Evaluating Micro-Power Management of Solar Energy Harvesting using a Novel Modular Platform

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Abstract. Micro-Power Management (µPM) is essential to supply power to autarkic sensor nodes from energy harvesting sources. As there are numerous ways to realize a µPM, the question arises of how to benchmark different managements under reproducible boundary conditions. In this paper we present these conditions for solar harvesting. Further, we propose a system efficiency definition, which is applicable to all self-powered systems. For verification, we use our modular construction kit, which is used to set up four different µPM configurations. We examined the interplay of state-of-the-art power converters with a supercapacitor array. As one result, the improvement of using a buck converter compared to an LDO was quantified by an increase of 10 percentage points in the system efficiency. The experiments show that the modular setup and the boundary conditions are suitable for such investigations.

1. Introduction
A Micro-Power Management (µPM) is essential to supply power to wireless sensor nodes (WSN) from energy harvesting sources. There are various ways of realizing a micro power management, either with discrete electronic components or with commercial power management integrated circuits (PMICs). It is a challenging task to find the optimal solution: although the efficiency of individual components can be determined at certain operation points, it is not clear which operating point is most dominant in interplay with other components and in a realistic scenario. Moreover, additional losses may originate from component interaction. Furthermore, the question arises of how to measure the energy balance and benchmark different systems under realistic and reproducible boundary conditions. In this paper we answer these questions.

1.1. Related work
Several publications ([1], [2]) document that µPMs are realized in various ways. In these publications the system evaluation is usually limited to a single test run of a few days in a non-repeatable real-word scenario. Different approaches to address this issue and to estimate the system performance in an adequate way are presented in the following:

In battery-powered wireless sensor networks (WSNs) the lifetime can be used as a performance indicator as done in [3]. The authors show that using a dc-dc converter prolongs the lifetime to 30%. In [4] the authors implement an energy-aware duty cycle and take the number of active time slots as a figure of comparison. The boundary conditions are vague, using a real solar panel.
and a fluorescent lamp. The authors of [5] present a energy harvesting platform for evaluation of double-layer capacitor (EDLC, short: supercaps) and thin-film batteries in conjunction with power converters. A flaw is that the energy harvester (a solar cell) is oversimplified to a constant voltage power supply.

1.2. General structure of micro-power managements

Figure 1 shows a general structure of a µPM. The two blocks shown in green (energy extraction and voltage supply) are power converters. The energy extraction block is required to extract as much energy from a harvester as possible. Hence, the output impedance of the harvester and the input impedance of the extraction block need to match. The voltage supply block is required to supply a constant voltage (e.g. 3.3 V) to a load.

![Figure 1: The micro-power management supplies regulated power to loads from energy harvesting sources](image)

2. Methods and Materials

First, we present the harvesting scenario and propose the system efficiency as a performance indicator. Afterwards, we present the experimental setup comprising the modular construction kit, the solar cell simulator, the intelligent dummy load and the energy measurement. Then we illustrate the realization of the four different µPM configurations with the construction kit.

2.1. Harvesting scenario and system efficiency

Our design goal was to set up a harvesting scenario for all experiments, where the maximum amount of 200 J can be harvested and 100 J are consumed per day ($E_{\text{harv}}$ and $E_{\text{cons}}$). The energies equate to an average power of 2.31 mW and 1.16 mW, respectively. An energy storage is used, which is large enough to buffer the theoretic maximum of excess energy of 100 J ($\Delta E = E_{\text{harv}} - E_{\text{cons}}$). However, in reality there are several losses in the system mainly due to power conversion and only a certain amount of energy is stored ($E_{\text{stor}}$). To combine all quantities, we define the system efficiency $\eta$ in Eq. (1). An $\eta > 50\%$ means that excess energy can be stored.

