Solar Power Harvesting - Modeling and Experiences

Daniela Krüger, Stefan Fischer
Institute of Telematics
University of Lübeck
Ratzeburger Allee 160
23538 Lübeck, Germany
{krueger|fischer}@itm.uni-luebeck.de

Carsten Buschmann
coalesenses GmbH
Röntgenstr. 28
23562 Lübeck, Germany
buschmann@coalesenses.com

***Abstract*—As battery capacities are a key limiting factor of wireless sensor networks, harvesting energy from the environment is very attractive. For outdoor applications, solar power seems to be the best suited energy source. However, the amount of energy delivered from the sun changes significantly over the year, which makes the dimensioning of the panel difficult. In this paper we discuss the most important impact factors and introduce a model that predicts the harvested solar power and the battery charge over the year. In addition, we present experimental results of the first six month of our long term experiments for validating our model.**

I. INTRODUCTION

Traditionally wireless sensor networks are powered by primary batteries, which limits their lifetime or leads to high maintenance costs induced by exchanging drained batteries. In addition, the limited power source urges extremely low duty cycles, which introduces additional difficulties into the design protocols and applications.

Hence, different power supplies have been discussed - in particular systems that continuously harvest energy from the environment. An overview of potential power sources for wireless sensor networks such as air flow, pressure variation, vibrations, human power and solar energy is given in [1].

We explored solar-powered sensor nodes in the context of the FleGSens project [2], where a prototypic sensor network consisting of 200 iSense sensor nodes [3] for the surveillance of critical areas and properties is designed and set up. The FleGSens project concentrates on ensuring integrity and authenticity of generated alarms caused by trespassers, on robustness against attackers who may compromise a limited number of sensor nodes as well as on assuring availability over a reasonable period of time independent of season or weather. In order to achieve the intended network-lifetime, each node is equipped with a solar cell and a rechargeable battery.

However, solar cells provide energy dependent on their size, orientation to the sun and temperature of the solar module, their output varies heavily over the year. In this paper we present the design considerations we made during our work and summarize our observations to a practical design guide for solar powered systems.

We also present first experimental results to verify our prediction model and show how much energy different panel types yielded and to what extend their output power is influenced by the seasons.

The remainder of this paper is organized as follows. The next section presents related work. In Section III we discuss different impact factors influencing the efficiency and derive a model for predicting the monthly harvested solar energy. Section IV shows our experimental results and discusses their similarity to the model predictions. Finally, we conclude the paper with a summary and directions for future work.

II. RELATED WORK

Much research has yet been done in order to develop energy efficient protocols for sensor networks, but most publications do not consider harvesting technologies. Now that more and more harvesting systems exist researchers increasingly take into account the provided energy when designing protocols. The authors of [4] present a routing protocol for harvesting systems, while [5] describes a statistic-based approach to schedule tasks onto hardware and software. In [6] a real-time scheduling method is discussed that jointly handles constraints from both energy and time domain.

Based on heuristic techniques Kansal et.al. show in [7] and [8] how nodes can learn about their energy environment and use this information for task sharing among nodes. They use an exponentially weighted moving-average (EWMA) as an energy prediction model and adopt they duty cycle in case of over- or underestimation.

In contrast, the authors of [9] investigate in which way the duty cycle should be adapted when the harvested energy is not predictable.

Apart from the aforementioned publications, other authors focus on how energy harvesting systems should be designed. As mentioned above, [1] gives an overview over potential power sources, but discusses each source only briefly without considering different sizes or orientation of solar panels. Furthermore, it shows the differences between secondary battery chemistries like Lithium, NiMHd and NiCd. The authors of [10] discuss advantages and disadvantages of energy storage technologies, too.

Technical issues are also considered in [11] and [12]. The first introduces a power transferring circuit for optimally conveying solar energy into rechargeable batteries. The latter presents a multi-stage energy transfer system using two buffers for energy storage.

III. EXPECTED POWER ESTIMATION

The difficulty in deciding which kind of solar panel to choose for powering a sensor node is that the panel manufacturers only provide information on how much energy the panel can deliver under defined laboratory light conditions. These so called standard test conditions (STC) especially include a lighting energy of $100 mW/cm^2$. However, usually no indication is given how much solar radiation arrives at the panel over the year.

A. Impact Factors

The main corner stone when modeling the solar power that can be harvested over the year is data regarding the average monthly solar radiation R arriving at the surface.

