20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

Using Ambient Light Sensors on Smartphones to Improve the Performance of Solar Chargers

Christian Schuss[1], Tore Leikanger[1], Bernd Eichberger[2], Timo Rahkonen[1]

[1]*Electronics Laboratory, University of Oulu, Erkki Koiso-Kanttilan katu 3, 90570 Oulu, Finland*
christian.schuss@ee.oulu.fi, tore.leikanger@student.oulu.fi, timo.rahkonen@ee.oulu.fi
[2]*Institute of Electronics, Graz University of Technology, Infeldgasse 12, 8010 Graz, Austria*
bernd.eichberger@tugraz.at

Abstract – **This paper discusses the opportunities that exist to collect environmental data with the help of portable devices such as mobile phones. Under indoor environmental conditions, ambient data is vital in order to improve the performance of solar energy chargers. Sensing the light intensity and the temperature level can significantly contribute towards improving the output power of photovoltaics. For example, if the most beneficial location is known for deploying solar chargers in buildings, up to 100 times more solar energy can be collected during the same amount of time in a less suitable location. Moreover, the amount of gathered energy can be predicted and provided as helpful information for users. We analyse the performance of different types of ambient light sensors which are available in today's smartphones. Additionally, we present a measurement platform which allows the gathering of ambient data with any type of mobile phone.**

I. INTRODUCTION

Nowadays, mobile phones increasingly provide numerous functionalities for their users, leading to the use of the name smartphones for such devices [1]. Along with these additional user features are embedded sensors which obtain data from the surrounding environment. Due to the high energy demand as a result of the increased amount of hardware and software in today's mobile phones, the battery life became a major issue and bottleneck for portable devices. A few years ago significant improvements in standby and operating times were achieved, many smartphones still need to be charged every day or even during the day to maintain power levels [2–4].

This progression towards higher energy demands of portable devices is only expected to continue into the future [2–4]. Various gadgets have been recently introduced which are helpful in prolonging the battery life of devices. One of these accessories are solar energy chargers which collect energy from the sun in order to charge an internal battery pack. The collected solar energy can then be used for charging portable devices such as mobile phones [5], [6]. It is worth noting that the system structure of solar chargers has to be efficient so that solar energy can also be gathered from light sources both indoors and outdoors [7].

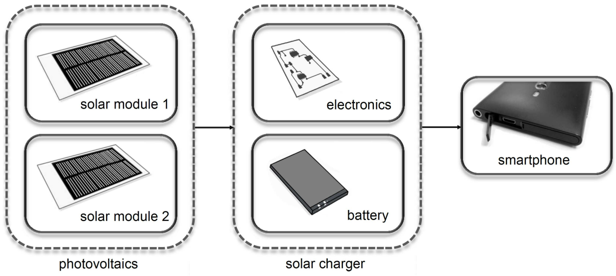

Fig. 1. Basic system structure of solar energy chargers.

Fig. 1 illustrates the basic system structure of solar chargers which we designed in previous research [5–7]. Due to variations in energy demands of users, the opportunity is given to connect more than one solar module at the same time. This possibility is also helpful in overcoming unfavourable or indoor environmental conditions. As seen in Fig. 1, the solar charger contains a battery. As such the solar charger does not require a permanent connection with the mobile phone. The solar charger only needs to be connected with the mobile phone during the charging procedure [7], [8]. This feature is important to satisfy user demands [1].

However, inside buildings, the position of solar chargers is crucial. In [7], we described the output power of photovoltaics (P_{PV} [W]) as the following function:

$$P_{PV} = f(\lambda, T_c, V_{oc}, I_{sc}, A_{PV}, m_{PV}, \alpha_{PV}) \quad (1)$$

where λ [W/m^2] is the solar radiation level, T_c [K] is the temperature of the photovoltaic (PV) cell, V_{oc} [V] is the open-circuit voltage, I_{sc} [A] is the short-circuit current, A_{PV} [m^2] is the size of photovoltaics, m_{PV} is the material of photovoltaics, and α_{PV} [°] is the orientation of the photovoltaics towards the light source. In this paper, we focus on the improvement of P_{PV} under indoor environmental conditions. Instead of λ, we use the illuminance E_V [lx] for the amount of light on surfaces. The light intensity depends strongly on the distance (d [cm]) of the solar module from

ISBN-14: 978-92-990073-2-7

the light source and the orientation of the solar module towards the light source.

