**International Journal of Sustainable and Green Energy**
2021; 10(3): 92-98
http://www.sciencepublishinggroup.com/j/ijsge
doi: 10.11648/j.ijrse.20211003.12
ISSN: 2575-2189 (Print); ISSN: 2575-1549 (Online)

# Energy Demand and Its Implication on Wind/PV System Sizing in Machakos, Kenya

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**To cite this article:**
Kennedy Muchiri, Joseph Ngugi Kamau, David Wafula Wekesa, Churchill Otieno Saoke, Joseph Ndisya Mutuku, Joseph Kimiri Gathua. Energy Demand and Its Implication on Wind/PV System Sizing in Machakos, Kenya. *International Journal of Sustainable and Green Energy*. Vol. 10, No. 3, 2021, pp. 92-98. doi: 10.11648/j.ijrse.20211003.12

**Received**: August 4, 2021; **Accepted**: August 17, 2021; **Published**: August 24, 2021

**Abstract:** Energy is an essential factor underpinning all elements of economy in the society. Its utilization greatly depends on the individual's lifestyle and habitation. In rural areas, people use less electronic appliances compared to urban areas. However, the rapid development in technology and variety of applications have triggered the desire for more power in both rural and urban regions. To meet the energy demand, the world's generation capacity has to keep growing. Renewable energy sources offer a better solution in quenching this demand. This paper presents the findings on energy utilization and a suitable sized wind/PV system model for an average rural household in Machakos. Energy demand assessment was done using probability sampling which involved clustering and random selection of households. The range of daily energy load in Machakos was found to be 0.052 to 4.23 kWh with most of the households consuming less than 1.5 kWh in a day. The daily average energy consumption for the three selected zones namely; Katheka-kai, Kiandani and Kathiani were 1.092, 0.99 and 1.4 kWh respectively, with an average load of 1.161 kWh. Over 50% of the households consume less than 1 kWh per day where the average loads were 0.56, 0.59 and 0.595 kWh respectively, with a daily average of 0.582 kWh. A wind/PV systems was sized for a sample household with a load of 0.588 kWh. Based on the minimum month solar insolation of 4.677 kWh/m$^2$ and the available wind speed range of 1.0-10.0 m/s in the sites, a stand-alone wind/PV hybrid system was sized with component sizes as: 12 V, 165 W Panel, 12 V, 250 AH battery, 12 V, 225 W inverter and a wind turbine with a cut in, rated and cut-off wind speeds of 1.0, 5.0 and 15.0 m/s.

**Keywords:** Energy Demand, Load Profile, Rural Electrification, PV Sizing, Wind Turbine Sizing

## 1. Introduction

Provision of energy to any developing county is important to alleviate poverty and spur its social-economic development. This fact has been acknowledged by the UN in their Sustainable Development Goals built on the millennium development goals [1, 2]. Eradication of energy deficiency can be done through the execution of sustainable development goal number 7, which aims at providing affordable and universal access to electricity by 2030 [3]. Even though it is quite costly to achieve this using the extended grid connection only for the scattered and sparsely populated rural areas, It is necessary to ensure a balance between the energy demand and the energy supply for consumers [4-6]. Estimation of the impact of electrification on development has been discussed in literature. Studies on rural electrification have reported it as a factor that leads to improvement in employment, education, agriculture and health sectors [7-9]. Much of this energy demand comes from developing nations [10]. The high cost of energy creates a heavy burden to low income households in developing countries. This makes them spend over 20% of their income on energy, policy makers as a result view energy poverty in communities with a sense of urgency [11]. To mitigate this poverty, a solution lies in creating energy access through exploitation of alternative sources of energy available in nature like solar, wind and biomass [12]. The demand for more energy is always increasing depending on the living standards of consumers. This demand therefore calls for a new technology of energy generation to reliably ensure continuous power supply to consumers. Prior to designing, sizing and installation of renewable energy systems, thorough load demand assessment and analysis is important [13-15]. Previously, energy demand evaluations have successfully been done in Kenya and other African countries forming basis for successful implementation of renewable energy systems. Diemuodeke *et al.*, 2017 [16] assessed domestic energy demand of coastline of Niger Delta in Nigeria. HOMER hybrid optimization software was used to estimate the demand for determining the best PV system reporting a daily load demand estimate of 5.640 kWh. Bilal *et al.*, presented an optimal sizing problem of solar-wind system design with a storage to minimize the loss of power supply probability at Potou, Senegal's north coast. Load profile influence on the system design was investigated and a high cost implication on optimal configuration was reported [17]. Energy demand assessment done in Kikwe village in Tanzania reported a total daily energy demand of 601.335, 54.425, 70.01 and 31.254 kWh for residential, community, commercial and small-scale industrial loads respectively. The whole village daily load was 757.024 kWh with a peak load of 56 kW and a minimum of 5 kW. A daily average energy demand for a small-scale house was reported as 1.2 kWh [13]. This closely compares to the average rural households in Machakos with most consuming below 1.5 kWh per day. By 2015, the installed capacity of Tanzania was 1129 MW which was not enough to serve both rural and urban areas due to high consumption rate [18]. Sparse demography was noted as one of the factors that partly hinder national grid development in rural and semi urban areas making it costly to setup [19-21]. Such demographic feature in a country make renewable sources like wind and solar promising in creating of energy access to consumers [22, 23]. Magambo, 2010 [24] did a study on household electricity demand and consumption patterns in Nairobi-Kenya middle income class estates. He reported an average monthly energy consumption of 208 kWh and an annual average of between 285 W and 3.6 kW power demand per household. This is comparable to the average energy loads for households in Machakos region.