Figure 1 shows the according data for Hamburg, Germany, stated in mWh/cm^2 per month. It was measured on a surface

Month	Daily solar radiation [mWh/cm^2]	Days in month	Monthly solar radiation [mWh/cm^2]
Jan	85	31	2635
Feb	155	28	4340
Mar	255	31	7905
Apr	360	30	10800
May	440	31	13640
Jun	490	30	14700
Jul	440	31	13640
Aug	430	31	13330
Sep	330	30	9900
Oct	205	31	6355
Nov	105	30	3150
Dec	50	31	1550
∑		365	101945

Fig. 1. Average monthly solar radiation for Hamburg ($R(M)$).

tilted by $45°$ towards south, yielding a yearly cumulative radiation of $1.020kWh/m^2$ [13]. The monthly radiation must then be multiplied with the solar panel size A to get the monthly received radiation.

However, only a fraction of the solar radiation can be converted into electrical power. This is due to a number of impact factors that reduce the harvested energy.

First of all, each solar panel features a specific efficiency, i.e. a reduction factor e_{panel} that accounts for the fact that the panel converts only a fraction of the received solar energy into electric power must be introduced.

Second, the radiation angle reduces the harvested energy. While the standard test conditions assumes that the solar radiation hits the panel orthogonally, this is unrealistic for real deployments as the sun moves over the day as well as over the year. Hence, the factor $a = \cos(\alpha)$ must be included, where α is the angular deviation from orthogonal radiation.

Third, if the harvested electric power is passed through a voltage regulator or used for charging a battery, losses will occur here as well, yielding a reduction factor e_{el} accounting for the efficiency of the electronics.

For most WSN applications, the sensor nodes operate in alternating phases of activity and low power sleep modes. During the sleep phases, the nodes dissipate hardly any power, the harvested energy cannot directly be consumed but must be stored. A common way is to use a rechargeable battery, as it can accommodate large amounts of energy. However, an additional difficulty arises when considering charging: common battery technologies exhibit temperature limits to the charge process. For example, lithium-ion batteries can neither be charged below 0°C nor above 45°C.

As a result, there will be times during winter when solar power is available but cannot be stored in the battery because it is too cold. The same holds for the summer, when temperatures in the enclosure can exceed the temperature limits especially at noon. Both effects result in a typical monthly temperature corridor exceedance loss L. However, it must be admitted that the influence of the factor is not well-explored yet, the values we assumed for our model are listed in Figure 2.

Finally, the battery capacity deserves some attention. Assuming that the sensor node dissipates more energy than the solar panel can deliver during winter (especially during December, January and February), this deficit can be compensated by energy stored in the battery before (at times when the panel supplied more energy than spent by the node). The larger the battery capacity C, the longer periods of insufficient solar power can be sustained, and the more power can be dissipated during these periods.

B. Model

Considering the impact factors (c.f. Figures 1 to 3) discussed above, we designed a model for predicting the energy that can be harvested with a solar panel as well as for estimating the battery charge development over the year under the condition of a given power dissipation of the sensor node.

Month	Temperature corridor exceedance loss
Jan	25%
Feb	10%
Mar	0%
Apr	0%
May	10%
Jun	25%
Jul	25%
Aug	10%
Sep	0%
Oct	0%
Nov	0%
Dec	10%

Fig. 2. Assumed energy loss due to temperature exceedance ($L(M)$).

Description	Symbol	Value	Unit
Battery capacity	C	21120	mWh
Panel size	A	170	cm^2
Panel Efficiency	e_{panel}	0.07	
Electrical loss	e_{el}	0.7	
Angular loss	a	0.7	
Duty cycle	d	0.179	
Sleeping node power dissipation	P_{sleep}	0.165	mW
Maximum node power dissipation	$P_{running}$	148.5	mW
Average node power dissipation	P_{node}	26.72	mW
Starting month	t_{start}	6	

Fig. 3. Constant parameters with example values.

The harvested solar energy $E_{solar}(M)$ in a certain month $M \in \{1, ..., 12\}$ can be predicted as

$$E_{solar}(M) = (1 - L(M))\, e_{el}\, e_{panel}\, A\, a\, R(M)$$

by considering the temperature exceedance loss of the particular month M, the electrical efficiency, the panel efficiency, the panel size, the loss due to the radiation angle and the amount of solar radiation during M.

