Multi-source Energy Harvesting System for Sensor Nodes

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Abstract. To prolong the lifetime of sensor nodes, energy harvesting systems are installed with sensor nodes for harvesting energy from environmental sources like sunlight, wind speed and so on and recharge their batteries. Widely utilized energy harvesting systems depend on sunlight and wind speed, which are predictable. However, the energy produced by the solar light is not continuous during the daytime and null at night. Energy produced by wind speed is not sufficient for powering the sensor nodes all the time. To resolve this problem, we have proposed a multi-source energy harvesting system which harvests energy from both solar light and wind speed. We also discuss how energy is produced by our proposed multi-source energy harvesting system. Our proposed multi-source energy harvesting system comprises of the real-world sensor node platform, solar panel and wind turbine. Results from simulation analysis clearly manifests that our proposed multi-source energy harvesting system extracts more energy as compared to energy produced by a single solar panel or a wind turbine.

Keywords: IoT · Sensor node · Solar energy · Wind energy
Multi-source energy harvesting system

1 Introduction

An IoT network is composed of wired and wireless devices such as sensor nodes and actuators. Sensor nodes have the capability of monitoring environmental phenomena and transmitting the measured data. Sensor nodes are the front end of the IoT devices as they connect the world's physical objects with the internet [1]. An actuator is a device which uses data collected and analyzed by sensor nodes to control the IoT system [1]. For simplification, in this paper, we have considered IoT systems comprising of sensor nodes only. Sensor nodes are powered by the fixed capacity batteries, due to which sensor nodes operate for the limited duration as long as the battery lasts. The lifetime of a sensor is calculated as the time taken to discharge the battery below the threshold which is required by sensor for performing their operations. Energy harvesting is one of the most promising techniques used for extending the lifetime of sensor nodes.

Energy harvesting system extracts energy from the environmental sources (like solar, water, wind, etc.) and human body sources (like footfall, walking, etc.) and converts this energy into usable electrical energy to power the sensor nodes. Batteries

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are still necessary for sensor nodes as electrical energy produced by harvesting systems is uncontrollable and insufficient to continuously power them. When the energy harvesting system extracts more energy as compared to required energy then, remaining energy recharges the battery for later use. When energy produced by energy harvesting systems is insufficient then, sensor nodes are powered by the batteries. Sensor node remains unavailable temporarily if the battery level is below the lowest threshold or energy produced by energy harvesting system is insufficient for powering the sensor node. To avoid this period, we need to manage the battery recharge and energy production cycles.

In literature, several solar and wind energy harvesting systems are used such as Heliomote [2], Prometheus [3], Everlast [3] and micro horizontal and vertical scale wind turbines [4] respectively. A large number of sensor nodes use this type of harvesting systems. A drawback of these systems is that they support only one form of energy and can be used in locations where this energy source is available. To ensure the energy availability, a number of research works proposed the use of multi-source energy harvesters such as Smart Power Unit [5], Ambimax [6] and Plug and Play [5]. By using a wind turbine with a photovoltaic cell, more amount of energy is harvested then a single photovoltaic cell or a wind turbine. In Ambimax [6], authors compare the performance of Ambimax (multi-source) with Prometheus (Single source-solar) and shows that Ambimax generates more amounts of energy then Prometheus that too in less time. Ambimax [6] is not a feasible solution in real-world IoT systems because author uses a fan in place of wind turbine and fixed its speed at approximately 8.3 m/s.

Thus in this paper, we proposed a multi-source energy harvesting system which consists of a real world sensor node platform, photovoltaic cell and wind turbine. The rest of the paper is organized as follows: Firstly in Sect. 2, we discuss our proposed multi-source energy harvesting system which consists of a real sensor node, photovoltaic cell and proposed wind turbine for IoT system. In Sect. 3 we discuss, how usable energy is produced by proposed multi-source energy harvesting system. In Sect. 4 we discuss the energy consumption model and finally in Sect. 5 we discuss the conclusion.

