Optimisation of solar power intake for wireless sensor networks at temperate latitudes

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Abstract—In many outdoor locations solar power provides the greatest power densities for energy harvesting to power wireless sensor networks in comparison to other practical alternatives such as wind, vibrations or temperature gradients. Since solar power is highly variable with location and time, it is necessary to optimise the sensor nodes for individual locations. Presented here, is an assessment of the solar power availability in Manchester, UK (53°28′N, 2°14′W). Wireless sensor nodes are typically low power devices with intended perpetual operation and thus the temporal distribution of available power is important together with the total amount of energy drawn over a given time period. Here we examine direct and diffuse solar radiation data over a period of three years and present methods for the deployment of solar cells for sensor nodes to optimise sensing and communication scenarios. As local weather conditions are highly variable and stochastic in the medium term, we base the future node performance on the weather from a previous year. From analysis of the weather data, the hardware requirements for the sensor node are then made from the power consumption of the sensor node for sensing, sleep and data transmission. It was found that to maximise the time over which the solar irradiance exceeds that required to power our demonstration sensor node, the solar cell should be positioned horizontally.

Keywords - wireless sensor networks; energy harvesting; energy budgeting; solar power

I. INTRODUCTION

Recent advances in energy harvesting have opened up the possibility for the development of perpetually powered wireless sensor networks [1-3]. The most commonly used power sources for energy harvesting are shown in Table 1 with their typical available power densities.

Although solar power offers the greatest peak densities, the chief drawback is limited and stochastic availability. This is particularly the case for mid latitudes where power densities are lower and daylight duration is more varied than in lower latitudes. Additionally, local weather patterns greatly influence solar availability over the medium term (hours and days). As such, average available solar power density is considerably less than the peak powers of 1 kW/m\textsuperscript{2} figure from direct sunlight typically used at lower latitudes.

As solar power is highly dependent upon weather conditions, weather forecasts have also been used to predict the future solar power for both supplying an energy network [5] and powering wireless sensor networks [6]. These rely on the specific forecasts for the location of the solar cell and allow the sensor node to modulate power consumption according to the present and future power availability [7-10]. The operation of solar powered sensor networks in low and variable lighting conditions have previously been studied in stochastic power situations [11].

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
Power source & Power density (\(\mu\text{W/cm}^2\)) & Condition \\
\hline
Solar & 6,000-10,000 & Manchester (UK), midday outside, direct sunlight, 10\% conversion efficiency \\
\hline
\hline
Vibrations & 200 [4] & \\
\hline
Temperature gradient & 40 [4] & 5°C temperature difference \\
\hline
Air flow & 330 [4] & Air velocity 5m/s, 5\% conversion efficiency \\
\hline
\end{tabular}
\caption{Typical transducer power densities from energy harvesting of common ambient energy sources.}
\end{table}

However, local weather forecasts being made by, or transmitted to, the sensor node, increase node complexity and power overhead and are still limited by the uncertainties inherent in all forecasts. In [12] hardware and protocols are examined where solar micro-generators are used to power sensor nodes. However the astronomical calculations were used to estimate the maximum available power available to the sensor nodes for a given time and location and did not take into account the often stochastic nature of local weather patterns.

Power management methods for adapting the sensor performance to the environment [2, 7] include duty cycling [7, 13, 14] and process scheduling [15].

Here we seek to maximise the consistency of the harvested power from a solar cell over time. This contrasts to grid connected solar cells for large scale energy generation where the total amount of energy is of greatest importance. As wireless sensor nodes need to operate as reliably and consistently as possible, the distribution of the power is of importance in addition to the total amount of energy generated over a given time period. An even spread of power over time minimises the capacity of the internal storage required and minimises the energy lost through charge/discharge cycles.
The energy harvested is analysed, and the minimum solar cell area required to operate the sensor node effectively is calculated under the expected range of power availabilities for a given power consumption of the sensor node. The orientation of the solar cell is then optimised for operation throughout the year to maximise the time for which the harvested power exceeds the minimum power requirement of the sensor node under the expected power availability.