Energy access directly influences the development index resulting to improved life expectancy, education level and better standards of living [25, 26]. Innovative ways therefore need to be sought to create access to clean and safer energy from renewable sources like solar and wind which are readily available and vast in nature. Most of the available studies have only dealt with solar and wind energy demand on large scale basis. A gap still exists for low scale energy consumption load patterns. To bridge this gap, this study focused more on energy demand on small scale basis by considering household with energy load less than 1 kWh per day. Energy load demand in three selected rural zones of Machakos region is presented. Thereafter, a sample average household load from the three zones is used to size a wind-PV hybrid system as a model for other rural households in the County.

## 2. Materials and Methods

In this study, descriptive research design approach was adopted where data was gathered by use of questionnaires and interviews. The analyzed result provides insights into the why and how of research enabling the researcher draw valid inferences and give recommendations pertaining the problem under study [27].

### *2.1. Target Population and Resource Energy Potential and Distribution*

This study was done in three sites, Katheka-kai and Kiandani in Machakos sub-county and Kathiani in Kathiani sub-county. Machakos County is located in the equatorial zone, a region which has huge potential of solar radiation and significant wind resource enough to support renewable hybrid energy systems. The annual yearly solar insolation in the region is 2130 kWh/m$^2$ an average of 5.8 kWh/m$^2$/day. Of much consideration in system sizing in this study is the minimum insolation which occurs in the month of July. The minimum insolation was 145 kWh/m$^2$ an average of 4.677 kWh/day. This implies that Machakos regions experience 4.667 solar peak hours at 1 kilowatt in a day in the month of July. These are the solar peak hours, a key parameter in PV system sizing. Wind resource in the county has its wind speeds ranging between 0.5 m/s and 10.0 m/s presenting a positively skewed distribution with $c$ and $k$ Weibull parameter values of 2.68 m/s and 1.9, respectively. Cumulatively, 98.5% of wind speeds ranged from 0.5 m/s to 5.0 m/s forming the predominant range of wind speeds available in the region. The maximum wind power density was 200 W/m$^2$ and an average power density range of 15-25 W/m$^2$. The wind energy was well complemented by the solar energy which had an average daily power density range of 390-650 W/m$^2$ and a maximum range of 1030-1556 W/m$^2$.

According to the 2019 Kenya population and housing census [28], Machakos County has an approximate area of 6037.2 sq. km occupied by a population of over 1,421,932 people. This translates to a population density of 236 people per sq. km. Of much interest in this research is Machakos and Kathiani sub counties which are among the top most populated areas. Machakos Sub-county has an area of 280.1 Sq. km with a population of 170606. This translates to a population density of 609 people per sq. km. Kathiani sub-county with an area of 204 sq. km closely follows with a population of 111890 people. This makes a population density of 640 people per sq. km. Two of the zones, Katheka-kai and Kiandani have been selected from Machakos Sub-county while Kathiani is from Kathiani sub-county. Katheka-kai has 6755 households with a population of 24579 people, Lower Kiandai has 6284 households with a population of 17841 people while Kathiani has 6596 households with a population of 24928 people. In this rural sites, a few of the household have national grid connection which hardly meets their huge energy load triggered by the ever rising population density. Standalone wind-PV hybrid system is a viable resolution in seeking to fill this energy demand gap in these rural households.