II. SMARTPHONE SENSORS

A. Number and Varieties of Sensors

Smartphones which are currently available on the market offer different types of sensors for their users. Commonly, the number of sensors depends on the price level of the mobile phone. At a price level of about €100 or $125, smartphones contain two or three sensors such as an accelerometer and magnetic field sensor. At higher price levels, > €200 or $250 several more sensors are included as standard in mobile phones. In particular, an ambient light sensor (ALS) is available which can provide vital information about the surroundings in indoor locations.

Table 1 summarises the types of installed sensors in the smartphones which are part of this investigation. The considered mobile phones are the Samsung Galaxy S2 Plus (GT-i9105P), the Samsung Galaxy S3 LTE (GT-i9305) and the Samsung Galaxy Nexus (GT-i9250). All three smartphones also feature the opportunity for near field communication (NFC) and Bluetooth (v3.0 or v4.0).

However, especially in case of the ambient light sensor, the manufacturer and type of sensor varies between the investigated smartphones. Table 2 presents information on the parameters of the light sensors. Range 1 is the specified range in which the accuracy of the measurement is ensured by the manufacturer, while range 2 is the illuminance when the sensor gets saturated.

Table 1. Available sensors on the mobile phones

Sensor Type	S2 Plus	S3 LTE	Nexus
Accelerometer	x	x	x
Magnetic field sensor	x	x	x
Ambient light sensor	x	x	x
Proximity sensor	x	x	x
Gyro sensor	x	x	x
Pressure sensor	-	x	x

Table 2. Information on the sensors of the smartphones

	S2 Plus	S3 LTE	Nexus
Manufacturer	Capella	Capella	Sharp
Type	CM3663	CM36651	GP2A
Function	ALS	Color-ALS	ALS
Range 1	16000 lx	11796 lx	55000 lx
Range 2	200000 lx	85745 lx	135000 lx
Resolution	5.0 lx	1.0 lx	0.1 lx
Consumption	0.75 mA	0.20 mA	0.75 mA

Additionally, the light sensors of the Nokia Lumia 520 and the Nokia Lumia 820 are analysed in this investigation. Windows Phone 8.1 allows applications to access hardware information and measure the illuminance (E_V) with the help of the ALS. Here, the Nokia Lumia 520 is an entry-level model with a retail price below €100 or $125. Altogether, it can be said that Nokia smartphones offer a similar variety on sensors than Samsung mobile phones.

Fig. 2. Indoor conditions in a library.

B. Requirement for Sensing the Environment

Sensing possible positions for solar chargers beforehand can significantly increase the amount of solar energy which can be gained during a particular period of time. Fig. 2 shows a typical example of an indoor location, an open learning environment of a library. In such a location, no electrical sockets are close by in order to charge smartphones with energy from the power grid. It is also important to know that at present only a small share of the produced electricity worldwide comes from renewable resources. The majority of our demand is satisfied with non-renewable energy sources such as nuclear power and fossil fuels which include coal, gas and oil [9].

C. Amount of Solar Energy Indoors

As seen in Fig. 2, there are many opportunities available to deploy solar chargers such as chairs, tables, bookshelves, and so on. However, due to the different location of light sources, it is vital to allocate the most beneficial place for solar chargers. It is therefore advisable to quickly sense the surrounding environment and collect ambient data to inform decisions on positioning. The ambient light sensor can be used to gather the required information quickly and efficiently.

Under indoor environmental conditions, PV cells made out of amorphous silicon (a-Si) show superior performance in comparsion with photovoltaics made out of monocrystalline silicon (mono-Si). Commonly, light sources are designed to match the visible light range of the human eye. Fig. 3 illustrates the spectrum of photovoltaics over different wave lengths. It can be seen that the spectrum of a-Si overlaps widely with the visible light spectrum.

