International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:9, No:5, 2015

Small Scale Solar-Photovoltaic and Wind Pump-Storage Hydroelectric System for Remote Residential Applications

Seshi Reddy Kasu, Florian Misoc

***Abstract*—**The use of hydroelectric pump-storage system at large scale, MW-size systems, is already widespread around the world. Designed for large scale applications, pump-storage station can be scaled-down for small, remote residential applications. Given the cost and complexity associated with installing a substation further than 100 miles from the main transmission lines, a remote, independent and self-sufficient system is by far the most feasible solution. This article is aiming at the design of wind and solar power generating system, by means of pumped-storage to replace the wind and /or solar power systems with a battery bank energy storage. Wind and solar pumped-storage power generating system can reduce the cost of power generation system, according to the user's electricity load and resource condition and also can ensure system reliability of power supply. Wind and solar pumped-storage power generation system is well suited for remote residential applications with intermittent wind and/or solar energy. This type of power systems, installed in these locations, could be a very good alternative, with economic benefits and positive social effects. The advantage of pumped storage power system, where wind power regulation is calculated, shows that a significant smoothing of the produced power is obtained, resulting in a power-on-demand system's capability, concomitant to extra economic benefits.

***Keywords*—**Battery bank, photo-voltaic, pump-storage, wind energy.

I. INTRODUCTION

THIS article is aiming at the design of a small power generating system by using renewable energy sources, wind and solar photovoltaic, employing a pumped-storage system, to replace the commonly-used battery bank energy storage. This research evaluates the energy efficiency of wind and solar pumped-storage power generation system, and it demonstrates that it is well suited for remote residential applications with intermittent wind and/or solar energy. Through design and cost analysis, it is shown how this type of power system, could be a very good alternative, with economic benefits and positive social effect. The advantage of pumped storage power system is evaluated for conditions of intermittent wind, showing a significant improvement of power regulation, resulting in a power-on-demand system capability, concomitant to added economic benefits.

II. BACKGROUND

Providing electricity to remote residential location is costly and technically challenging; from the point of view of system design, system construction, operation and maintenance. Current renewable energy systems relay on battery banks for energy storage, which proves to be costly, requiring periodic maintenance/monitoring, and to be dangerous, to some extent (because of the acidic electrolyte, and the flammable/ explosive Hydrogen-rich gasses that can leak into the storage building).

A. Proposed Designs in Research Papers

The design focuses on wind-solar and pumped-storage hybrid power supply system, consisting of photo-voltaic power generation, wind power generation, hydro-electric power generation and other subsystems. The design works according to the solar energy distribution characteristics of site area. L. R. Li et al. used solar panels and a wind turbine to gather energy from sun's radiation and the intermittent wind [1]. The solar and wind energy is converted into electrical energy, in the form of DC current by means of converters, and is used to drive the motor that pumps water to a reservoir placed at a pre-determined height. The micro hydro-electric power subsystem is used to supplement the power generation capability, and provide power whenever sun and/or wind energy is not available, i.e., night time with no wind. The design is efficient for large power generation systems.

Similarly, the design proposed by Nichita et al. team operates to provide power-on-demand [2], while the design proposed by Li et al., thus reducing the size of the entire system and by using less number of components [1].

B. Disadvantages/Problems

The two large size models, mentioned above, cannot be used for residential applications due their large size, high cost and lower efficiency, as compared to the model proposed in this paper. Since the energy from the natural resources is not constant, it is foreseen a level of fluctuation in the power generation, leading to some ups and downs in the power generation. As such, grid integration could result to breakdown of the system.

C. Renewable Energy Sources

Renewable energy is derived from the natural processes and is constantly replenished. In its various forms, it derives directly from the sun, or from heat generated deep within the

---

S. R. Kasu is with the Kennesaw State University, Southern Polytechnic College of Engineering, Marietta, GA, 30060 USA (e-mail: skasu@ spsu.edu).

F. Misoc is with the Kennesaw State University, Southern Polytechnic College of Engineering, Marietta, GA, 30060 USA (phone: (678) 915-7423, e-mail: fmisoc@ kennesaw.edu).

earth. Included in the definition is electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, and bio fuels and hydrogen derived from renewable resources.