2 Energy Harvesting System

We proposed a real world multi-source energy harvesting system comprises of a real sensor node platform, photovoltaic cells and wind turbine. The system comprises super capacitor and rechargeable batteries for powering the sensor nodes in situations when there is no or very less solar light and no wind. The main aim of our system is to extract energy from the sun light and wind speed and transform it into usable electrical energy for recharging the batteries. Battery and super capacitor is charged in following ways: by default, harvested energy is stored in the super capacitor. Secondly, when super capacitor charge is above the threshold value, then harvested energy is transmitted into rechargeable batteries. Sensor nodes are powered in following ways: by default, during day time when there is solar light, sensor nodes are powered by the solar energy. Secondly, during night time or cloudy days when there is no solar light, sensor nodes are powered by super capacitors connected to the multi-source energy harvesting system. Thirdly, when there is no solar light and no energy in super capacitor, then sensor nodes are powered by the rechargeable batteries.

In our work, we consider MSX-005F photovoltaic cell, a polycrystalline cell manufactured by BP-SOLAR. MSX-00SF photovoltaic cell is made up of semiconductor material silicon, with the property of transforming photon energy to electricity with the help of photovoltaic effect. Photovoltaic cell acquires small space because total surface area of this solar module is 36 cm^2 only. The maximum output power (P_m) produced by the MSX-00SF photovoltaic cell is 500 mW. The maximum power voltage (V_{ld}) and the current at which photovoltaic cell operate is 3.3 V and 150 mA respectively. The open circuit voltage and short circuit current of the photovoltaic cell is 4.6 V and 160 mA.

The efficiency of photovoltaic cell is the percentage of the amount of solar light transmitted by photovoltaic cells into usable electric power. The efficiency (η) of photovoltaic cells is calculated by using Eq. (1) where P_m is the peak power produced by the MSX-005f photovoltaic cell (in watts), D is the solar radiance incident on the surface of the photovoltaic cell (in W/m^2) and A is the total surface area of the photovoltaic cell (in m^2). The efficiency of the photovoltaic cells depends upon the solar radiance and size of the photovoltaic cell. Solar radiance depends upon the various factors like geographical location where photovoltaic cell is placed, sun angle, solar time. According to the manufacturers, efficiency of MSX-005F solar module is 11.38%.

$$\eta = \frac{P_m}{D \times A} \tag{1}$$

The micro scale wind energy harvester PIMWEH [7] is considered as promising option for our multi-source energy harvesting system. Firstly, wind speed is converted into mechanical wind turbine power by using wind turbine of diameter 9 cm and efficiency 34.1%. Then PZT converts mechanical wind turbine power to AC electrical power with efficiency of 26.1%. LTC3588-1 converts the AC electrical power into DC electrical power, with efficiency of 35.7%. As per [7], a 3.3 V pure DC voltage is generated at 11 KΩ resistive loads. The overall experimental efficiency of the wind energy harvester is 3.2%.

Both solar and wind energy harvester are connected to Waspmote [8], an open source low power wireless sensor platform. Note, however, we can also use any other sensor platform in place of Waspmote and similarly solar and wind energy harvester according to our needs. Waspmote 9 is based on ATmega1281 microcontroller and operates at 14.74 MHz frequency. Waspmote contains: built in 8 KB SRAM, 4 KB EEPROM, 128 KB Flash memory and 2 GB SD card slot. Dimensions of Waspmote are $73.5 \times 51 \times 13$ mm. Waspmote is powered by a single battery of voltage 3.3–4.2 V and operates in four operational modes: Normal, Sleep, Deep Sleep and Hibernate. The energy requirement of Waspmote platform is shown in Table 1.

Table 1. Waspmote energy requirement [8].

