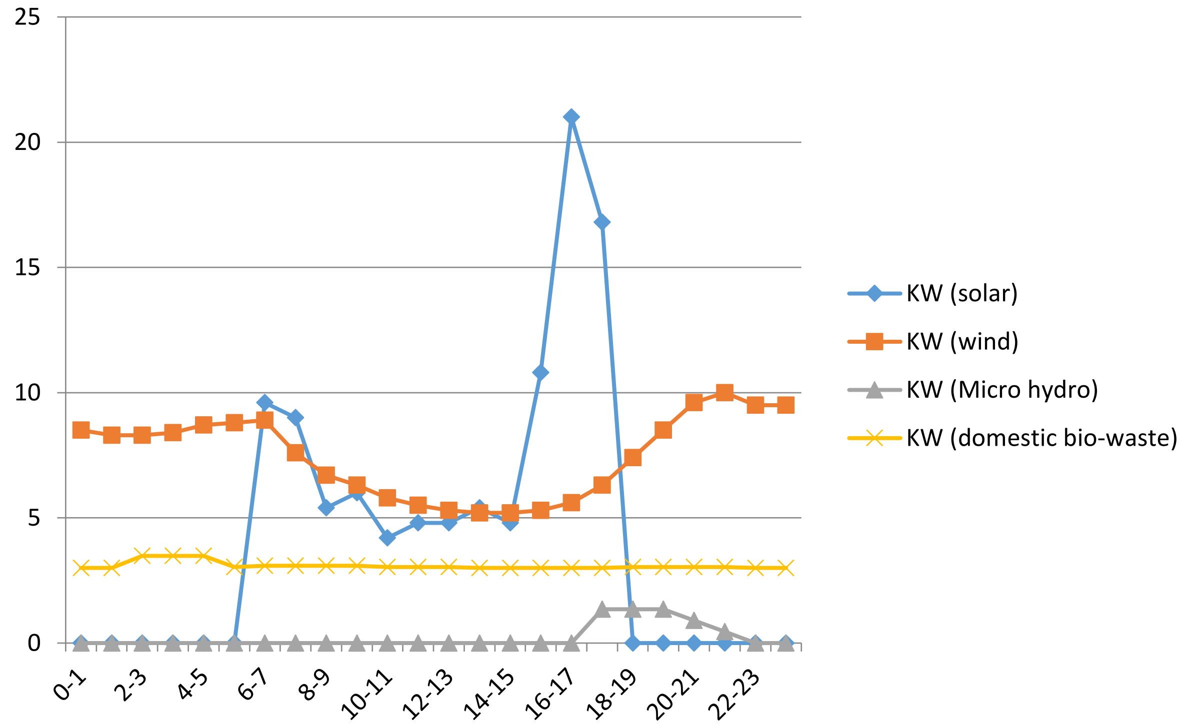

Figure 6a: Hourly renewable power estimate for season 1 (at rated PV=2.4MW, Wind=2.5MW, MH=100KW, DWB=1MW)