Let's assume that the sensor node exhibits a power dissipation of $P_{running}$ at full operation and of P_{sleep} when sleeping. Then, if the node is running at a duty cycle of $d \in [0.0; 1.0]$, i.e. if the node is awake $100\, d$ per cent of the time and sleeps during the rest, the average power dissipation P_{node} is

$$P_{node} = d\, P_{running} + (1 - d)\, P_{sleep}$$

The energy dissipated by the node in a certain month M can then be approximated by

$$E_{dissipate}(M) = P_{node}\, 24\, DiM(M)$$

where DiM yields the number of days in month M.

Now that that all input values are defined, the energy stored in the battery over the course of time can be calculated.

Given that $E(0)$ is the initial battery charge, the energy $E(t)$ at the end of a month can then be estimated by

$$\begin{array}{rcl} E(t) & = & min\{C, E(t-1) + E_{solar}(M(t)) - E_{dissipate}(M(t))\} \\ M(t) & = & ((t - 2 + t_{start})\, mod\, 12) + 1 \end{array}$$

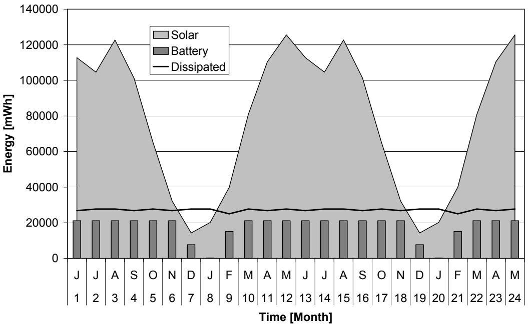
where $t \in \mathbb{N}$ indicates the months since which the system is running and $t_{start} \in \{1, ..., 12\}$ is the starting month of the estimation. The helper function $M \colon \mathbb{N} \Rightarrow \{1, ...12\}$ converts the monotonously growing t into the proper month index according to the starting month t_{start}.

The below Figure shows an example run of the battery energy model. It uses the values given in Figures 1 to 3. Highlighted cells in Figure 4(a) indicate that the node dissipated more energy than the solar cell harvested, i.e. that it drained the battery. Note that the duty cycle was set to 25% (c.f. Figure 3), which is the maximum that can be sustained over the winter months. Further increasing it would lead to negative values in column three of Figure 4(a), indicating that the sensor node ran out of battery in the according month.

The table data is additionally visualized in Figure 4(b). It becomes obvious that the monthly power dissipation stays more or less constant (and varies only slightly due to the different number of days per month), while the harvested power heavily varies over the year. During times when less power is harvested than dissipated, the battery is drained. Its charge goes down to about 2000mWh in January because of the low harvesting power during winter. As the battery capacity is 21120mWh, the charge graph never exceeds this threshold.

t	$((t-2+t_{start}) \bmod 12)+1$	E(t) [mWh]	E_{solar} [mWh]	$E_{dissipate}$ [mWh]
0		21120		
1	6	21120	104958	24683
2	7	21120	97390	25506
3	8	21120	114211	25506
4	9	21120	94248	24683
5	10	21120	60500	25506
6	11	21120	29988	24683
7	12	8895	13280	25506
8	1	2203	18814	25506
9	2	16350	37185	23038
10	3	21120	75256	25506
11	4	21120	102816	24683
12	5	21120	116868	25506
13	6	21120	104958	24683
14	7	21120	97390	25506
15	8	21120	114211	25506
16	9	21120	94248	24683
17	10	21120	60500	25506
18	11	21120	29988	24683
19	12	8895	13280	25506
20	1	2203	18814	25506
21	2	16350	37185	23038
22	3	21120	75256	25506
23	4	21120	102816	24683
24	5	21120	116868	25506

(a) Table representation



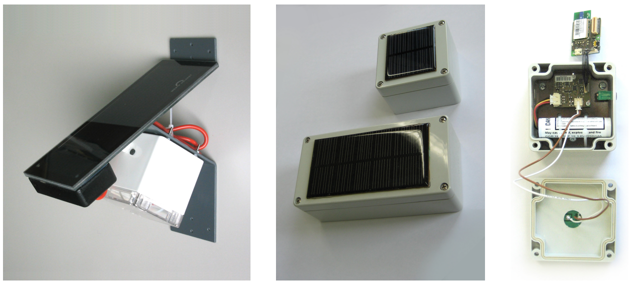
(b) Graph representation

Fig. 4. Battery energy prediction over a 24 month period.

IV. EXPERIMENTAL RESULTS

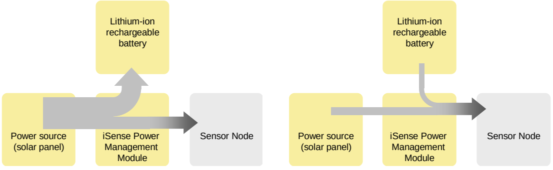
To validate the model, we started an experimental evaluation in December 2008. We used iSense sensor nodes [3] that were connected to three different types of solar cells (Figure 5).

