Conference Proceedings

ASES National Solar Conference 2016

San Francisco, CA, USA July 10-13, 2016

A Case Study on the Merits and Design of a Solar Powered Internet of Things: Intelligent Window Shades

David Drake[1], John Stewart Preston[1]

[1] McMaster University, Hamilton (Canada)

Abstract

The Internet of Things (IoT) is the concept of integrating smart electronics into ordinary objects so that all these devices can work together to provide advanced services to their user. Estimates of the value of this market are in the trillions and are recognized by market surveys and company estimates. Conventional wired power is not appropriate for all IoT devices. Of available energy harvesting techniques, solar is one of the most mature, robust and energy dense solutions. A case study of the design of a solar powered window shade is reviewed. Methods to ensure the prototype can: cheaply optimize power generation, operate robustly and function with energy neutrality are reviewed. These design techniques could be applied to other solar powered IoT devices.

Keywords: *Internet of Things, Energy Harvesting, Solar, Design, Prototype, Energy Neutrality*

1. Internet of Things

The internet of things (IoT) is an exciting, developing field. Objects with integrated communication electronics, sensors and actuators can work together to provide coordinated, intelligent, services. Collecting data from industrial assets for use in a predictive maintenance schedule has been shown to save up to 12% on scheduled repairs and up to 30% on overall maintenance costs while avoiding up to 70% of breakdowns (GE, 2015). Using smart tags on patients and advanced analytics to optimize patient flow, a leading Florida based hospital was able to reduce wait times by 68% (GE, 2015). Smart, networked devices have been shown to reduce waste and provide useful services in many different contexts.

Various market specialists have developed methods to quantify the value of the IoT. General Electric (GE) (2015) reports that the value of industrial IoT, neglecting consumer or retail, to be $500 billion by 2020, increasing to $15 trillion by 2030. Cisco reports that between 2013 and 2022 the entire value of IoT will be $14.4 trillion (Bradley et al., 2013). By analyzing the house sales of automated and conventional homes, Petersen et al. (2001) found that home buyers are willing to pay a 27% premium for homes with automated systems. Not only is IoT useful, it also a technology with current market value and should be developed further.

2. Benefits of Solar Energy Harvesting

Devices that require portability, remote deployment or cheap installation, may not be adequately serviced by conventional wired power. Rabaey et al. (2000) discussed the implications of installing individual wiring for sensors, estimating the cost at $200 per sensor. Portable batteries are commonly used to solve this problem, but batteries have a finite capacity and there is a maintenance cost associated with replacing or recharging dead batteries. Harvesting energy from a local source offers a potential solution to this problem.

A simple IoT device gathers and relays information about its location. Such a device requires a microcontroller, transceiver, sensor and power supply. These designs typically require between 15-1500 μW

doi:10.18086/solar.2016.01.05 Available at http://proceedings.ises.org

while in sleep mode and 5,000-80,000 µW while active (Beeby and White, 2010). More complicated IoT devices, such as a motorized window shade, would include an actuator to allow the system to respond to external conditions, further increasing power requirements. Modifying the duty cycle so the node is put to sleep more frequently will reduce its average power demand.

A variety of different energy sources and their potential electrical energy densities are presented in Table 1. While each of solar, piezoelectric and thermoelectric technologies are able to supply a similar level of power to an IoT device's sleep power, there are several advantages to solar. The unattenuated natural sunlight provides around 100 mW/cm^2 of radiant flux which a solar cell can convert into roughly 15 mW/cm^2 of electricity. Experimental work has indicated that a double pane window with a LOE180 coating from Cardinal Glass industries will transmit up to 70% of useful light. An alternative product, a triple pane window with a heavier LOE272 coating, was found to only transmit 30% of useful light. Even considering this light attenuation, a solar cell with direct line of sight of the sun could generate orders of magnitude more power than alternatives. An indoor solar cell can only generate around 15 µW/cm^2; an amount on par with thermal and piezoelectric alternatives. Even though power may be limited by dim indoor lighting, application mobility is not. Light spreads throughout a well-lit room allowing an energy harvester to be placed in many locations. Further, the maturity of solar technology makes the technology affordable and easy to source.