We envisage the developed wireless sensor network powered by this energy harvesting method to be deployable for the remote monitoring of critical assets within the National Grid gas transmission network. Wireless sensor networks have the potential for monitoring remote infrastructure including pipelines [16]. When powered through energy harvesting, the potential for sustainable sensing in remote environments is expanded. As the power availability is spatially variable, the sensor network must be tailored to each specific deployment location. The analysis undertaken here enables the developed sensor network to be created specifically for solar energy harvesting and used in the temperate marine climate dominant throughout the UK.

We present the contributions in sections as follows. Section II contains an outline of the methodology used. In Section III we present an overview of the specific analytical functions used in the calculation. Section IV presents the results of an assessment of the power available for use in an operational sensor network.

II. METHODOLOGY

Solar irradiance from over the year 2011 is used to calculate the orientation of a solar cell. Two different scenarios are envisaged to fulfil different criteria for a solar cell. Under the first condition the total amount of energy harvested over a year is maximised. Under the second, the time is maximised for which the irradiance exceeds a given threshold. By calculating the relative position of the sun for every value of the measured irradiance, the axial solar irradiance can be calculated. Consequently the solar flux through an arbitrarily orientated surface, can then be evaluated for all measured values of solar irradiance.

A solar orientated surface tracking the position of the sun over the year so that the solar radiation is always normal to the cell surface would harvest the maximum energy possible over the year. For low power sensor nodes, it is impractical to use a solar tracking cell as the energy expense would negate the advantages of increased harvested energy. Additionally, for remote monitoring the power harvesters need to be durable and simple. The irradiance upon the cell can then be calculated from the solar irradiance and the angle between the normal to the cell surface and the sun.

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![Diagram showing the calculation of the optimal orientation of a solar cell](image)

Figure 1 Outline of the method for calculation of the optimal orientation of the solar cell from past solar data. Flowchart showing the calculation of optimal orientation for a solar cell using recorded solar data.

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III. METHOD

The solar irradiance data had been collected by the Whitworth weather station at The University of Manchester every 1 minute over the year for both direct and diffuse solar radiation. The irradiance data is obtained using a horizontal pyranometer, recording the solar flux through the horizontal plane. The value of the direct solar radiation in the direction of the sun is then given by

$$H_d(t) = \frac{H_{\theta=0}(t)}{\sin \theta(t)}$$  \(1\)

where \(\theta\) is the elevation of the sun and \(H_d\) and \(H_s\) are the irradiances upon a horizontal surface and one angled towards the sun.

The direct irradiance upon a surface is represented by the vector \(C\) as shown in Figure 2. This can be calculated by taking the scalar product of the cell vector, \(C\), and the solar vector, \(S\). The diffuse solar irradiance upon the surface is from across the whole sky. Therefore, in the present analysis it is assumed that the incident radiation is omni-directional and that zero contribution is made from light reflected from the ground. It is also assumed that there are no obstructions above the horizon. The reference weather station is located on the roof of a tall building and thus fulfils these assumptions. The diffuse radiation incident upon an angled cell can be given by

$$H_{\theta,\phi}(t) = H_{\theta=0} \times (\theta + 90)/180$$  \(2\)

The irradiation for the surface over a one year period can then be obtained through integration as follows:

$$E_{\theta,\phi} = \int_0^{187.5} H_{\theta,\phi}(t) \, dt$$  \(3\)
By enumeration of data points where the surface irradiance exceeds a given critical threshold, the total duration where solar power alone can be sufficient to power the sensor node is calculated. MatLab scripts were developed to perform the necessary vector calculations.

The sensor node used here is built around a low-power micro-processor from Texas Instruments (TI) with additional temperature and humidity sensors. In sleep mode the entire sensor draws 5 μA and each measurement cycle (sensor interrogation, data conditioning and data transmission) draws 350 μJ. Thus operating the sensor with a 10 second sleep cycle draws an average power of 40 μW. The solar cell used is an amorphous silicon cell with a surface area of 32 cm². Given a solar cell efficiency of 10% [17] and a DC-DC converter power consumption of 20 μA [18] an incident irradiance of 0.5 W/m² is sufficient to power the sensor continuously. Given that it can be expected that the solar cell will be illuminated for a minimum of 6 hours per day, a minimum average irradiance of 1 W/m² during daylight hours will harvest sufficient energy during the day to power the sensor overnight and provide continuous sensing.