Parameter	Value			
Battery Voltage				3.3 – 4.2 V
Consumption	ON	Sleep	Deep Sleep	Hibernate
	9 mA	62 µA	62 µA	0.7 µA
GPS Module	ON			OFF
	36 mA			0 µA
SD Card	ON			OFF
	14 mA			0 µA
XBEE	ON	Sleep		OFF
	37-64 mA	1-93 mA		0 µA
Accelerometer	ON			Hibernate
	65 mA			O µA
GPRS Module	ON	Sleep		Hibernate
	10-400 mA	1-2 mA		56 µA

3 Proposed System Model

This section presents the system model used for production of total energy that is harvested from solar cell and wind turbine. Total amount of harvested energy is calculated by adding the amount of energy separately harvested from sunlight and wind energy respectively. Mathematically, we can compute the power output produced by MSX-00F by using Eq. (2). The power output produced by MSX-00F depends on the various factors like location where it is placed and climatic condition. For example, if we consider daily averaged solar irradiance D = 4.29 KWh/m^2 then the amount of power produced by MSX-00Fby using Eq. (2) is 49.90 Wh. Figure1 show the monthly averaged solar power output generated by MSX-005F solar cell (by using Eq. (2)) corresponding to data of solar irradiance in Thanesar (Haryana, India) for all months of the year. Value of the monthly solar radiance is taken from the NASA Program: RETScreen [9] i.e., solar irradiance (D) is: 3.58, 4.39, 5.59, 6.1, 6.4, 6.2, 5.5, 5.14, 5.23, 4.71, 4.02, 3.36 KWh/m^2/day. We can clearly see from the Fig. 1 the amount of energy harvested by MSX-00F depends on the solar irradiance i.e., greater the solar irradiance, larger amount of energy is harvested by MSX-00F solar panel.

$$P_{so} = D \times \eta \times A \tag{2}$$

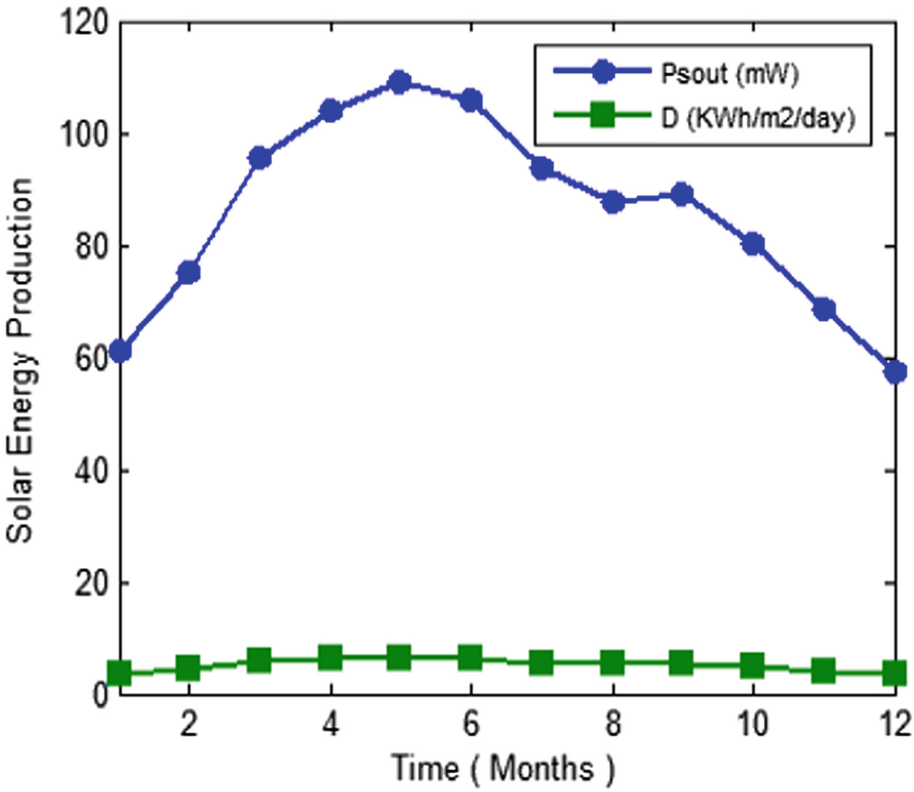

Fig. 1. Monthly averaged solar power produced by MSX-00F and monthly averaged solar irradiance in Thanesar (Haryana, India)