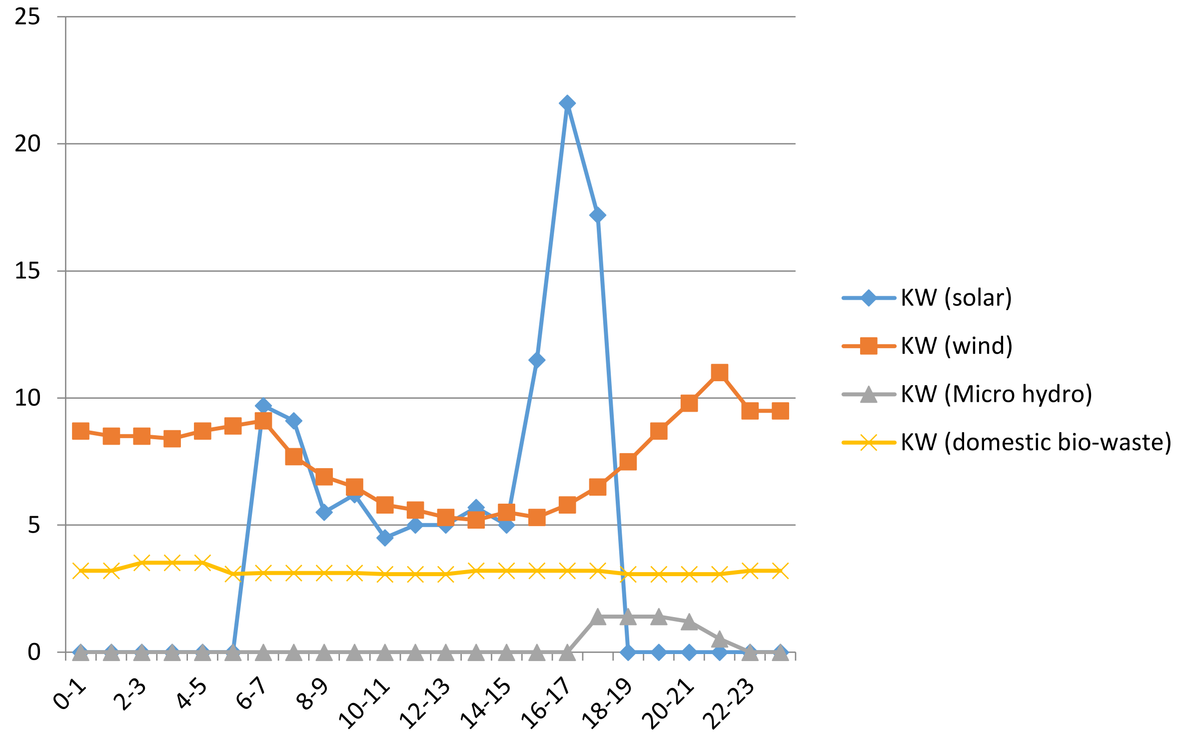

Figure 6b: Hourly renewable power estimate for season 2 (at rated PV=2.4MW, Wind=2.5MW, MH=100KW, DWB=1MW)