Table 3. Comparison of measurement results (Samsung smartphones)

Instrument 1 Vernier	Instrument 2 Voltcraft	Instrument 3 S2 Plus	Instrument 4 S3 LTE	Instrument 5 Nexus	Distance to light source
396.4 lx	401 lx	315 lx	798 lx	512.1 lx	190 cm
427.8 lx	430 lx	340 lx	856 lx	550.5 lx	182 cm
457.7 lx	459 lx	360 lx	914 lx	583.4 lx	175 cm
505.3 lx	510 lx	405 lx	1022 lx	648.1 lx	164 cm
552.7 lx	554 lx	440 lx	1107 lx	737.3 lx	157 cm
687.9 lx	690 lx	545 lx	1372 lx	889.4 lx	139 cm
831.8 lx	836 lx	660 lx	1644 lx	1048.1 lx	125 cm
1222.7 lx	1230 lx	950 lx	2292 lx	1388.6 lx	100 cm
1964.2 lx	1982 lx	1410 lx	3371 lx	1861.5 lx	75 cm
2345.6 lx	2380 lx	1775 lx	4207 lx	2615.2 lx	63 cm
4462.8 lx	4490 lx	2710 lx	6421 lx	4229.2 lx	40 cm

Table 4. Comparison of measurement results (Nokia smartphones)

Instrument 2 Voltcraft	Instrument 6 Lumia 520	Instrument 7 Lumia 820 (1)	Instrument 8 Lumia 820 (2)	Instrument 9 Lumia 820 (3)	Distance to light source
400 lx	322.3 lx	1295.6 lx	926.3 lx	1239.2 lx	190 cm
427 lx	345.7 lx	1414.9 lx	989.9 lx	1370.3 lx	182 cm
455 lx	366.5 lx	1461.1 lx	1035.2 lx	1420.8 lx	175 cm
514 lx	418.6 lx	1638.6 lx	1174.0 lx	1609.7 lx	164 cm
548 lx	430.7 lx	1719.6 lx	1242.7 lx	1714.3 lx	157 cm
690 lx	556.9 lx	2122.6 lx	1518.0 lx	1984.5 lx	139 cm
835 lx	665.1 lx	2432.7 lx	1752.1 lx	2417.8 lx	125 cm
1242 lx	971.0 lx	3348.0 lx	2415.7 lx	3226.0 lx	100 cm
1978 lx	1459.8 lx	4803.7 lx	3411.1 lx	4606.5 lx	75 cm
2380 lx	1829.1 lx	5813.8 lx	4085.1 lx	5619.6 lx	63 cm
4010 lx	2778.2 lx	9438.5 lx	6792.4 lx	8593.6 lx	45 cm

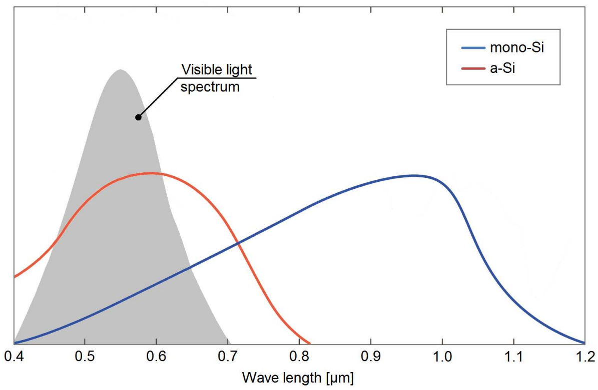

Fig. 3. Spectrum of PV cells and visible light spectrum.

III. MEASUREMENT OF THE ILLUMINANCE

A. Measurement Equipment

Beside the three smartphones, calibrated measurement equipment was used to measure the illuminance under different distances to the light source. The first measurement instrument was a Vernier light sensor (LS-BTA) and together with the Vernier SensorDAQ, the sensor provided a 13 bit-resolution up to 150000 lx. The sensor itself is a Hamamatsu S1133 photodiode which provides a voltage that is proportional to the light intensity. The other measurement instrument was a Voltcraft BL-10L, a basic instrument to evaluate illuminance, for example in office buildings. This can measure up to 40000 lx.