### *2.2. Estimation of Household Energy Demand*

Due to the transitory nature of wind and solar renewable resources, hourly estimation of energy demand and daily load profile of a given household is utmost in sizing an optimal renewable energy system suitable for installation in a given household. Data collected was done using probability sampling method which involved clustering and random sampling of household as representatives of the entire population (households) to draw energy demand inferences. This was done to limit time and resources by reducing the number of cases to be considered. Figure 1 is a chart showing the probability sampling approach steps used. Yamane, 1967 provides a simplified method of determining the sample size (*n*) of a given population using the equation 1 [29].

$$n = \frac{N}{1 + N(e)^2} \tag{1}$$

where *N* is the size of the population and *e* is the precision level. Based on this approach, an average of 6545 household in each of the three zones with a confidence level of 90% and a precision of 10% gave a sample size of 98.45. This is approximately 100 households.

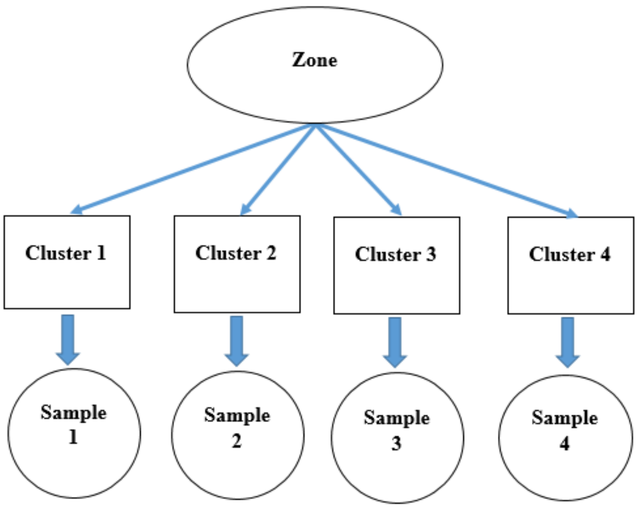


***Figure 1.*** *Flow chart showing probability sampling method.*

### *2.3. Data Collection*

Data collection in the three sites was based on the active appliances present in a household. The three zones were each divided into villages considered in this study as clusters. Four clusters were used and a survey undertaken in 25 households selected randomly from each cluster to assess the total daily energy consumption. The sample of 100 households was used as a representative of the whole zone to draw inferences on energy utilization level of an average rural household. Primary data was then collected by interviewing the household heads in each cluster. The questionnaire items were; the electrical appliances available and their power rating, sources of energy used, household size, monthly income and the time of use of each electrical appliance per day. An average household was found to have an average of 4 to 5 people and the common domestic appliances in rural communities were those used mainly in lighting, communication and entertainment purposes. These appliances were phones, bulbs, TV sets, radio, heater, funs, iron box, hoofers, hair drier and blenders. A few households contained appliances like fridge, oven and cookers which consume slightly higher energy. Daily load analysis was done using End-Use method which entails customer appliance ownership application [30]. This method sums up the products of time of operation and the power rating for all active appliances. Total and average loads were calculated using equations 2 and 3 respectively, [24]

$$E_{Total} = \sum_{i}^{N} P^K t \tag{2}$$

$$E_A = \frac{1}{N_H} \sum_{i}^{N} P^K t \tag{3}$$

where E is the energy, P is the power rating of the appliance, k represents an appliance, t is the time of use, N is the number of appliances, $E_A$ is the daily average value per zone, and $N_H$ is the total number of households per zone. This data was used to derive the daily demand curve which gave an appropriate demand model for an average rural household.

## 3. Results and Discussion

This section presents the energy loads distributions and daily load profiles for three rural zones of Machakos. A sample household with an energy load of less than 1 kWh is also presented and considered as a model for sizing Wind-PV hybrid system suitable for similar average households in the county.

### *3.1. Energy Demand Analysis*

Data on energy utilization pattern was carried out in three sub-location, Katheka-kai and Lower Kiandani in Machakos sub-county and Kathiani in Kathiani sub-county all in Machakos county. Energy demand data was collected using a questionnaire and grouped to determine the distribution of energy consumption in the three sub-locations. Tables 1 and 2 shows the average energy loads in all four clusters in every zones while Table 3 shows household frequencies distribution in terms of their level of daily energy loads.