Wind power is growing at the rate of 30% annually, with a worldwide installed capacity of 282,482 megawatts (MW) at the end of 2014, and is widely used in Europe, Asia, and the United States. At the end of 2012 the photovoltaic (PV) capacity worldwide was 100,000 MW, and PV power stations are popular in Germany and Italy. Solar thermal power stations operate in the USA and Spain, and the largest of these is the 354 MW SEGS power plant in the Mojave Desert. The world's largest geothermal power installation is The Geysers in California, with a rated capacity of 750 MW. Brazil has one of the largest renewable energy programs in the world, involving production of ethanol fuel from sugar cane, and ethanol now provides 18% of the country's automotive fuel. Ethanol fuel is also widely available in the USA.

Renewable energy replaces conventional fuels in four distinct areas: electricity generation, hot water/space heating, motor fuels, and rural (off-grid) energy services. Renewable energy provides 31.4% of electricity generation worldwide as of 2013. Renewable power generators are spread across many countries, and wind power alone already provides a significant share of electricity in some areas: for example, 14% in the U.S. state of Iowa, 40% in the northern German state of Schleswig-Holstein, and 49% in Denmark. Some countries get most of their power from renewable, including Iceland (100%), Norway (98%), Brazil (86%), Austria (62%), New Zealand (65%), and Sweden (54%).

III. POWER STATION

Fig. 1 illustrates the design of a power station that contains PV generation, wind power generation, pumping and hydropower and other subsystems. According to the solar energy distribution characteristics of site area, in the area both light radiation and radiation intensity is larger during the day, it is except morning and night, the periods of light during the day are more evenly distributed, daytime distribution regularity is similar. Then from PV generation material's photoelectric effect analysis, currently, effective power generation time bears a closer relationship with the sensitivity of optical materials and no significant relationship with capacity. Therefore, it could find the corresponding starting and ending point for power generation according to different light intensity distribution during the day approximate, the period between the two points is the time of photovoltaic materials can be sensitive to the light, but also is the effective work time of photocell in the daytime. The effective period of wind power generation is also affected by the local natural conditions, specific embodied in each period's wind size and continued stability during the daytime, could find the corresponding starting and ending point for power generation according to similar approaches, then determine the effective working days of wind turbine generator. Furthermore pumping systems are affected by the impact of water source and available water supply. Water power of this system can constitute a self-circulation system through pumping unit, external water mainly used as supplement water source; the system demand for water is lower.

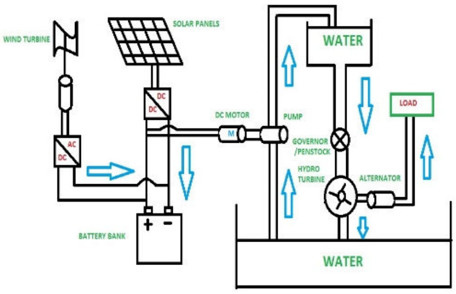


Fig. 1 Photovoltaic and wind pump-storage system

A. Working

From Fig. 1 it can be seen that both the renewable energy sources wind turbine and solar panel is connected to a battery bank where the number of batteries are inter connected to store the power. The output of the wind turbine is AC voltage whereas the battery stores only DC voltage so; the output of the wind turbine is connected to a rectifier that converts AC voltage to DC voltage. Thirty solar panels are connected in series to each other to the battery through the DC–DC converter. The power from both solar and wind systems is used to drive a DC motor connected a pump to take water from the reservoir on the ground to the reservoir on the building which is 15m high. Then the water from the upper reservoir is exerted to the turbine by controlling the force using penstock. The mechanical energy from turbine is converted into electrical energy through an alternator and then supplied to the load through an inverter that converts DC to AC.

The water from the turbine is again collected to the tank and then pumped up to the reservoir. From the upper reservoir the water is again exerted on to the turbine with force and this continues until the power station comes to shut down.

B. Lack of Sun and Wind Scenario

Assuming that both energy sources; solar and wind energy are not available, due to incremental weather, night time, etc., the micro-scale design has the alternative to overcome this condition for some duration of time. In this design, a 3kW motor is used to pump the water from the bottom of a reservoir to the second reservoir situated at a higher elevation, and to a small battery bank, capable of storing nearly 7.6kWh, in order to provide some of its power to the motor-pump system. This strategy enables the system to maintain the hydro-electric system capability. The hydro-electric system alone is capable of generating electric power through an impulse-type Pelton turbine, where the water flowing thru a penstock exerts pressure on turbine, thus generating nearly 5kWh which is half the residential load. The customer can run half of appliances by using this power. A worst case scenario, assumes the complete failure of the hydro-electric system. In this circumstance, the energy stored in the battery bank is converted to AC, via a DC–AC converter, and can be used for nearly 5 hours, being capable or running 75% of the appliances. But this design is only for the areas where sunlight and wind are continuously supplying energy for the whole year.