To provide the sensor node with sufficient power to operate overnight (up to 18 hours), the battery capacity thus has to be at least 720 μAh. By maximising the time for which the harvested power exceeds the threshold required to operate the sensor node and provide sufficient power to charge the battery for powering the sensor overnight, the sensor node minimises the charging/discharging of the battery. As each charge cycle reduces the lifetime of the battery and the charge/discharge cycle has a non-unity efficiency, this is beneficial for the long-term deployment of the sensor node.

IV. RESULTS

The orientation of a solar cell influences both the total amount of energy that may be harvested over a given time frame and the distribution of the power.

As can be seen in Figure 3, the maximum time for which the incident solar irradiance exceeds 10 W/cm² occurs when normal to the solar cell is vertical (θ = 90°). This is not the same orientation as that for maximum total energy, as shown in Figure 4.

As can be seen in Figure 3, the maximum time for which the incident solar irradiance exceeds the critical threshold of 50W/m² as a function of the cell orientation (as defined in Figure 2). The time is indicated by the colour.

As can be seen in Figure 3, the maximum time for which the incident solar irradiance exceeds 10 W/cm² occurs when normal to the solar cell is vertical (θ = 90°). This is not the same orientation as that for maximum total energy, as shown in Figure 4.

Figure 3 The time for which the solar irradiance exceeds the critical threshold of 50W/m² as a function of the cell orientation (as defined in Figure 2). The time is indicated by the colour.

Figure 4 The solar energy density upon an angled plane as a function of the orientation for the sum of diffuse and direct radiation. The maximum energy density is $3.4380 \times 10^{9} \text{J/m}^2$ and occurs at $\theta = 67^\circ$, $\phi = 186^\circ$.

Figure 5 shows the time for which the irradiance exceeds 100 W/cm² as a function of the cell orientation. As can be seen, whereas for low thresholds the orientation of the cell towards due south ($\phi = 180^\circ$) decreases the time for which the threshold is exceeded, for greater thresholds
greater durations of excess energy occur when the cell is angled towards the south.

As shown in Table 4 the orientation of the cell to maximise the duration over which the solar irradiance exceeds a critical threshold is a function of the threshold itself.

As shown in Table 2, the maximum energy harvested occurs when the solar cell is orientated with $\theta = 67^\circ$, $\phi = 186^\circ$.

<table>
<thead>
<tr>
<th>Radiation</th>
<th>Max. Energy ($\times 10^4$ J/m$^2$)</th>
<th>$\Theta$ ($^\circ$)</th>
<th>$\Phi$ ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>1.8967</td>
<td>47</td>
<td>186</td>
</tr>
<tr>
<td>Diffuse</td>
<td>1.8815</td>
<td>90</td>
<td>-</td>
</tr>
<tr>
<td>Direct +</td>
<td>3.4380</td>
<td>67</td>
<td>186</td>
</tr>
<tr>
<td>Diffuse</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 The maximum solar energy incident upon the cell occurs for different orientations of the cell for diffuse and direct radiation.

<table>
<thead>
<tr>
<th>Radiation</th>
<th>Max. Time (s)</th>
<th>$\Theta$ ($^\circ$)</th>
<th>$\Phi$ ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>7.01496 $\times 10^5$</td>
<td>74</td>
<td>174</td>
</tr>
<tr>
<td>Diffuse</td>
<td>1.4610 $\times 10^7$</td>
<td>90</td>
<td>-</td>
</tr>
<tr>
<td>Direct +</td>
<td>1.4625 $\times 10^7$</td>
<td>90</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3 The time for which the irradiance exceeds the critical threshold, $P_c$, for diffuse and direct radiation ($P_{crit} = 10\, \text{W/m}^2$).

The distribution of solar irradiance is such that with increasing critical thresholds, the optimal orientation changes, as shown in Table 4.