Like sunlight, the amount of power harvested by PIMWEH [7] from wind speed is calculated by using Eq. (3) where, ρ is the air mass density in Kgm^{-3}, A is the turbine rotor area in m^2 and v is wind speed in m/s. The air mass density is calculated at 1 atmospheric pressure with the help of an online calculator [10]. Area of wind turbine is calculated by using Eq. (4) which depends on rotor radius R (in m). The amount of power output produced by wind energy harvester depends on the climatic conditions like wind speed. For example, if we consider daily averaged solar irradiance $v = 3.70$ m/s then the amount of power produced by PIMWEH by using Eqs. (3) and (4) is 6.13 mW. Figure 2 shows the monthly averaged wind power generated by PIMWEH [7] (by using Eq. (3)) corresponding to the data of monthly average wind speed in Thanesar (Haryana, India) for all month of the year. Value of the monthly wind speed is taken from the NASA Program: RETScreen [9] i.e., wind speed is: 2.87, 3.37, 3.70, 3.69, 2.98, 3.18, 2.61, 2.55, 2.31, 1.99, 2.58, 2.76 m/s. We can clearly see from the Fig. 2 the amount of energy harvested by PIMWEH depends on the wind speed and rotor diameter.

$$P_{wo} = \frac{1}{2} \times \rho \times A \times v^3 \tag{3}$$

$$A = \pi R^2 \tag{4}$$

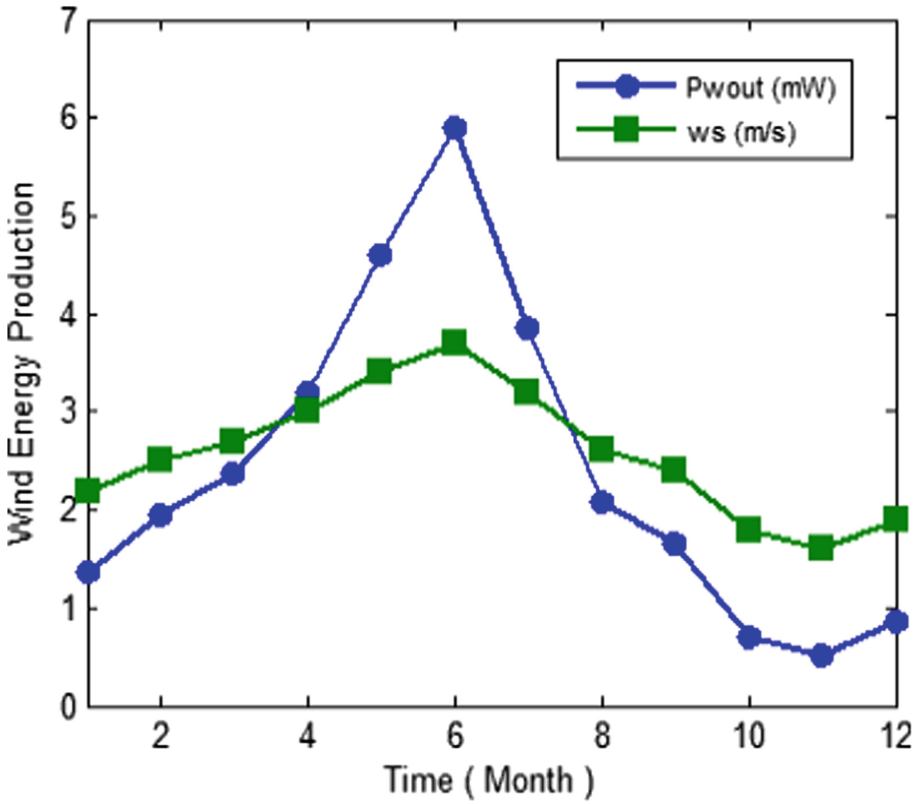

Fig. 2. Monthly averaged wind power produced by PIMWEH and monthly averaged wind speed in Thanesar (Haryana, India)