IV. DATA COLLECTION

A. Solar Radiation

Solar radiation is a reliable source of energy that is received in the form of relatively diffuse energy. Its daily cycle varies and may be influenced greatly by meteorological conditions such as cloud, haze, and fog. Being radiant energy, solar energy cannot be stored directly. Global solar radiation data are readily available and reliable for all locations [2]. The solar resource was used for the energy system is in the area of Marietta-United States of America with geographical coordinates defined as: latitude N 33°, longitude W 84°, and altitude 1700m above sea level. The solar radiation data for this region were obtained from the National Aeronautics and Space Administrative (NASA) surface meteorology and solar energy website [4]. The annual estimated average solar radiation is 4.74 kWh/ m^2/day. The solar radiation data inputs as used in HOMER software, on the right axis of which is the clearness index of the solar irradiation is depicted in Fig. 2. The clearness index is automatically generated by HOMER when the daily radiation data are entered [5].

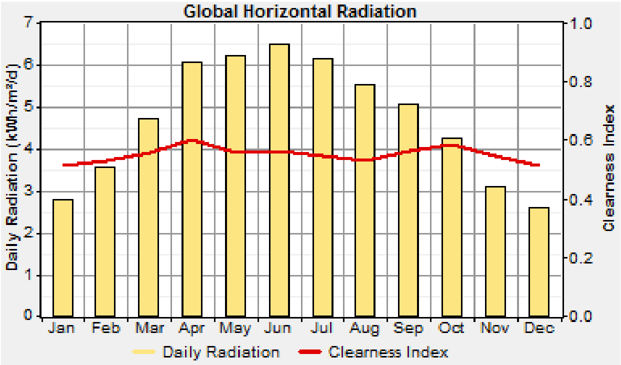


Fig. 2 Monthly average solar radiation for Marietta, GA, USA

B. Wind Speed

Since the energy from the solar panels is not sufficient to provide the average daily energy demand, wind turbine can be used to provide the remaining power needed [6]. Based on the wind speed data obtained from an anemometer tower (that installed at Weather Channel station, Marietta), the average monthly wind speed variations measured at 10, 20, and 40m above the surface of the earth. The data measured at 20m above the surface of the earth are depicted in Fig. 3, and it shows a wind speed range from 2.9 m/s to 4.0 m/s.

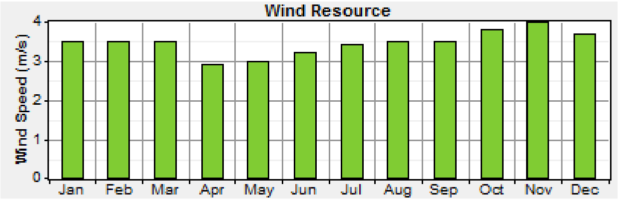


Fig. 3 Monthly average wind speed in Marietta, GA, USA

C. Electrical Load Demand

A typical sample of the daily load profile for the residential purpose is shown in Fig. 6. From the load profile, it can be seen that the maximum demand occurs during a daytime from 6 pm to 6 am as this is the during night times. The scaled annual average energy demand of the studied building is as simulated by HOMER software.

V. COST ANALYSIS

A. Specifications of the System

Renewable energy systems are best suited to reduce dependence on fossil fuel using available wind speed and solar radiations [7]. A configuration of a renewable energy system is shown in Fig. 5. It consists of solar modules coupled to wind turbine, converter, hydro turbine and battery bank.

In this study, all calculations, simulation, and optimization such as hourly operation of each system, and technical and economic performance parameters have been done by HOMER tools. The results of techno-economic analysis of integration between solar panels, wind turbine, inverter, hydro turbine and batteries will be presented.

B. Solar/PV System

Solar energy is one type of the renewable energy resources, which can be converted easily and directly to the electrical energy by PV converters. In this paper, to fulfill the basic load demand, the nominal power rating for the PV modules was set at 10kW. The PV modules consist of solar panels, MA36/45 modules configured into independent sub arrays. Each sub array consists of 16 modules. The PV module is a polycrystalline silicon type with maximum output of 10 kW. In this project, the initial cost of a 10kW solar PV panel is $6386 US, with a replacement cost of $4000 US. Derating factor is a scaling factor applied to the PV array power output to compensate the reduction in PV module efficiency [3]. In this simulation, the derating factor is assumed to be 80%. The ground reflectance of solar radiation is 20%, and operational and maintenance (O&M) cost for PV array is $200 US, and the lifetime is assumed to be 25 years.