Tab. 1: Sources of ambient energy

Energy Source	Converted Electrical Power Density	Information Source
Solar Cell (outdoor average)	15,000 µW/cm^2	AM 1.5 Spectrum
Solar cell (inside through double pane LOE180 window)	10,500 µW/cm^2	Experimental
Solar cell (inside through triple pane window with two coatings of LOE272)	4,500 µW/cm^2	Experimental
Solar cell converting indoor light	15 µW/cm^2	Paradiso and Starner 2005
5°C temperature gradient using thermoelectric generator	60 µW/cm^2	Paradiso and Starner 2005
Vibrating Microwave with Piezoelectric	60 µW/cm^3	Roundy 2003
75 dB Acoustic Noise with Piezoelectric	0.003 µW/cm^3	Roundy 2003

3. Motorized Window Blind Case Study

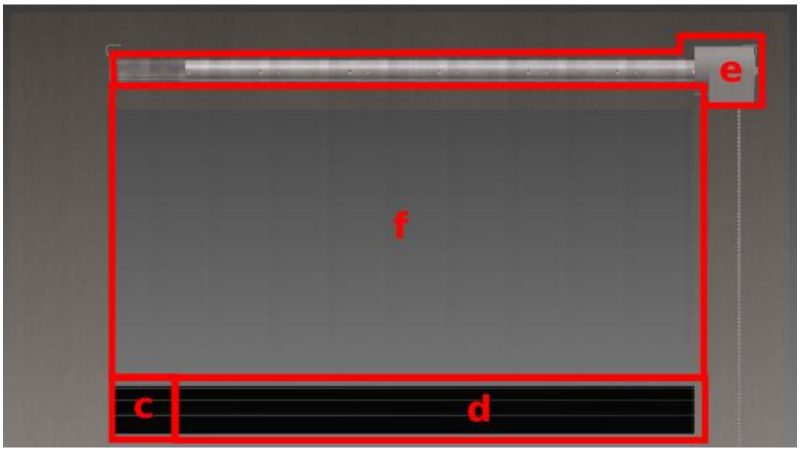
As an IoT device, motorized window shades provide several benefits to their users. O'Brian et al. (2013) conducted a comprehensive review of studies exploring occupant use of window shades over the past 35 years. Multiple studies have concluded that when window dressings are easier to operate, building inhabitants will use them more frequently implying that the user receives improved utility from the device. One study noted an increase in use by a factor of three by introducing automated controls. Occupants are not likely to use their window dressings to optimize energy performance of the building. They don't modify the position of window dressings in anticipation of future thermal conditions; instead they change blind position for immediate needs such as reduction of glare or improved privacy. This problem is exacerbated in public areas like hallways, waiting areas, or shared offices because people do not want to disturb other occupants or will not be in that space long enough to be bothered by the thermal conditions. Automated IoT solutions could predictively manage shades to optimize a building's passive thermal performance while also offering inhabitants a more convenient method of operating nearby window blinds.

The large power density of photovoltaic cells using window attenuated solar irradiance is quite high. Since window blinds are naturally placed directly behind a glazing, it makes sense to use solar energy to power this device. The remainder of this section examines the unique design features and analysis used to integrate solar power into a motorized blind prototype.

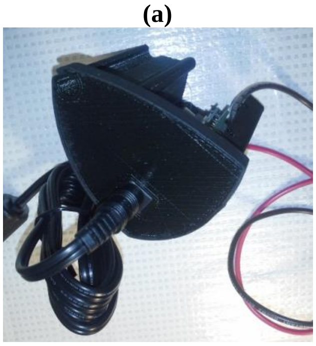
3.1. Prototype

The completed motorized blind prototype is shown in Fig. 1 (a) with images of the various subsystems shown in Fig. 1 (b)-(f). It was constructed by adding custom electronics and actuators to a conventional roller shade. This type of window dressing requires a bottom rail to keep the suspended fabric flat. The prototype's bottom rail was redesigned to integrate a solar array. A full electrical system was designed to ensure wireless uninterrupted operation. Nickel Metal Hydride (NiMH) batteries were selected to receive a trickle charge from the solar array and provide power to the device when light is not available. A microcontroller tracks operation and control's when the motor moves the blinds. A wireless chip connects the prototype to the user's local Wi-Fi network to communicate directly with a server without the need of any intermediary device. The majority of control electronics are hidden with the top cylinder of the blind to hide the operating circuitry from the sight of the user.