The energy produced by the solar panel is calculated by using Eq. (5). Like solar energy, wind energy (E_{wo}) is calculated. Total Energy Power Output (P_o) is calculated by combining power separately generated by solar panel and wind turbine. Total Energy Production (E_P) is calculated by combining energy produced by solar panel and wind turbine as shown in Eq. (7). Total power output we get after adding the amount of energy harvested by MSX-00SF and PIMWEH is shown in Fig. 3. As shown in Figs. 1, 2 and 3, more amount of energy is harvested after combining solar and wind energy harvester as compared to a single solar panel or a wind energy harvester.

$$Esp = \frac{P_{so}}{V_{Id}} \quad (5)$$

$$P_o = P_{so} + P_{wo} \quad (6)$$

$$E_p = E_{sp} + E_{wp} \quad (7)$$

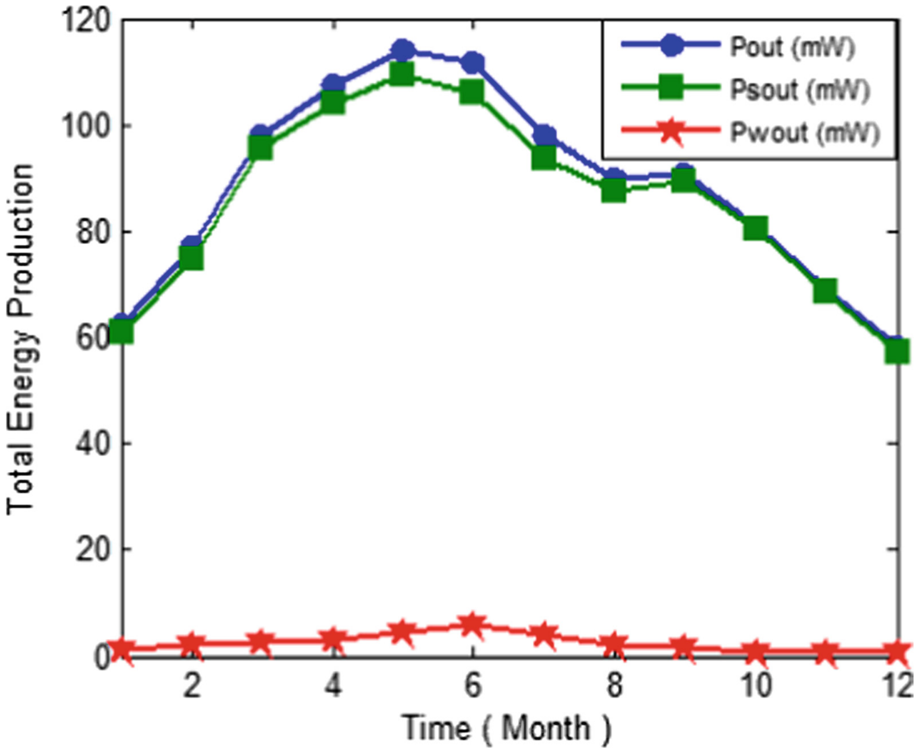

Fig. 3. Monthly averaged total power, solar power and wind power produced by our proposed multi-source energy harvesting system, MSX-00F and PIMWEH in Thanesar (Haryana, India)

Mathematically we can also calculate the amount of energy produced by photovoltaic cell at any time t by using the zenith angle. For calculating the solar power at any instance of time, firstly we need to calculate the instantaneous solar irradiance at that time. The instantaneous solar irradiance at any time t in a day varies according to the climate changes at that time and zenith angle (θ_z) between vertical axes of earth surface and the sun. Solar radiance at time t is calculated [11] by using Eq. (8). Zenithangle θ_z [11] is computed by using Eq. (9) where γ is the latitude of geographical location where photovoltaic cell is placed $\boldsymbol{\beta}$ is solar declination angle and h is time of day. β is calculated by using Eq. (10) where d represents the specific day of the year, d $\in [1, 365]$. h is calculated by using Eq. (11) where t is the solar time and $t \in$ [0, 23].