C. Wind Turbine

Since the energy from the PV panels is not sufficient to provide the average daily energy demand, a wind turbine cell can be used to provide the remaining power needed. [8] The fundamental equation governing the mechanical power capture of wind turbine rotor blades which drives the electric generator is given by (1) [9].

$$P_m = \frac{1}{2}C_p.\rho.A.V_{wind}^3 \quad (1)$$

where q is the air density (kg/m^3), A is the rotor sweep area, V is the wind velocity (m/s), and C_p represents the power coefficient of the wind turbine. Thus, if the air density, swept area, and wind speed are assumed constant, the output power of the wind turbine will be a function of the power coefficient.

TABLE I
SYSTEM COST

System number	Components	Nominal Power (kW)	Capital Cost (US$)	Replacement Cost (US$)	Operating and Maintenance Cost (US$)	Life Time (yrs)
1	Solar Panels	10	6386	4000	200	25
2	Wind Turbine	3	9000	9000	360	25
3	Battery Bank	7.9	800	800	100	12
4	Converter	14	600	600	10	20
5	Hydro Turbine	23.5	2000	2000	150	25

The wind turbine is normally characterized by its C_p–TSR characteristic, where the TSR is the tip speed ratio and is given by:

$$TSR = \frac{\omega.R}{V} \quad (2)$$

In (2), R and ω are the turbine radius and the mechanical angular speed, respectively and V is the wind speed. To keep power coefficients at its maximum value, operating TSRs must be held at its optimal value by controlling rotor speeds according to reference rotor speeds at incoming wind speeds using a maximum power point tracking (MPPT) controller.

In this simulation, the Generic 3kW (DC) type wind turbine was chosen. Table I shows the costs of the wind turbine. For economic assessment, the operating and maintenance cost is assumed to be 4%.

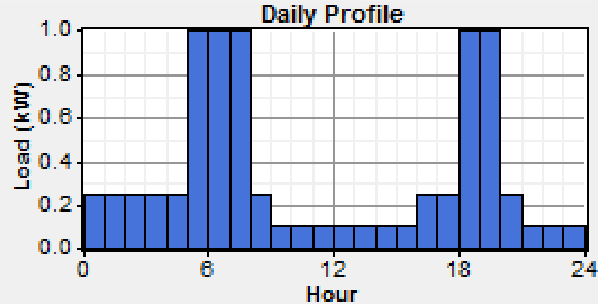


Fig. 4 Average hourly load profile

D. Battery Bank

Energy supply systems based on renewable energy sources require energy storage because of their fluctuation and the insufficient certainty of supply. One of the ways for energy storage is the use of the battery bank. Due to the stochastic nature of the electrical output of PV system and wind turbine, energy storage is needed to supply the load "on demand" by storing energy during periods of high bright sun. When the total outputs of the PV array and wind turbine are more than the energy demand, the battery bank is charged.

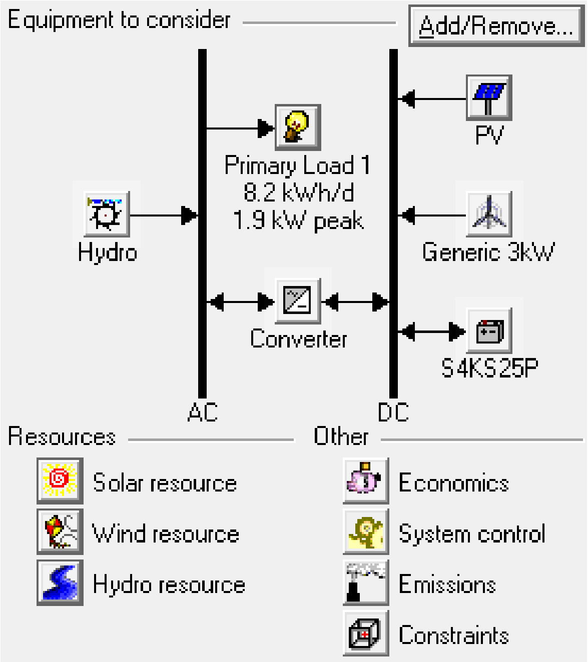


Fig. 5 System diagram

HOMER tools assume that the properties of the battery remain constant throughout its lifetime and are not affected by external factors such as temperature

In order to produce higher energy capacity, batteries are connected in series, which form battery string. The estimated price of each battery is $200 US, with a replacement cost of $200 US. This type of battery is characterized by its versatility of application and zero-maintenance design. The life expectancy of the battery is 10 years. The 4V battery bank originally consisted of 7.6 kWh of storage.