(a)



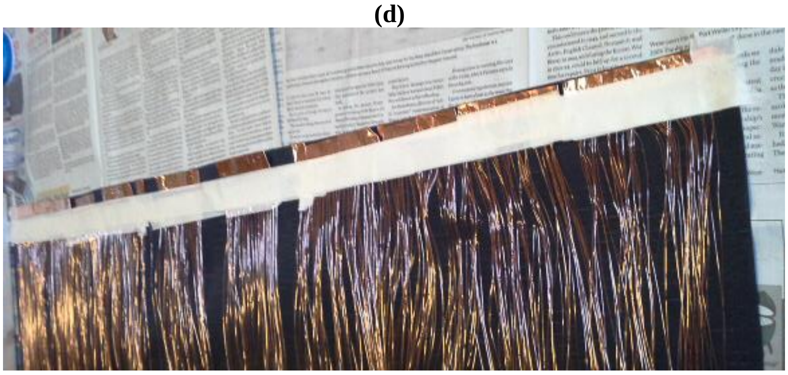
(b)



(c)

(d)

(e)



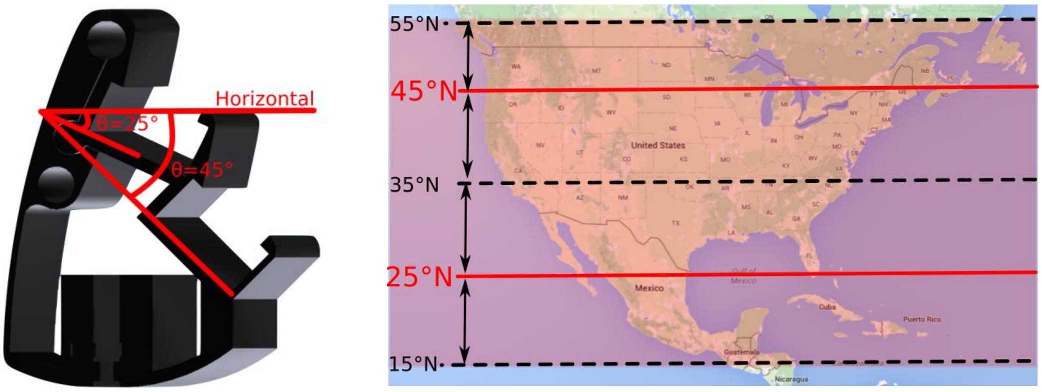
(f)

Fig. 1: Images of the prototype assembly. (a) is the entire assembled prototype. (b) illustrates the various subsystems that are shown in images (c)-(f). (c) is a backup recharging mechanism while the primary solar harvesting array is shown in (d). The electronics that operate the window blind are shown in (e). The solar array and control electronics are connected through conductive fabric shown in (f).

3.2. Economical Power Optimization

Many methods are known to improve the ability of solar panels to generate electricity. Many variables must be considered while implementing these techniques such as increased component cost, or extended development time. Some well-known techniques were simplified to optimize electrical generation in the solar powered blind prototype.

The more direct light a solar cell receives, the greater the output power. Tracking solar farms use this to their advantage by employing automated systems that physically manoeuvre panels to maximize direct sunlight. A lower cost technique is to mount solar panels at a static angle that maximizes their yearly generation potential. North American solar farms that employ this technique typically orient their panels due south at an angle equal to the location's latitude. Studies have shown that the maximum energy generated is insensitive to panel tilt within $\pm 10°$ of the optimal tilt angle (Rowlands et al., 2011) (Qui and Riffat, 2003). To ensure this prototype has versatile generation capability, the bottom rail was designed with grooves capable of holding two rows of solar panels tilted at angles 25° and 45° from the horizontal as shown in Fig. 2 (a). One of the two rows will be mounted at near its optimal static angle for the large population of potential users who live in latitudes of 15°N to 55°N. There are additional advantages to this configuration such as a smoother overall power generation profile. For example, in a southern location, the shallow tilt should produce more power overall, but at certain times, like sunrise or sunset, the sun may be low in the sky allowing the steeper tilted array to pick up the slack.



(a) (b)

Fig. 2: Cheap methods of optimizing power. (a) shows the angled grooves where solar arrays are installed at the bottom rail. These angles were designed to optimize incident light collection at a variety of latitudes. (b) shows the lattitudes where these angles are optimized (red lines) and the region where one of the arrays collects near optimal solar energy (red overlay).

The available power from a solar array is a function of the terminal voltage and can vary from its maximum to a level near zero. Maximum power point trackers (MPPT) are commonly employed in large scale commercial generation facilities to ensure that solar modules operate near their theoretical maximum. While a custom MPPT could be designed for IoT applications it would require development time and the extra cost of parts.