Finally the hourly averaged solar power output is computed by using Eq. (12). Figure 4 shows the hourly averaged solar power generated corresponding to some specificday of January, May, July, September and November, i.e., 26th January, 27th may, 16th july, 24th September and 4th November, in Thanesar (Haryana, India) by using Eqs. (8–12). As shown in Fig. 4, the solar irradiance is approximately zero before sunrise and after sunset that's why the power output produced by MSX-00F is approximately zero before 6:00 am (sunrise) and after 6:00 pm (sunset). Figure 4 clearly shows that power produced by MSX-00F in a day make a parabola curve and maximum power output is produced at 12:00 h for all days of the year.

$$D(t) = D\,cos(\theta z) \tag{8}$$

$$\theta_z = cos^{-1}(sin\gamma sin\beta + cos\gamma cos\beta cosh) \tag{9}$$

$$\beta = 23.45^o \times \left(360^o\left(\frac{284+d}{366}\right)\right) \tag{10}$$

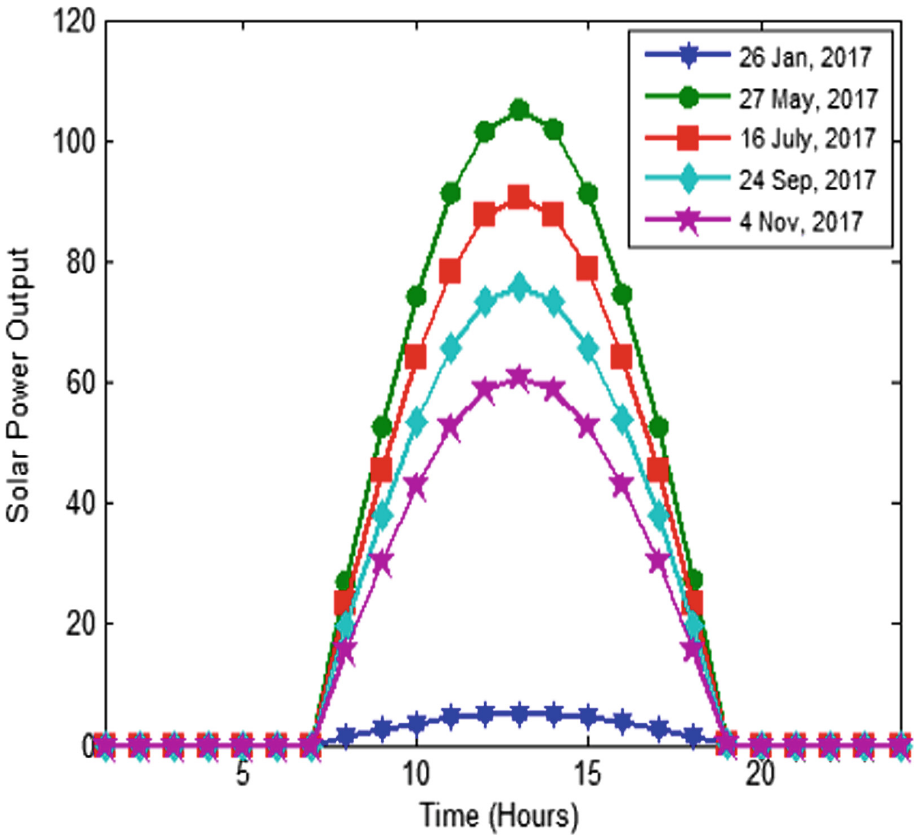

Fig. 4. Hourly averaged solar power output produced by MSX-00F for some specific days of the year

$$h = 15^o(t - 12) \tag{11}$$

$$E_{so}(t) = \frac{(D(t) \times \eta \times A)}{V_{ld}} \tag{12}$$

Similar to solar power, for calculating the wind power at any instance of time, firstly, we need to calculate wind speed at that time. The instantaneous wind speed at any time t depends upon the climatic conditions and daily averaged wind speed. Wind speed at any time t is calculated by using Eq. (13) [12] where h is the hour, $h \in [0, 23]$ at which wind speed is calculated, W_h represent wind speed at any hour h and W_a represent the daily averaged wind speed. Figure 5 shows the hourly averaged wind power output generated corresponding to some specific day of January, May, July, September and November, i.e., 26th January, 27th may, 16th july, 24th September and 4th November, in Thanesar (Haryana, India) by using Eq. (13). As shown in Fig. 5, like solar power there is no fixed time when amount of energy harvested by wind speed is zero. Figure 5 clearly shows that power produced by PIMWEH is not depends on the timing of the day.