As shown in Figure 5(c), the nodes were equipped with a special power management module, a lithium ion rechargeable battery and a solar panel. The power management module distributes the power provided by the solar panel in an intelligent way. If the panel can deliver more power than the sensor node requires, it charges the lithium ion battery (c.f. Figure 6(a)). Otherwise, it reduces the battery drainage by supplying the node with the solar power (c.f. Figure 6(b)) as much as possible and drawing the rest from the battery.



(a) Large. (b) Medium, Small. (c) Inside view.

Fig. 5. Panel types and node setup



(a) Charging (b) Reducing discharge

Fig. 6. Energy Flows.

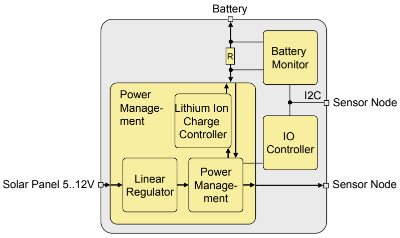


Fig. 7. Power Management Concept.

Figure 7 shows a conceptual view of the solar power management module. The Solar power is fed into the power management component through a linear regulator. For charging the battery, a charge controller in integrated as well. The battery current flows into and out of the battery are monitored and logged, the battery monitor also accumulates the currents during charging and discharging cycles, and hence provides precise information about the energy currently stored within the battery.

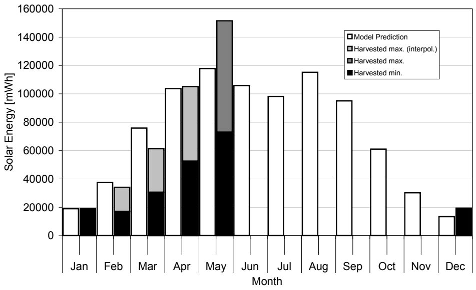
	Large Panel	Medium Panel	Small Panel
Panel efficiency	0.09	0.12	0.11
Panel size	170	81.25	37.05
Open circuit voltage at MPP	6	9	5
Short circuit current at MPP	250	109	81
Electrical efficiency	0.8	0.4	0.63
Radiation angle efficiency	0.8	0.7	0.7

Fig. 8. Technical cell data and model settings.

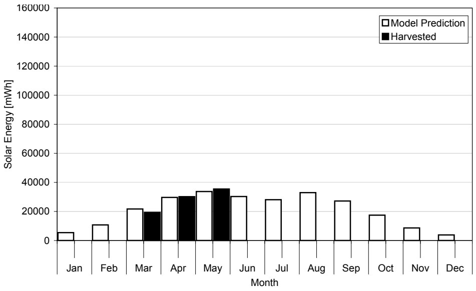
The table in Figure 8 summarizes some technical data of the solar panels used as well as the model settings used below.

Figure 9 shows both predicted and measured harvested energy for the three panel types. The values predicted by the model are always indicated by white bars, while the dark bars indicate the energy harvested in reality. Note that so far, real-world data is available for a small number of months only.

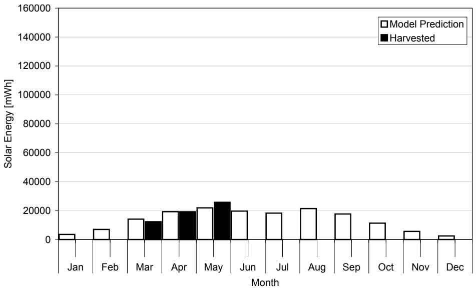
The different dark bars in Figure 9(a) need some further explanation. The black bars indicate the harvested energy by our first test node equipped with a large solar panel. It can



(a) Large Panel



(b) Medium Panel



(c) Small Panel

Fig. 9. Experimental Results.

be seen that prediction and measured values highly resemble during the first two months of our experiment - December and January. After that - from February to May - the according harvesting results are pretty disappointing. In April we found the reason for this: Because the battery was fully charged most of the time, only a fraction of the available solar energy could be harvested.

In order to find out how much energy could really be harvested, we employed additional sensor nodes in May and ensured that at least one of them at a time harvested the full solar energy into an empty battery. The according amount of energy harvested in May is indicated as the dark gray *Harvested max* bar. We then interpolated the energy that could have been harvested from February to April and indicated it with the light gray *Harvested max (interpolated)* bars.