***Table 1.*** *Average of the total energy loads per cluster in kWh.*

| | Katheka-kai (kWh) | Kiandani (kWh) | Kathiani (kWh) |
|---|---|---|---|
| Cluster 1 | 0.97 | 1.008 | 1.375 |
| Cluster 2 | 1.399 | 1.054 | 1.498 |
| Cluster 3 | 0.943 | 0.954 | 1.356 |
| Cluster 4 | 1.054 | 0.985 | 1.367 |
| Average | 1.09 | 0.99 | 1.4 |

***Table 2.*** *Cluster average energy loads for household consuming below 1 kWh per day.*

| | Katheka-kai (kWh) | Kiandani (kWh) | Kathiani (kWh) |
|---|---|---|---|
| Cluster 1 | 0.43 | 0.589 | 0.550 |
| Cluster 2 | 0.64 | 0.578 | 0.579 |
| Cluster 3 | 0.57 | 0.473 | 0.614 |
| Cluster 4 | 0.50 | 0.645 | 0.643 |
| Average | 0.56 | 0.590 | 0.596 |

***Table 3.*** *Household load frequency distribution.*

| Load (kWh) | Zone A (Katheka-kai) % | Zone B (Kiandani) % | Zone C (Kathiani) % | Total | Total % |
|---|---|---|---|---|---|
| 0-1 | 60 | 53 | 42 | 155 | 52 |
| 1-2 | 24 | 38 | 32 | 94 | 31 |
| 2-3 | 13 | 9 | 17 | 39 | 13 |
| 3-4 | 3 | 0 | 7 | 10 | 3 |
| 4-5 | 0 | 0 | 2 | 2 | 1 |
| 5-6 | 0 | 0 | 0 | 0 | 0 |

The daily energy loads for the rural households ranged between 0.052 kWh and 4.23 kWh where 52% of the consumers use less than 1 kWh. The average daily load for the three selected zones Katheka-kia, Kiandani and Kathiani was 1.092, 0.99 and 1.4 kWh translating to a cumulative average of 1.161 kWh. This implies that most rural households in Machakos County consume less than 1.5 kWh of energy daily. This can be attributed to low incomes slowing down social-economic developments in the region. The average energy demand for the households that consume less than 1 kWh was found to be 0.56, 0.59 and 0.595 kWh in Katheka-kai, Kiandani and Kathiani respectively. These load averages give an average daily load of 0.582 kWh adds up to approximately 213 kWh in a year for rural households consuming below 1 kWh of energy. It was noted that demand greatly depends on peoples' life style and habitat. Figure 2 shows the load utilization levels in three rural sites of Machakos County.

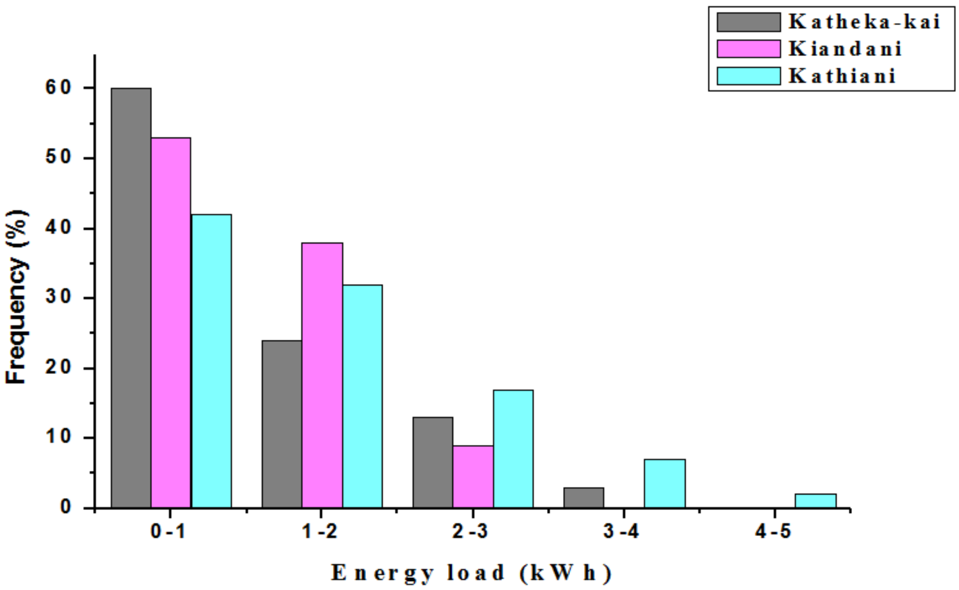


***Figure 2.*** *Energy utilization levels in Katheka-kai, Kiandani and Kathiani zones.*

A pie chart for the sum of all rural households in the three rural sites was plotted as shown in Figure 3. In urban areas people use more appliances most of which are advanced compared to those in rural areas.