$$\eta = \frac{\text{result}}{\text{efford}} = \frac{E_{\text{cons}} + E_{\text{stor}}}{E_{\text{harv}}}$$  \hspace{1cm} (1)

| $E_{\text{harv}}$ | $E_{\text{cons}}$ | $\Delta E$ | $E_{\text{stor}} | \eta=100\% $ | $E_{\text{stor}} | \eta=90\% $ | $E_{\text{stor}} | \eta=75\% $ | $E_{\text{stor}} | \eta=50\% $ | $E_{\text{stor}} | \eta=25\% $ |
|------------------|------------------|------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 200 J            | 100 J            | 100 J      | 80 J                        | 50 J                        | 0 J                         | -50 J                       |

Table 1: Overview of the energy amounts used to determine the system efficiency
2.2. Modular construction kit
To systematically evaluate different µPMs we developed a modular construction kit, which is shown in Fig. 2. It consists of standardized modules and a base board. Each module incorporates a dedicated power management function like a power converter, current sensor, comparator, power switch, energy storage or a load. Banana plugs are installed to connect harvesters, loads and laboratory equipment. Further details are available in our previous work [6].

![Fig. 2: Construction kit which is used to set up the experiments in an example configuration](image)

2.3. Performance of the solar cell simulator
The design goal was to represent a solar harvester which can deliver up to a total amount of energy of 200 J per day. To accomplish that, we assumed that a solar cell had an area of \( A = 0.67 \text{ cm}^2 \) and took the standard global radiation of \( G = 100 \text{ mW cm}^{-2} \). The relation between the irradiance intensity and the short-circuit current \( I_{SC} \) is linear. Laboratory devices have measured \( I_{SC} \) of over 42 mA/cm\(^2\) and commercial solar cells are between 28 mA/cm\(^2\) and 35 mA/cm\(^2\) [7]. We took 30 mA/cm\(^2\) as a representative figure, resulting in a total \( I_{SC} \) of 20 mA of the cell.

The solar cell simulator is based on the one-diode solar model utilizing a real diode and an adjustable current source. This effort is needed to simulate the non-linear harvester impedance and to create the appropriate conditions for MPPT. We chose the GBJ1506 as diode and a Keithley 2400 source meter as adjustable current source. The mock-up harvester was characterized by an impedance sweep, resulting in an I-V curve, shown in Fig. 3. The fraction between the voltage at maximum power point (\( V_{mpp} \)) and the open-circuit voltage (\( V_{oc} \)) is 81.4%. The peak cell efficiency at an intensity of one sun (\( \eta_{cell,p} \)) is 19.1%.

![Fig. 3: I-V curve of the solar cell simulator. The short-circuit current \( I_{SC} \) is 20 mA](image)

![Fig. 4: Standard solar day defined by trigonometric functions](image)
2.4. Standard solar day scenario
The standard solar day in our scenario consists of a sunny morning and a cloudy afternoon and is well-defined by trigonometric functions, as given in Fig. 4 where the time \( t \) is given in hours. As the cell efficiency varies with the irradiance intensity, the electrical output power was evaluated at every point of the day curve. The integration over 24h of the electrical output power yields a total amount of energy \( E_{PV,day} \) of 212.6 J. This is slightly higher than the desired \( E_{harv} = 200 \) J and accounts for losses due to non-perfect impedance matching in reality.

2.5. Intelligent dummy load
An intelligent load like a microcontroller and a sensor is represented in our test setup by two precision resistors (tolerance = 0.1%) and two nMOS transistors. The design goal was to represent a system which has an energy consumption of 100 J per day, which equates to an average power consumption of 1.16 mW. For a simple but realistic scenario we chose the period to 3s and the on-time to 30 ms, resulting in a duty cycle \( d \) of 1%. Furthermore, we chose 100 Ù for the on-resistance \( R_{on} \) and 100 kÙ for the off-resistance \( R_{off} \). The average power is then calculated by Eq. (2) and yields 1.20 mW for \( V_{cc} = 3.3 \) V:

\[
P_{\text{avg}} = d \cdot P_{\text{active}} + (1 - d) \cdot P_{\text{sleep}} = V_{cc} \cdot \left( d \cdot \frac{V_{cc}}{R_{on}} + (1 - d) \cdot \frac{V_{cc}}{R_{off}} \right)
\]  
(2)

2.6. Current and voltage measurement
To determine actual values for \( E_{harv}, E_{stor} \) and \( E_{cons} \) of the µPM, currents and voltages are measured at three nodes. Namely, before the energy extraction, to and from the storage and after the voltage supply. For the measurements, modules with an INA226 current-shunt monitor IC are used. The shunt resistors used have a resistivity of 1 Ù with a precision of 0.2%. For readout, a datalogger module was developed, which further controls the dummy load and makes all data accessible via USB. All sensor modules and the datalogger are energy independent (powered over USB) to not falsify the energy balance of the system under test.