The harvested energy of the smaller solar panels is shown in Figure 9(b) and 9(c). Prediction model and measured values highly match even though both devices harvested a bit more than expected in May.

V. CONCLUSION

Supplying a sensor network with solar energy promises nearly perpetual operation, but several impact factors significantly influence the amount of potentially harvested energy and must be taken into account when design decisions are made. We presented a model that allows to predict both the harvested energy as well as the corresponding battery charge. We verified our model by long term experiments with different solar panels whose results are also shown. Even though the energy harvested in reality basically follows the predictions of the model, further work is needed.

The first results presented here for example hint that the values assumed for the temperature exceedance loss are not very realistic. However, the experiments will provide additional data that will help to improve the model.

In addition, we are planning to implement a duty cycle control system that is based upon the models presented here.

REFERENCES

[1] S. Roundy, D. Steingart, L. Frechette, P. Wright, and J. Rabaey, “Power sources for wireless sensor networks,” in *Wireless Sensor Networks, First European Workshop, EWSN*, ser. LNCS, no. 2920. Springer, 2004, pp. 1–17.

[2] P. Rothenpieler, D. Krüger, D. Pfisterer, S. Fischer, D. Dudek, C. Haas, A. Kuntz, and M. Zitterbart, “Flegsens - secure area monitoring using wireless sensor networks,” *Proceedings of World Academy of Science, Engineering and Technology*, 2009.

[3] C. Buschmann and D. Pfisterer, “iSense: A modular hardware and software platform for wireless sensor networks,” 6. Fachgesprch Drahtlose Sensornetze der GI/ITG-Fachgruppe Kommunikation und Verteilte Systeme, Tech. Rep., 2007. [Online]. Available: www.coalesenses.com

[4] T. Voigt, H. Ritter, and J. Schiller, “Utilizing solar power in wireless sensor networks,” in *LCN ’03: Proceedings of the 28th Annual IEEE International Conference on Local Computer Networks*. Washington, DC, USA: IEEE Computer Society, 2003, p. 416.

[5] A. Nahapetian, P. Lombardo, A. Acquaviva, L. Benini, and M. Sarrafzadeh, “Dynamic reconfiguration in sensor networks with regenerative energy sources,” in *DATE ’07: Proceedings of the conference on Design, automation and test in Europe*. San Jose, CA, USA: EDA Consortium, 2007, pp. 1054–1059.

[6] C. Moser, D. Brunelli, L. Thiele, and L. Benini, “Real-time scheduling for energy harvesting sensor nodes,” *Real-Time Syst.*, vol. 37, no. 3, pp. 233–260, 2007.

[7] A. Kansal and M. B. Srivastava, “An environmental energy harvesting framework for sensor networks,” in *ISLPED ’03: Proceedings of the 2003 international symposium on Low power electronics and design*. New York, NY, USA: ACM, 2003, pp. 481–486.

[8] A. Kansal, J. Hsu, S. Zahedi, and M. B. Srivastava, “Power management in energy harvesting sensor networks,” *ACM Trans. Embed. Comput. Syst.*, vol. 6, no. 4, p. 32, 2007.

[9] C. M. Vigorito, D. Ganesan, and A. G. Barto, “Adaptive control of duty cycling in energy-harvesting wireless sensor networks.” in *SECON*. IEEE, 2007, pp. 21–30. [Online]. Available: http://dblp.uni-trier.de/db/conf/secon/secon2007.html#VigoritoGB07

[10] V. Raghunathan, A. Kansal, J. Hsu, J. Friedman, and M. Srivastava, “Design considerations for solar energy harvesting wireless embedded systems,” in *IPSN ’05: Proceedings of the 4th international symposium on Information processing in sensor networks*. Piscataway, NJ, USA: IEEE Press, 2005, p. 64.

[11] C. Alippi and C. Galperti, “An adaptive system for optimal solar energy harvesting in wireless sensor network nodes,” in *IEEE-Transactions on Circuits and Systems: Part I, Fundamental theory and applications*, no. 55(6), Jul. 2008, p. 17421750.

[12] X. Jiang, J. Polastre, and D. Culler, “Perpetual environmentally powered sensor networks,” in *IPSN ’05: Proceedings of the 4th international symposium on Information processing in sensor networks*. Piscataway, NJ, USA: IEEE Press, 2005, p. 65.

[13] Fachverlag für Energie-Markting und -Anwendungen, “Photovoltaik - Strom aus der Sonne,” 2004.