E. Converter

A converter is required for a system in which DC components serve as an AC load or vice versa. It can operate as a rectifier which converts AC to DC, an inverter which converts DC to AC, or both. The estimated capital cost of an inverter is $600 US, and replacement cost of $600 US. A lifetime of 20 years was assumed in which the both inverter and rectifier efficiencies were assumed to be at 90%, for all sizes considered. The 32 HOMER was used to simulate each system with power switched between the inverter and the generator.

VI. RESULTS AND DISCUSSIONS

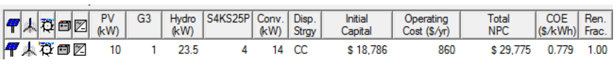
A. Simulation of Power Station by HOMER Tools

In this study, the selection and sizing/dimensioning of components of the hybrid energy system have been done using NREL's HOMER software. HOMER is general-purpose hybrid system design software that facilitates design of electric power systems for stand-alone applications. Input information to be provided to HOMER includes: electrical loads (1 year of load data), renewable resources (1 year of solar radiation data), component technical details/costs, constraints, controls, type of dispatch strategy, etc. HOMER is a simplified optimization model/code, which performs hundreds or thousands of hourly simulations over and over (to ensure best possible matching between supply and demand) to design the optimum system. It uses life-cycle cost to rank order these systems. It offers a powerful user interface and accurate sizing with detailed analysis of the system. The software performs automatic sensitivity analyses explaining the sensitivity of the hybrid system design to key parameters, such as the resource availability or component costs. The simulation was done with a project's lifetime of 25 yr. Moreover, an annual interest rate of 8% was used in the economic calculations. The schematic diagram of the stand-alone hybrid energy system as designed in HOMER simulation software is shown in Fig. 7. This system has an average AC load of 8.2kWh/days, with the peak load of 1.9kW. HOMER allows input of the operating reserve in the system. The result of here required the operating reserve to be 10% of the hourly load, plus 60% of PV array, and 40% wind turbine power output.

B. Power Station and Optimization Results

Hourly solar radiation and wind speed measurements for a period of 1 yr were imported into HOMER tools to calculate monthly average values of clearness index and daily radiation. The annual average global radiation is 4.72 kh/m2/day with an annual average clearness index of 0.555, and the annual average wind is 3.46 m/s. The results are displayed, an overall form in which the top-ranked system configurations are listed according to their NPC for possible system type. Fig. 6 shows a list of the possible combinations of system components in the overall form. The table has been generated based on inputs selected. The system was simulated to evaluate its operational characteristics, annual electrical energy production, annual electrical loads served, excess electricity, RE fraction, capacity shortage, unmet load, etc. some environmental impact parameters of the system. A load-following control strategy was followed in the simulation. Under this strategy, whenever a power generator is needed it produces only enough power to meet the demand.

Load following strategy tends to be optimal in systems with a surplus of renewable energy. The results of the simulation showed that this system had a total annual electrical energy production of 15825kWh, which the total energy produced from a PV array is higher than the energy generated from wind turbine. All results related to the electric energy production, and electric energy consumption is summarized in Fig. 6.



PV (kW)	G3	Hydro (kW)	S4KS25P	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
10	1	23.5	4	14	CC	$ 18,786	860	$ 29,775	0.779	1.00

Fig. 6: Analysis of the Combination

According to the results of the optimization process, the optimal energy system comprises 10kW PV modules, one wind turbines (3kW each), 14kW converter and four batteries, as shown in Fig. 5. The cost of energy (COE) of the studied systems is $0.783 US/kWh, whereas the initial capital required and NPC are $32,831 US, respectively. This could be a good choice for implementation as the contribution made by renewable resources is quite significant. In Fig. 6 it is shown the average monthly electrical production of this system. The assessed values about total annualized cost and net present costs for each component of the energy system are presented in Table I.