The prototype's battery pack was connected directly to the solar array. The battery voltage dictates the operating point of the solar array. The NiMH battery pack is made of 12 series cells and operates between a range of 10.9 V and 17.5 V based on the remaining charge. The solar array is 32 series cells with a peak power point located at about 16 V when illuminated with 1 sun. The battery forces the solar cells to operate at a level near their maximum power point as shown in Fig. 3. This simple connection expedited the development of a working prototype that operates near the maximum power point. The benefits of integrating a custom MPPT can be revisited in future design iterations.

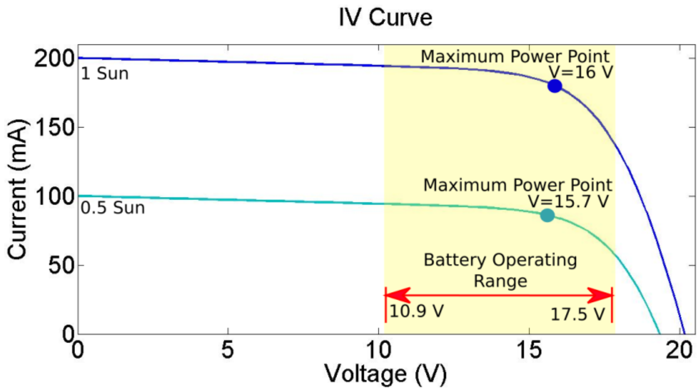


Fig. 3: The IV curve of the solar cell with the operating range of the battery overlaid in yellow. The battery pack enforces a near optimal terminal voltage on the solar array.

3.3. Robust Operation

Consideration must be given to the variability of the environments this device could be deployed in. Care was taken to ensure the design would operate where impinging sunlight was unreliable.

Window grilles or external obstructions such as a leafy tree could cause spotty covering of direct sunlight. When shaded, series-connected solar cells become loads that limit the ability of the series stack to generate current. One solution is to wire cells in parallel. A shaded cell would not contribute current, but would not inhibit other cells from contributing current either. This solution was applied to the extent feasible. Four stacks of 32 series solar cells were placed in parallel. The 32 series cells were necessary to match the battery pack's operating voltage. To further improve performance, Schottky bypass diodes were placed across every 8 cells. If significant shading occurred across 8 cells, current from the remainder of the stack could flow through the diode with reduced system losses.

It is possible that the solar array could end up entirely shaded, forcing the system to operate off battery power until the battery is depleted of charge. A secondary recharging mechanism was designed to allow users to recharge the system in a convenient and accessible way. Fig. 1 (c) shows a wall adapter power supply plugged into the bottom rail to provide power to recharge the system. This mechanism doesn't require the user to open up their device. By locating the connection in the bottom rail, users can access the connector with minimal effort.

3.4. Energy Neutral System

In order to keep the solar powered blind running continuously the system must operate with energy neutrality. This means that the total energy harvested must equal the energy used. This concept contrasts the business models of solar farms that sell electricity immediately as it is generated. Energy neutrality was ensured by including battery storage to power the load in the absence of light.

With any self-powered system, it is necessary to develop an understanding of what ambient energy is required for the system to stay reliably powered. This section reviews several techniques used to analyse the required irradiance to balance the solar powered blind prototype. These techniques assume a sinusoidal irradiance profile as shown in Fig. 4. Given various day lengths, the input irradiance varies from 0 mW/cm^2 to a maximum value, Φ_{max}. The following analysis techniques estimate what value of Φ_{max} would allow the system to operate continuously.

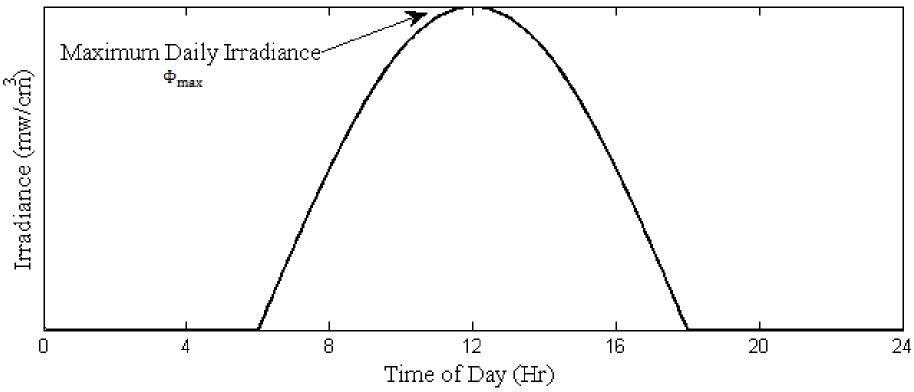


Fig. 4: Assumed daily irradiance profile used for energy balance. This particular profile considers a 12 hour day, however, other day lengths have been considered.