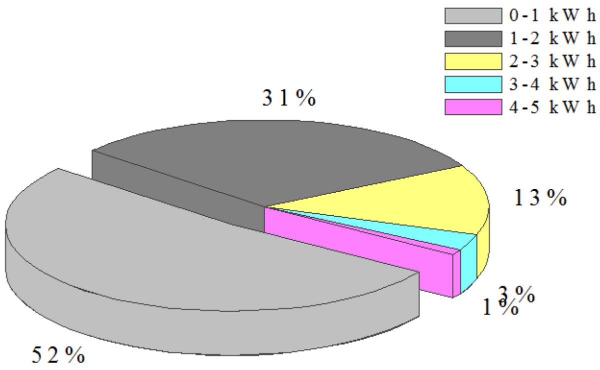


***Figure 3.*** *Energy demand pattern in the three selected zones.*

The three zones form part of the remote community of Machakos County where people hardly have access to national grid and the few that are connected have challenges in maintenance and payment of the monthly power bills. A few households where people are financially stable rely on small solar panels that hardly meet the load demand.

Notably, most households in the remote areas do not use the electrical appliances made for cooking or heating/cooling rooms due to their high cost. Table 4 presents appliances available in a basic rural household that consumes less than 1 kWh/day. Such a basic household selected in the three zones was considered for hybrid system sizing in this study.

***Table 4.*** *A sample load demand for an average rural household in Machakos.*

| Appliance | Rating (W) | Hour of use per day | Total units (Wh) |
|---|---|---|---|
| 4 bulbs | 11 | 5 | 220 |
| 2 Radios | 50 | 3 | 300 |
| 3 Phones | 8 | 2 | 48 |
| 1 Lamp | 10 | 2 | 20 |
| Total | 178 | 12 | 588 |

Total energy demand was determined by counting the number of active appliances, their power rating and the time of use in a day as earlier explained. Considering the variations in the level of energy utilization in the rural areas, a set of data for energy demands below 1 kWh per day collected from three zones was used to configure the wind-solar PV hybrid energy system model. A rural household sample with a daily energy load of 0.588 kWh was used to size a hybrid system as a model for an average rural household in Machakos. Figure 4 shows the daily average energy consumption curve for an average rural household in the region.

The curves indicated that energy loads are high for a short period of time in a day. Comparatively much energy is used between 5:00 pm and 10:00 pm. This is the period when people are back to the house after the daytime activities. Energy is mainly used for lighting, televisions, radios and phones available in the household. After 10:00 pm energy consumption level falls drastically. During this time most people are asleep and most of the electrical appliances are turned off apart from security lights which use minimal energy. The minimal use of energy at night minimizes drainage of batteries at night when solar insolation is zero. The need for energy at night also justifies the need for integrated hybrid system with an alternative source of energy other than solar which would complement in power supply satisfactorily.

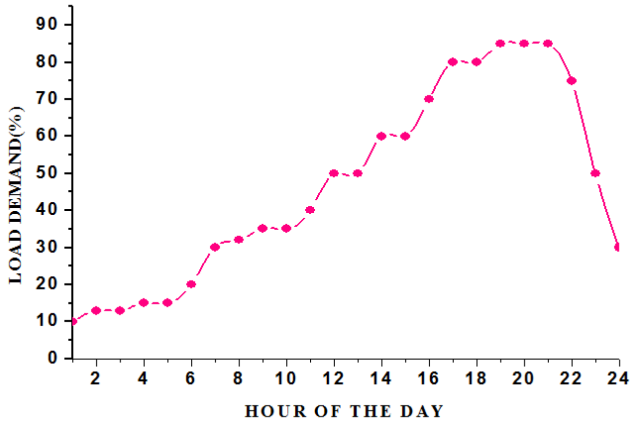


***Figure 4.*** *Hourly load demand profile for an average rural household in Machakos.*

Wind resource has been analyzed and found to be a potential complement to solar resource due to its availability during the day and at night especially in the worst periods of solar insolation. Wind and solar energy potentials and their complementarity nature have made them a viable resource in development of hybrid systems to help meet the rising energy demand in rural households of Machakos.