Table 3 provides an example measurement with Samsung smartphones while Table 4 illustrates measurement results from Nokia smartphones under the same conditions. The different distances to the light source can be established by the use of an office table, a few books, a personal computer (PC), a bookshelf, a closet, and so on. $\varepsilon_{rel,I1,I2}$ is the relative error between measurement instrument 1, the Vernier light sensor, and 2, the Voltcraft BL-10L, which is obtained as follows:

$$\varepsilon_{rel,I1,I2} = 0.72 \pm 0.48\,\%$$

$\varepsilon_{rel,I2,I3}$, $\varepsilon_{rel,I2,I4}$, and $\varepsilon_{rel,I2,I5}$ are the error levels for the Samsung Galaxy S2 Plus (GT-i9105P), the Samsung Galaxy S3 LTE (GT-i9305) and the Samsung Galaxy

Nexus (GT-i9250), respectively, compared with the illuminance measured by the Voltcraft BL-10L. Afterwards, the error levels $\varepsilon_{rel,I2,I6}$, $\varepsilon_{rel,I2,I7}$, $\varepsilon_{rel,I2,I8}$, and $\varepsilon_{rel,I2,I9}$ for one Nokia Lumia 520 and three Nokia Lumia 820 are calculated.

$$\begin{aligned}
\varepsilon_{rel,I2,I3} &= -\,23.99 \pm 5.52\,\% \\
\varepsilon_{rel,I2,I4} &= +\,88.10 \pm 17.39\,\% \\
\varepsilon_{rel,I2,I5} &= +\,18.92 \pm 13.45\,\% \\
\varepsilon_{rel,I2,I6} &= -\,21.76 \pm 3.55\,\% \\
\varepsilon_{rel,I2,I7} &= +\,190.91 \pm 34.70\,\% \\
\varepsilon_{rel,I2,I8} &= +\,107.63 \pm 24.64\,\% \\
\varepsilon_{rel,I2,I9} &= +\,180.84 \pm 36.67\,\%
\end{aligned}$$

In Table 3, it can be seen that the Samsung Galaxy S2 Plus consistently provided a light intensity that was too low, whereas the Samsung Galaxy S3 LTE regularly measured twice as much. The Samsung Galaxy Nexus obtained the closest value to the two conventional measurement instruments. In Table 4, the Nokia Lumia 520 provided the most acceptable measurement results, while one of the Nokia Lumia 820 measures up to three times the available illuminance. However, it is worth noting that the error levels between measurement instruments and smartphones are non-linear over the measured illuminance range.

B. *Linear Increase of Output Power*

Fig. 4 shows the theoretical output power (P_{th} [W]) of a solar module (size: 20 x 16 cm) which was measured under the same distances to the light source as in Table 3 and Table 4. It can be seen that the amount of power is proportional to the illuminance which increases linearly with the light intensity. Hence, if measurements of ambient light sensors are correct, it is possible to estimate the amount of solar energy.

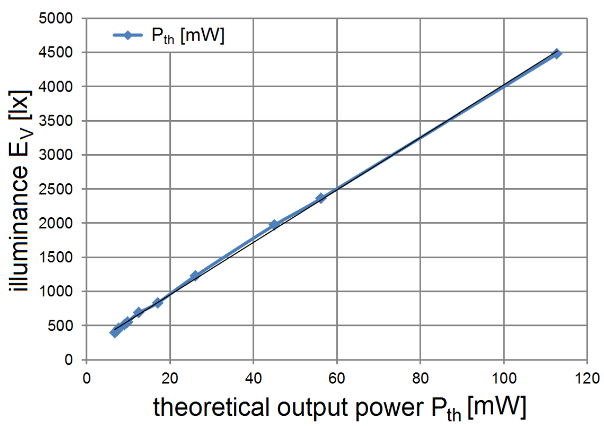

Fig. 4. Increase of the theoretical output power.

C. *Repeatability of Measurements*

At various distances to the light source, measurement of the illuminance was repeated in order to obtain statistical information (mean value and standard deviation). At each position, the ambient light sensor was covered for a short period of time so that E_V was about 0 lx. Afterwards, the sensor was uncovered and E_V was measured again. At the same position, the measurement was repeated 10 times. The following values were obtained with the Nokia Lumia 820 (instrument 8):

$$\begin{aligned}
\bar{E}_V &= 924.3 \pm 2.0\,lx && \text{at d = 190 cm} \\
\bar{E}_V &= 979.5 \pm 4.5\,lx && \text{at d = 182 cm} \\
\bar{E}_V &= 1036.6 \pm 4.3\,lx && \text{at d = 175 cm} \\
\bar{E}_V &= 1172.7 \pm 6.1\,lx && \text{at d = 164 cm} \\
\bar{E}_V &= 1247.3 \pm 3.9\,lx && \text{at d = 157 cm} \\
\bar{E}_V &= 1511.0 \pm 2.5\,lx && \text{at d = 139 cm} \\
\bar{E}_V &= 1713.9 \pm 14.2\,lx && \text{at d = 125 cm} \\
\bar{E}_V &= 2421.4 \pm 14.5\,lx && \text{at d = 100 cm} \\
\bar{E}_V &= 3406.5 \pm 2.6\,lx && \text{at d = 75 cm} \\
\bar{E}_V &= 4089.8 \pm 8.2\,lx && \text{at d = 63 cm} \\
\bar{E}_V &= 6797.6 \pm 12.3\,lx && \text{at d = 45 cm}
\end{aligned}$$