3.4.1 Analytical Energy Balance

An analytic expression for minimum necessary irradiance can be developed using several simplifications. Consider an almost empty battery operating with a voltage of 10.9 V. This voltage is far lower than the typical peak power point of the solar array so the entire array is modelled by a simple current source that operates at its short circuit current point (I_{array}). This value varies from the datasheet value (I_{sc}) which is taken when the cell is illuminated by a standard flux (Φ_{std}) of 100 mW/cm^2. Equation 1 shows how the radiant flux density (Φ), measured in mW/cm^2, can be used to calculate I_{array}.

$$I_{array} = I_{sc}\frac{\Phi}{\Phi_{std}} \qquad \text{(eq. 1)}$$

If the solar cell is modelled as a current source that is linearly dependent with irradiance, the total amp hours that the solar cell produces in a day, Q_{Ahr}, can be evaluated with the integral shown in equation 2. This is a flexible form that considers a variable number of daylight hours, n_{hr}, with the time-dependant sinusoidal irradiance profile.

$$Q_{Ahr} = \int_0^{n_{hr}} \frac{I_{sc}\cdot\Phi_{\max}}{\Phi_{std}} \sin\left(\frac{t\cdot\pi}{n_{hr}}\right) dt = \frac{2\cdot n_{hr}\cdot I_{sc}\cdot\Phi_{\max}}{\Phi_{std}\cdot\pi} \qquad \text{(eq. 2)}$$

At the depleted voltage of 10.9V, the prototype requires an average of 8.74 mA to operate, or 210 mAhr over a day. By equating this to Q_{Ahr} and substituting the datasheet's short circuit current of 200 mA, an assumed day length of 12 hours, and the reference irradiance of 100 mW/cm^2, $\Phi_{\max}$ can be isolated and solved. This is done in equation 3. This method estimates 13.7 mW/cm^2 is necessary to keep the prototype continuously powered.

$$\Phi_{\max} = \frac{Q_{Ahr}\cdot\Phi_{std}\cdot\pi}{2\cdot n_{hr}\cdot I_{sc}\cdot} = \frac{210\cdot 100\pi}{4800} = 13.7\ mW/cm^2 \qquad \text{(eq. 3)}$$

3.4.2 Numerical Energy Balance

A more accurate estimate can be obtained by considering the many system nonlinearities. A model is currently being developed that considers the complete IV curve of the solar array, the voltage dependant power draw of the prototype's control circuit and the nonlinearities of the electrochemical battery. This model simulates the system by iterating through small time increments. At each time increment, the system's operating conditions are recalculated given changing battery voltage, load patterns and the time-varying irradiance profile. Several simulations were run to determine $\Phi_{\max}$ necessary to ensure the battery lost no charge over the course of 24 hours. The simulation considered various day lengths and batteries initialized with different amounts of stored charge. The results are shown in Fig. 5.