### *3.2. Wind/PV Energy System Sizing*

A model wind-PV hybrid energy system was sized based on the wind and solar daily energy potentials suitable to power a sample house load of 588 Wh per day.

#### *3.2.1. Solar PV Module*

According to Dunlops, [31], solar PV module ought to meet the load and system losses even in the worst case of solar insolation. This was considered in calculating the panel size as the ratio between the daily household load in watts to the solar peak hours in July. PV size was calculated as;

$$\frac{588Wh}{4.667hrs} = 125.7W \tag{4}$$

The PV module is up-scaled by a factor of 30% to cater for system losses, which are 10% temperature losses, 3% wiring losses and about 15% battery losses raising the system size to 163.4 Watts. Therefore, a PV module of approximately 165 Watts would be appropriate.

#### *3.2.2. Battery Capacity*

Considering a battery efficiency of 85% and depth of discharge of 75% with three days of autonomy, the battery capacity for a daily load of 588 Wh at a nominal voltage of 12 V was calculated as;

$$\frac{588Wh}{0.85\times0.75\times12V}\times3=230.6AH \tag{5}$$

A 12 V, 250 AH lead acid battery would be cheap and affordable for the household load.

### 3.2.3. Inverter

An inverter size suitable for the household load was 25% times the total appliance wattage. This is in accordance to a study done by Ariyo *et al.,* 2016 [32] which suggested a 25-30% rise of the inverter size to enable it withstand total household wattage. The inverter was calculated as;

$$178W\times1.25=222.5W \tag{6}$$

A 12 V, 225 W inverter would therefore be ideal for the household.

### 3.2.4. Charge Controller

The charge controller size would be rated using amperage and nominal voltage capacity of 12 V to match the PV module and the battery. The rating was calculated to be 1.3 times the short circuit current of the PV module. For a PV module with a short circuit current of 8.8 A, a controller rating of 15 A would be ideal.

### 3.2.5. Wind Turbine

Based on the wind speed in Machakos, a wind turbine with a cut in wind speed of 1.0 m/s, rated wind speed of 5.0 m/s and a cut off wind speed of 15 m/s would be most suitable for installation at the sites.

## 4. Conclusion

Energy utilization assessment results showed over 50% of rural households in Machakos consume less than 1 kWh daily attributed to the type and number of appliances owned. Energy demand is as high as 90% in the evening and at night though for a short time when people are back home from job. The range of daily energy load in Machakos was found to be 0.052 to 4.23 kWh with most of the households consuming less than 1.5 kWh in a day. The average daily load for the three selected zones Katheka-kai, Kiandani and Kathiani was 1.092, 0.99 and 1.4 kWh translating to a cumulative average of 1.161 kWh. The average household load for the less than 1 kWh household was 0.582 kWh where Katheka-kai, Kiandani and Kathiani had and average daily load of 0.56, 0.59 and 0.596 kWh respectively. Based on the minimum month solar insolation of 4.677 kWh/m$^2$ and the wind speed range of 1.0- 10.0 m/s, a stand-alone wind/PV hybrid system was sized for a sample average household with a load of 0.588 kWh per day. The component sizes were: 12 V, 165 W Panel, 12 V, 250 AH battery, 12 V, 225 W inverter and a wind turbine that can operate with a cut-in, rated and cut-off wind speeds of 1.0, 5.0 and 15.0 m/s. In the integration and sizing of solar and wind energy systems, their complementarity effect could increase the systems viability in mitigating energy poverty in rural households of Machakos. Future work will entail to a greater extent the design, fabrication and analysis of wind and PV system models for small-scale power generation. The study findings could be extended to key stakeholders for planning to create access to clean and sufficient renewable energy to Machakos rural energy consumers.

## Acknowledgements

This work was supported by the Kenya National Research Fund (NRF) Grant No: NRF/1/MMC/450 and Jomo Kenyatta University of Agriculture and Technology through my research supervisors Prof. J. N. Kamau, Dr. D. W. Wekesa, Dr. C. O. Saoke, Prof. J. N. Mutuku and Dr. J. K. Gathua.

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