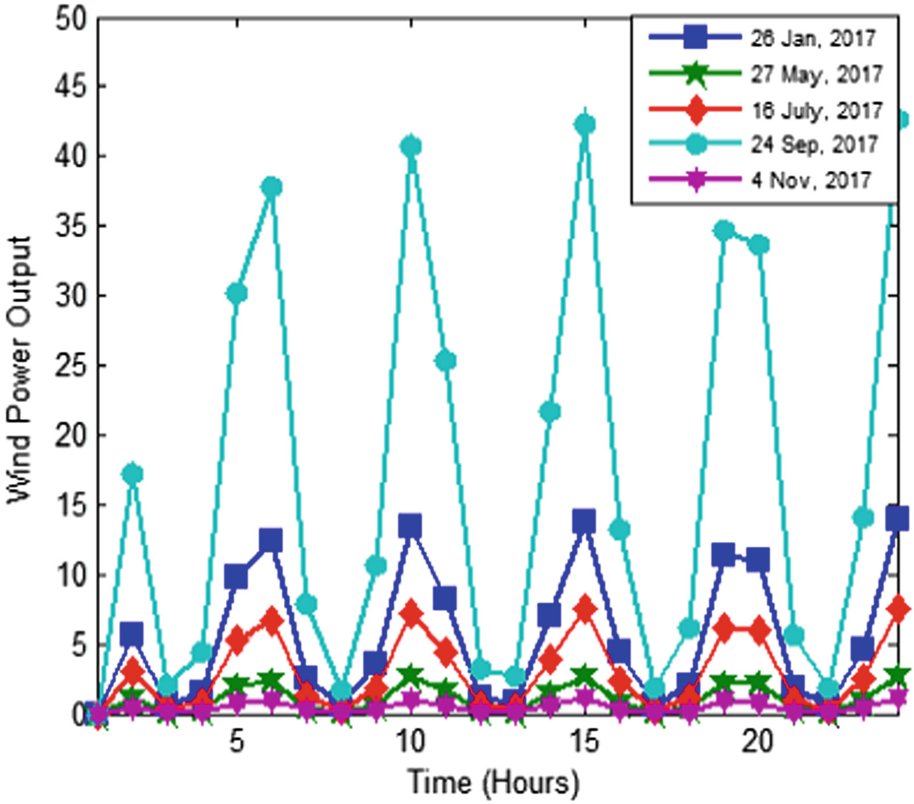

Fig. 5. Hourly averaged wind power outputs produced by PIMWEH for some specific days of the year

$$W_h = W_a + \frac{1}{2} W_a \times cos\left(\frac{h.\pi}{12}\right) \quad (13)$$

By Comparing Figs. 4 and 5 we can easily see that the amount of energy harvested from wind speed is very less as compare to amount of energy harvested from sunlight for same five days of a year. But Figs. 4 and 5 also shows that wind energy harvester also produces power for those hours when solar power output is zero, for example before sunrise and after sunset. If we combine the power output produced by theMSX-00F and PIMWEH, more amount of energy is harvestedas compare to single MSX-00F and PIMWEH. Figure 6 clearly shows more amount of energy is harvested by our multi-source energy harvesting system as compare to single solar cell and wind energy harvester. Figure 6 also shows that our proposed energy harvesting system produce energy for those hours when the amount of energy harvested by single solar cell is zero. With the increase in output power, definitely the lifetime of the sensor node will also increase.