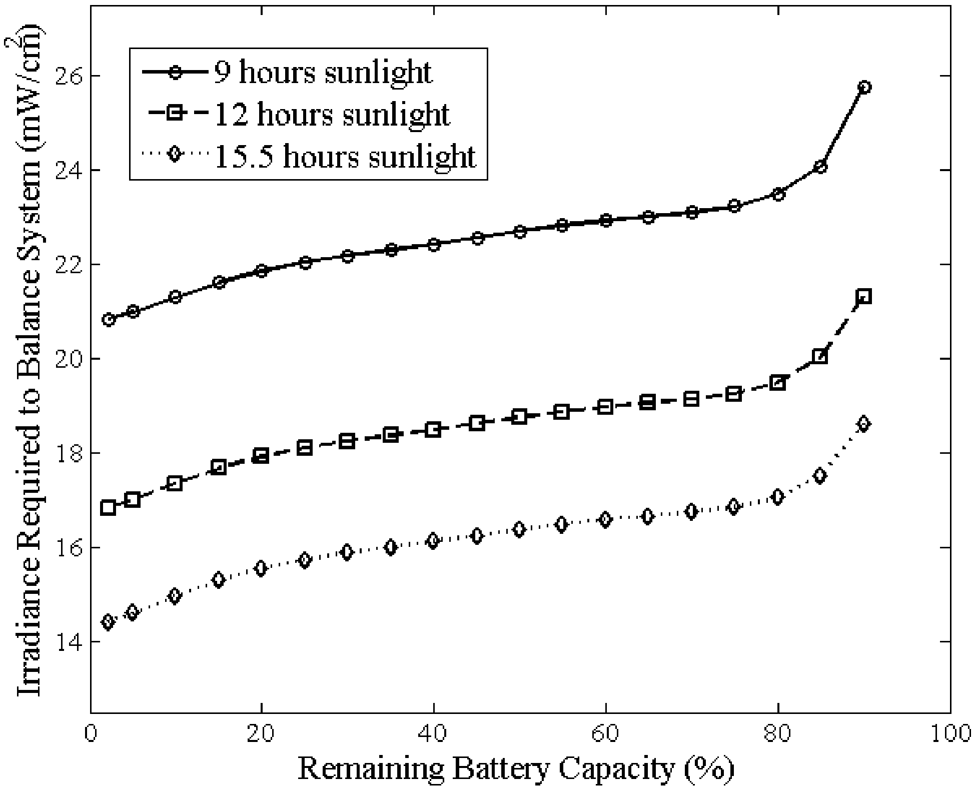


Fig. 5: Estimated input irradiance necessary to maintain the prototype's modeled battery charge given different initial stored charge. The simulation day lengths of 9, 12 and 15.5 hours are chosen to correspond with the with the day lengths in Hamilton, Ontario during the winter solstace, spring equinox and summer solstace, respectively.

As the amount of charge stored in a battery increases, its terminal voltage increases. More sunlight is required by the solar cell to produce enough current to keep the system balanced. As the day length increases more sunlight is collected overall, and the peak irradiance requirement is lowered.

3.4.3 Solar Blind Energy Balance Feasibility

The simplifications in the analytical model provide a ballpark estimate that undershoot the estimate when nonlinearities are considered. The numerical model predicts that a peak irradiance of 16.8 mW/cm^2 is required to balance this system for a 12 hour day while the analytical requires 13.7 mW/cm^2. Both analytical and numerical methods estimate the required Φ_{max} to be less than 30 mW/cm^2. As discussed in Section 2, experimental work indicates that a highly tinted window will attenuate direct sunlight by 30%, providing a peak irradiance of 30 mW/cm^2. These models imply that the prototype would be able to perpetually power themselves if they are placed behind a window with no further obstructions.

4. **Conclusion**

There is huge market potential for IoT products. Conventional wired power systems aren't appropriate for all products. Solar panels are a mature technology that uses a predictable and abundant light to provide electricity and can be a good alternative to wired systems. A case study of the design and operation of a motorized blind system was reviewed to discuss what design features were implemented to make the system operate continuously. Lessons from this case study can be applied to other solar powered IoT devices such as:

- Determine a static mounting angle that works for a large region of potential users.

- Design battery pack and solar array for direct connection to reduce development time.
- Ensure continuous power generation during intermittent shading by wiring solar cells in parallel or implementing bypass diodes in series stacks.
- Plan for outages and irregular use by including an alternative charging method.
- Perform an analytical energy balance to determine what situations are reasonable to use the system.

5. References

S. Beeby and N. White. 2010. Energy harvesting for autonomous systems. Artech House, Norwood, MA.

J. Bradley, J. Barbler and D. Handler. 2013. Embracing the internet of everything to capture your share of $14.4 trillion. Cisco white paper.

GE. 2015. Industrial internet insights report. GE white paper.

W. O'Brien, K. Kapis and A. Athienitis. 2013. Manually-operated window shade patterns in office buildings: A critical review. Building and Environment, 60, 319-338.

J. Paradiso and T. Starner. 2005. Energy scavenging for mobile and wireless electronics. Pervasive Computing, 4, 18-27.

T. Petersen, P. Williams and A. Mills. 2001. Analysis of the value of home automation systems. Facilities, 19(13/14), 522-530.

G. Qiu and S Riffat. 2003. Optimum tilt angle of solar collectors and its impact on performance. International Journal of Ambient Energy 24(1), 13-20.

J. Rabaey, M. Ammer, J. da Silva Jr, D. Patel and S. Roundy. 2000. Wireless Networking. IEEE Computer 33(7), 42-48.

S. Roundy. 2003. Energy scavenging for wireless sensor nodes with a focus on vibration to electricity conversion. PhD dissertation.

I. Rowlands, B. Kemery and I. Beausoleil-Morrison. 2011. Optimum solar-PV tilt angle and azimuth: An Ontario (Canada) case-study. Energy Policy 39, 1397-1409.