<table>
<thead>
<tr>
<th>$P_{crit}$</th>
<th>Time ($\times 10^5$ s)</th>
<th>$\Theta$ ($^\circ$)</th>
<th>$\Phi$ ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>14.625</td>
<td>90</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>11.429</td>
<td>90</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>8.9708</td>
<td>90</td>
<td>-</td>
</tr>
<tr>
<td>200</td>
<td>5.9272</td>
<td>86</td>
<td>190</td>
</tr>
<tr>
<td>250</td>
<td>2.2962</td>
<td>52</td>
<td>186</td>
</tr>
</tbody>
</table>

Table 4 The orientation of the cell to maximise the duration over which the solar irradiance exceeds a critical threshold is a function of the threshold.

V. DISCUSSION

Analysis of past weather data has shown that at a temperate latitude the total solar energy is split between diffuse and direct radiation sources. To optimise the harvesting of the direct and diffuse components different solar cell orientations are required. As diffuse radiation is omnidirectional, the greatest power density is achieved when the solar cell is horizontal and can harvest light from the whole sky. The power supplied by the direct radiation is more variable as it is influenced more dramatically by the weather. In the test location (Manchester, UK) the maximum energy harvested over a year from direct radiation is most when the solar cell is orientated at $\theta = 47^\circ$, $\phi = 186^\circ$. This is distinct from diffuse radiation where the maximum energy harvested is achieved when the solar cell is horizontal.

As direct solar radiation can achieve greater power densities than diffuse radiation, though the solar cell is not optimised for the direct radiation, high power densities are still possible.

By positioning the solar cell to maximise incident diffuse solar radiation, the time for which the incident solar radiation exceeds the 50 W/m$^2$ threshold is increased by 4.1% over that where direct solar radiation is optimised. As diffuse radiation has a lower irradiance, this reduces the total energy harvested by the sensor node by 4.0% over the course of the year. For powering a perpetual sensor node, the distribution of power over time in addition to the total energy available over the year that is of importance, despite the reduction in total harvested energy there is still an increase in functionality of the sensor node. By maximising the duration of energy harvesting, the sensor node is able to operate more consistently and increase sensor functionality, in turn increasing the available applications of the sensor network.

In the instance where the test sensor node is operated from two AAA batteries, the typical alkaline AAA battery has a capacity of 1150 mAh and a terminal voltage of 1.2 V, giving a combined energy capacity of 10 kJ. This would be sufficient to power the sensor node used here (with an average power consumption of 40 mW) for almost 8 years. However, for long term sensor deployment this may still limit the lifetime of the sensor node. A solar cell with a surface area of 32 cm$^2$ and an efficiency of 10%,
over the course of a year would harvest 1.1 MJ of energy, or the equivalent energy of 220 AAA alkaline cells. As ambient energy is limitless, a solar cell allows the sensor node to operate for the lifetime of the hardware without needing physical intervention. As many wireless sensor networks are located in remote or hostile environments, this presents an increase in the potential deployments of wireless sensor networks. Similarly, the solar cell used here, over the course of a year is capable of supplying 870 times the amount of energy required to power the sensor node used here with a 10 second sensing cycle.

As the sensor node is still required to operate when there is no ambient energy, a secondary cell is required to store energy. To power the sensor overnight (up to 18 hours) requires a cell with a capacity of 720 µAhr for the sensor node used here. This is 3 orders of magnitude less than that of a typical AAA rechargeable battery and can be provided by a small number of solid state lithium-ion cells [19].

VI. CONCLUSION

Thus in conclusion energy harvesting is able to provide sufficient power densities to be of practical use in low power wireless sensor networks. By utilising low power electronics, sensors and radios, a sensor network can operate with a maximum latency of 10 seconds within the confines of an energy harvesting power supply.

The orientation of the solar cell affects the duration and extent of the available power which is composed of direct and indirect solar radiation. We have shown from analysis of past solar radiation that to maximise the duration of energy harvesting, in a temperate and power limited climate, the solar cell should be orientated horizontally.

To summarise, here we have presented the orientation of the solar cell so as to maximise the duration of energy harvesting from solar radiation in a temperate climate to maximise the utility of a low power wireless sensor network.

ACKNOWLEDGEMENT

This work was supported by National Grid through an iCase studentship which is funded through the company’s Network Innovation framework. The authors would also like to thank the Whitworth Observatory for the kind use of the solar irradiance dataset.

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