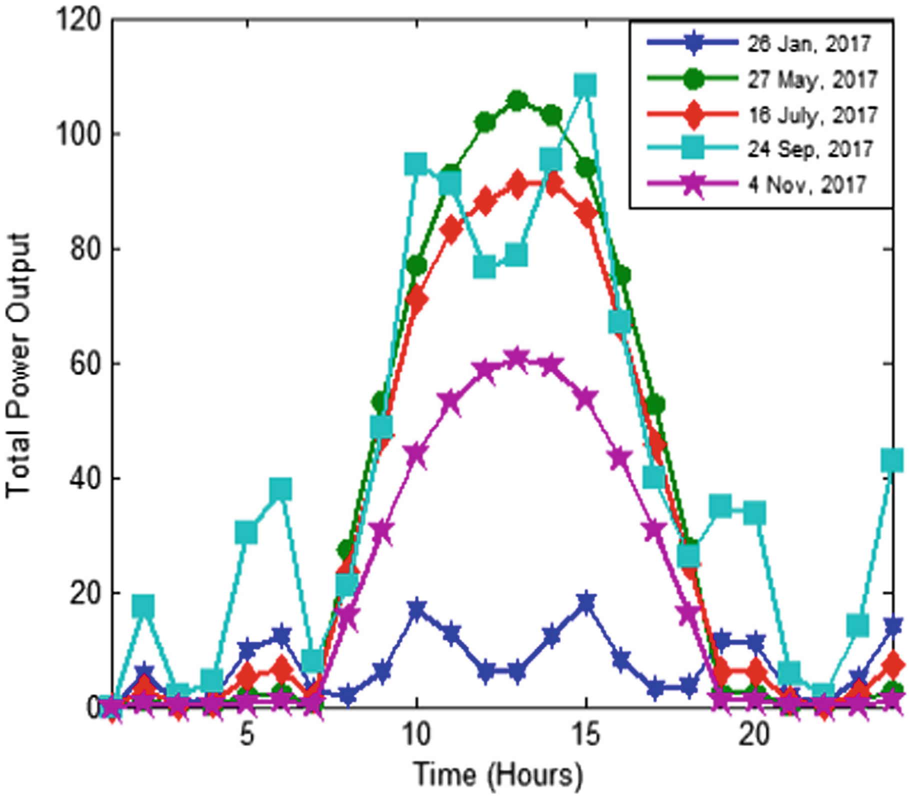

Fig. 6. Total hourly averaged (solar and wind) power outputs produced by our multi-source energy harvesting system for some specific days of the year

4 Energy Consumption Model

In this section, we present the energy consumption model of Waspmote. In our work battery is charged by energy produced by multiple source energy harvesting system and battery discharging depends on the energy consumption of component of waspmote. Discharging time of battery depends on two factors: first is the battery capacity and second is the amount of current draw required for working of sensor node. For example, consider Zero energy is produced by harvesting system then the discharge time of the battery is computed by using Eq. (14). For example, if capacity of the battery is 2500 mAh, and required current draw is 200 mA then total time taken to completely discharge the battery is 12.5 h. Note however the current draw required by any application is not constant, it depends on the requirement of the system. Similarly, charging time of battery depends upon two factors: first the capacity of the battery and second is the energy produced by the harvesting system. For example consider energy consumption is zero and battery is recharged by the energy harvested by energy harvesting system, then battery charging time is calculated by using Eq. (15). For example, capacity of the battery is 2500 mAh and the energy produced by the harvesting system is 25 mA then time taken for completely charging the battery is 100 h. However, note that the energy produced by the harvesting system depends on the geographical location, climatic condition and solar time.

$$Discharge\,Time = \frac{Battery\,Capacity\,(in\,mAh)}{Curent\,Draw\,(in\,mA)} \tag{14}$$

$$charge\,Time = \frac{Battery\,Capacity\,(in\,mAh)}{Produced\,energy\,(in\,mA)} \tag{15}$$

5 Conclusion

Energy harvesting systems have turned into an exceptionally engaging strategy to drag out the lifetime of IoT network. However, the energy produced by a single solar panel or a wind energy harvester is not sufficient to continuously fulfill the power demand of a sensor node. In this paper, we propose a multi-source energy harvesting system consist of solar panel and wind turbine. We compute the hourly averaged energy produced by our proposed multi-source energy harvesting system and the energy consumption of our Waspmote sensor node. The simulation results show that our multi-source energy harvesting system produces more energy as compared to a single solar panel or a wind turbine.

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