D. *Calibration of Ambient Light Sensors*

For energy predictions, it is possible to calibrate the ambient light sensor of smartphones, for example, with the help of luxmeters. In Fig. 5, the measurement results of one Nokia Lumia 820 (instrument 7) are compared with the measured illuminance by the Voltcraft BL-10L (instrument 2). A linear regression can be used to calibrate the ALS of the smartphone, as obtained from Equation (2). Therefore, at least two measurements must be made at two different distances (d_1 and d_2) in order to solve Equations (3) and (4).

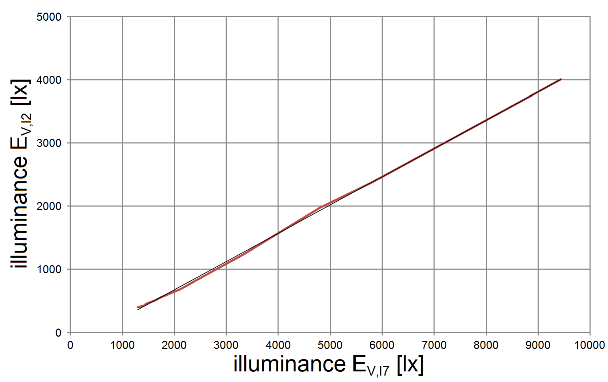

Fig. 5. Calibration of a smartphone with a luxmeter.

$$y(x) = ax + b \tag{2}$$

$$a = \frac{y_1(x_1) - y_2(x_2)}{x_1 - x_2} \tag{3}$$

$$b = y_1(x_1) - ax_1 \quad (4)$$

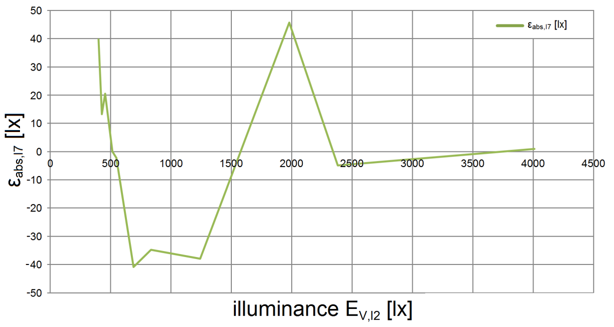

Fig. 6. Example for the absolute error after calibration.

After the calibration of the Nokia Lumia 820 ($a = 0.4481$ and $b = -220.31$), there is still an error present. Fig. 6 illustrates the absolute error (ε_{abs} [lx]) at different light intensities. However, the relative error at different distances to the light source is reduced significantly, obtained as follows:

Before calibration:

$\varepsilon_{rel,I2,I7} \quad = +190.91 \pm 34.70\ \%$

After calibration:

$\varepsilon_{rel,I2,I7} \quad = +0.56 \pm 4.19\ \%$

IV. MEASUREMENT WITH EXTERNAL SENSORS

Fig. 7 illustrates the system structure of the developed platform that was used to connect smartphones via NFC external sensors. Thus, mobile phones are able to receive information, for example from ambient light and temperature sensors. It is possible to use a Bluetooth communication interface instead of the NFC architecture. As seen in Fig. 5, sensors can be connected via the inter-integrated circuit (I^2C) bus.

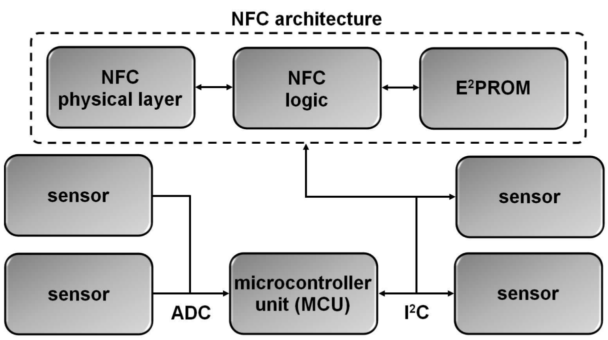

Fig. 7. System structure to integrate external sensors.