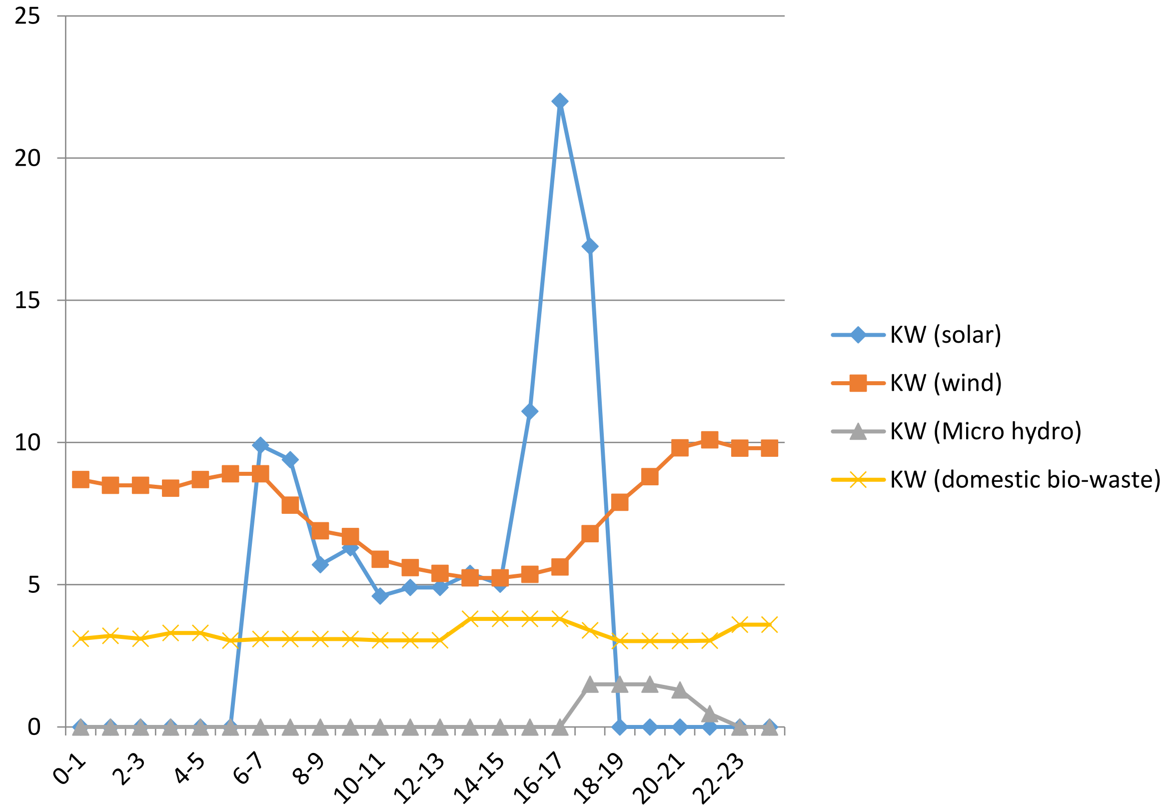

Figure 6c: Hourly renewable power estimate for season 3 (at rated PV=2.4MW, Wind=2.5MW, MH=100KW, DWB=1MW)

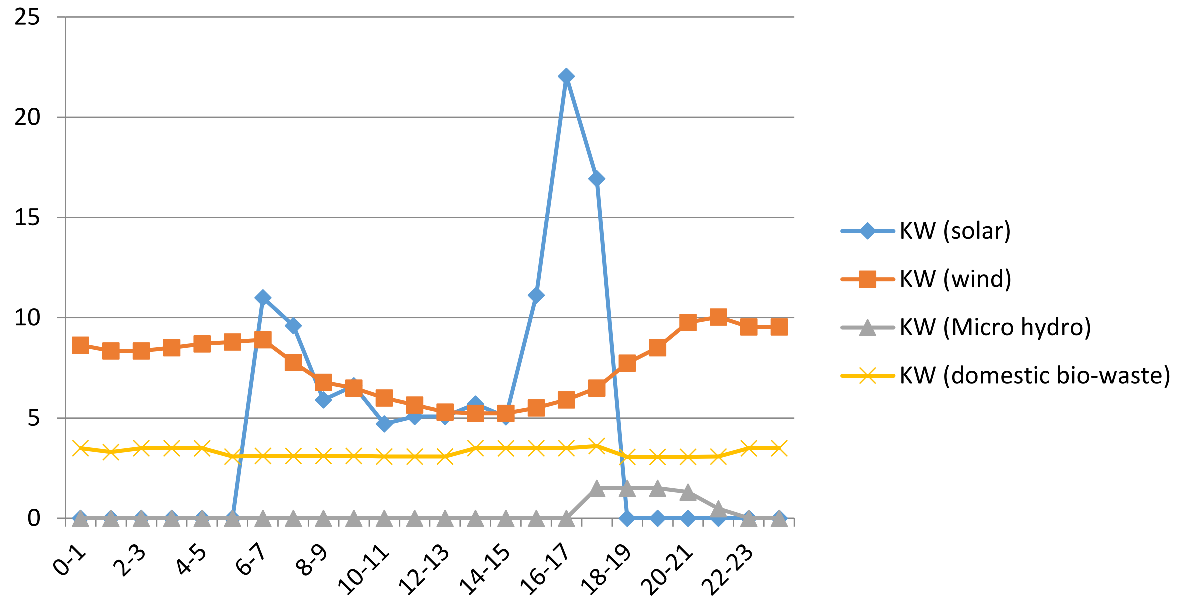

Figure 6d: Hourly renewable power estimate for season 3 (at rated PV=2.4MW, Wind=2.5MW, MH=100KW, DWB=1MW)

The flexibility of power system in ACU campus will benefit tremendously as the amount of power estimated as shown in Figure 6a to Figure 6d will enhance power system in the University with the rated power generated from solar photovoltaic of capacity 2.4MW, Wind energy of capacity 2.5MW, Micro-hydro of capacity 100KW and domestic waste biomass of capacity 1MW.

4. Conclusions

The development of power models for the integration of multiple renewable energy resources in ACU's power system aims to enhance power flexibility and the utilization of renewable energy resources, including solar energy, wind energy, micro hydro, and domestic bio-waste in hybrid distribution generation systems. To achieve this, the power models will incorporate various enhancements such as advanced wind and solar forecasting tools to accurately predict the output and ramping requirements of renewable sources. These tools will enable better planning and grid management, ensuring a stable power supply despite the intermittent nature of renewable energy. Sophisticated grid monitoring systems will be implemented to monitor the performance and behavior of the integrated renewable energy resources in real-time. This will facilitate effective control of the power system, minimizing over-generation and curtailment of excess renewable energy.

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