VII. CONCLUSIONS

The net financial benefit for altering the solar and wind power system into a solar-wind pump-storage power system is shown by cost analysis. No modifications were made to the type and number of solar panels or to the wind turbines used by Nichita all research team [2]. It is thus concluded that a significant improvement of the existing system was achieved, reducing the number of storage battery units and some of the power converters by using HOMER tools. It is necessary to emphasize that pump-storage power systems are best suited for locations/areas where "natural" water head is offered by the surrounding topography, whereas flat land topography would require expensive structural accommodations, resulting in a far more expensive design, as compared to the existing solar and wind power system (with battery storage capability).

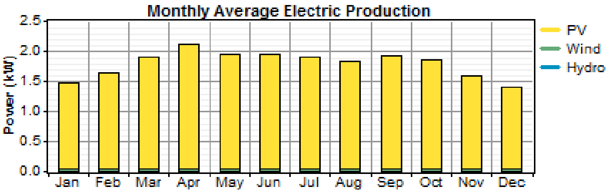


Fig. 7 Average monthly power generation

REFERENCES

[1] R. Li, B. Wu, X. Li, F. Zhou, Y. LI, "Design of Wind-Solar and Pumped Storage Hybrid Power Supply System," 3rd IEEE International Conference on Computer Science and Information technology, vol. 5, pp. 402-405, July 2010.

[2] C. Nichita, P. Livinti, P. Enache "Study Case of a Hybrid Wind-Photovoltaic System, Based on HOMER Simulation," Proceedings of Francophone Multidisciplinary Colloquium on Materials, Environment and Electronics," vol. 4, no. 1, pp 54-61 , May 2014.

[3] Homer Energy: http://homerenergy.com/software.html, 2012 edition

[4] Stackhouse, P. W. (). “Surface meteorology and Solar Energy,” US Atmospheric Science Data Center, November 2014 edition: https://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi?skip@larc.nasa.gov+s03#s03

[5] K. Y. Lau, M. F. M. Yousof, S. N. M. Arshad, M. Anwari, and A. H. M. Yatim, “Performance Analysis of Hybrid Photovoltaic/Diesel Energy System under Malaysian Conditions,” Energy, vol. 35, no. 8, pp. 3245–3255, 2010.

[6] M Eroglu, E Dursun, S Sevencan, J Song, S Yazici, O Kilic, “A Mobile Renewable House Using PV/Wind/Fuel Cell Hybrid Power System,” International Journal of Hydrogen Energy, vol. 36, no. 13, pp. 7985-7992, 2011.

[7] Belfkira R, Reghem P, Raharijaona J, Barakat G, Nichita C. Non Linear Optimization Based Design Methodology of Wind/PV Hybrid Stand Alone System. EVERE, Ecologic Vehicule.renewable energies, MONACO, March 26-29, 2009.

[8] Turkish State Meteorological Service Data Center, July 2009: http://www.meteor.gov.tr/site/urunler.aspx%u=tum

[9] P. Wang and R. Billinton, "Reliability benefit analysis of adding WTG to a Distribution System," IEEE Transactions on Energy Conversion, vol. 16, no. 2, pp. 134-139, June, 2001.

Seshi Reddy Kasu earned a B.Sc. of Technology from Jawaharlal Nehru Technological University in 2012 and he is currently pursuing a M.Sc. degree at Kennesaw State University, in Marietta GA, USA.

He worked as a Site Engineer in Ramana Industrials for two years and was a team leader for the construction of a Steam based 30MW Power Plant and the maintenance of a Steel Plant at Sathavahana Ispat Ltd., India. Currently, Mr. Kasu is working as a Graduate Assistant within the Electrical and Computer Engineering Technology, pursuing research on renewable energy systems. His previous research was on Multi Level Inverters in Power Electronics under Prof. Joshi V. Manohar.

Florian Misoc earned a PhD in Electrical Engineering from Kansas State University, in 2007, a M.S. in Engineering Technology from Pittsburg State University, in 1999, and B.Sc.in Physics from the University of Bucharest-Romania, in 1989.

He is an Associate Professor of Electrical and Computer Engineering Technology, at Kennesaw State University, in Marietta GA, USA. His research areas of interest are: Renewable Energy Systems, Power Electronics and Distributed Energy Systems.

Dr. Misoc is a Registered Professional Engineer in the state of Arkansas, and he is a reviewer for the IEEE Journal of Electric Power Components and Systems.