Sensors which do not feature an I^2C interface, for example light-to-voltage converters, can be connected to the analog-to-digital converter (ADC) of the microcontroller unit (MCU). As a result, many different types of sensors can be integrated in an easy way into the measurement platform. Collected data is transmitted to mobile phones for user support and therefore, it is possible for users to get an understanding of the surroundings and maximise the performance of solar chargers.

V. DISCUSSION AND CONCLUSION

Ambient light sensors of the investigated smartphones show a surprisingly large error in comparison to conventional measurement equipment. Even though manufacturers provide an accuracy of ± 15 %, measured values differed up to 200 % from each other. The non-linear error level makes it difficult to calibrate the ambient light sensors of smartphones. For example, a false reading due to a screen protector film of 10 % (clear film) or 20 % (matt film) could be corrected by shifting sensors readings horizontally. Current ambient light sensors of smartphones are capable of providing basic information. Users are able to evaluate locations which are more or less suitable to deploy solar chargers.

However, accurate readings of sensors are helpful and contribute to improve output performances and shorten recharging times. Moreover, energy predictions are interesting for the users of smartphones. Therefore, we propose the calibration of ambient light sensors of smartphones with the help of luxmeters. As a result, the relative error of measurements on the light intensity is reduced substantially. Additionally, we suggest the use of a measurement platform for smartphones without ambient light sensors to obtain vital ambient data and carry out predictions on the amount of solar energy which can be gathered during a particular period of time.

ACKNOWLEDGMENT

We wish to thank Infotech Oulu, the Nokia Foundation, the Tauno Tönning Foundation, and the Faculty of Information Technology and Electrical Engineering of the University of Oulu for financially supporting this research.

REFERENCES

[1] D. Ferreira, A.K. Dey, and V. Kostakos, "Understanding Human-Smartphones Concerns: A Study of Battery Life", Lecture Notes in Computer Science, vol. 6696, 2011, pp. 19-33.

[2] D. Jia, Y. Duan, and J. Liu, "Emerging technologies to power next generation mobile phone electronic devices using solar energy", Frontiers of Energy and Power Engineering in China, vol. 3, issue: 3, 2009, pp. 262-288.

[3] D. Ferreira, E. Ferreira, J. Goncalves, V. Kostakos, and A.K. Dey, "Revisiting Human-Battery Interaction With An Interactive Battery Interface", Proceedings of

the 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp), 2013, pp. 563-572.

[4] C. Li, W. Jia, Q. Tao, and M. Sun, “Solar Cell Phone Charger Performance in Indoor Environment", IEEE 37th Annual Northeast Bioengineering Conference (NEBEC), 2011, art. no. 5778623.

[5] C. Schuss, and T. Rahkonen, “Use of Mobile Phones as Microcontrollers for Control Applications such as Maximum Power Point Tracking (MPPT)", Proceedings of the IEEE 16th Mediterranean Electrotechnical Conference (MELECON), 2012, pp. 792-795.

[6] C. Schuss, and T. Rahkonen, “Photovoltaic (PV) Energy as Recharge Source for Portable Devices such as Mobile Phones", Proceedings of the 12th Conference of FRUCT Association, 2012, pp. 120-128.

[7] C. Schuss, B. Eichberger, and T. Rahkonen, “Design Specifications and Guidelines for Efficient Solar Chargers of Mobile Phones", 11th International Multi-Conference on Systems, Signals Devices (SSD), 2014, pp. 1-5.

[8] S. Park, B. Koh, Y. Wang, J. Kim, Y. Kim, M. Pedram, and N. Chang, “Maximum Power Transfer Tracking in a Solar USB Charger for Smartphones", IEEE International Symposium on Low Power Electronics and Design (ISLPED), 2013, pp. 88-93.

[9] S. Pacala, and R. Socolow, “Stabilization wedges: Solving the climate problem for the next 50 years with current technologies", Science, vol. 305, 2004, pp. 968-972.