2.7. Power management setups
Table 2 shows the four chosen µPM configurations. We varied the energy extractor with state-of-the-art ICs, namely the BQ25570 and the ADP5090, and furthermore, we varied the voltage supply block to compared buck converter vs. LDO, both by simply replacing the modules.

In the experiments the excess energy is buffered in two supercaps connected in series (WPL2R72561626 from YEC). One capacitor has a nominal capacity of 25 F and tolerates a voltage of 2.7 V. The energy storage capability from \( V_{c,min} = 3.3 \) V to \( V_{c,max} = 5.4 \) V can be estimated to 114 J, which is larger than \( \Delta \hat{E} \) and thus is sufficient for the experiments.

Figure 5 shows the setup of configuration #3 with the modular construction kit in full detail. The thick green wires are power connections and the thin orange wires are control signals (I²C and digital I/O). In the experiments we cut the first 6 h of the standard solar day (Fig. 4) and started the experiment at \( t = 6 \) h with a pre-charged supercap of 3.4 V. We conducted the experiments in a room with a controlled temperature of 22 °C.

| config | energy extractor | voltage supply |
|--------|-----------------|----------------|
| #1     | BQ25570         | internal buck of BQ |
| #2     | BQ25570         | LDO MCP1700    |
| #3     | ADP5090         | TPS62736       |
| #4     | ADP5090         | LDO MCP1700    |
3. Results

In the following we compare the results of the four system configurations. In Fig. 6 the top series of curves shows the trend of the harvested energy $E_{\text{harv}}$ over one day. The final values at $t = 30\,\text{h}$ are summarized in Table 3 and range from 184.7 J and 192.4 J. We observed a mismatch (% mism.) of 11.3% in average with respect to the theoretic maximum of 212.6 J. In Fig. 6 the bottom series of curves shows the trend of the consumed energy over one day. The consumed energies are slightly (max. 8%) above the desired value of 100 J. The standard deviation $\sigma_{\text{cons}} = 0.94\,\text{J}$ underlines the reproducibility of the experiments.

In Fig. 7 the trend of the stored energy ($E_{\text{stor}}$) over one day is shown. The final values differ significantly, ranging from 11.2 J to 38.8 J. As comparison the theoretic maximum of storable energy ($E_{\text{harv}} - E_{\text{cons}}$) is shown in dashed lines, which represents a system efficiency of 100%. Based on the values $E_{\text{cons}}$, $E_{\text{stor}}$ and $E_{\text{harv}} = 212.6\,\text{J}$, the system efficiency at $t = 30\,\text{h}$ is calculated using Eq. (1) as listed in Table 3.

The trend of the stored energy can be separated into three sections: from $6\,\text{h} < t < 6.7\,\text{h}$ the harvested energy is too low to fully supply the load and thus the storage is discharged. From $6.7\,\text{h} < t < 16.5\,\text{h}$ the power-converters generate excess energy which is stored in the supercap. At $16.5\,\text{h} < t$ the energy balance is negative and thus the storage is discharged again.

Figure 5: Schematic of the construction kit with the complete µPM setup of configuration #3

![Schematic diagram of the construction kit](image)

Figure 6: Trend of harvested energies (top series of curves) and consumed energy amounts (bottom series of curves) over one day

![Graph showing energy trends](image)

Figure 7: Trend of the theoretic maximum of storable energy (top series) and the actual stored energies (bottom series) over one day

![Graph showing storage balance trends](image)
Table 3: Final values at \( t = 30 \) h for the internal energies and system efficiencies

| config | \( E_{\text{harv.}} \) | % mism. | \( E_{\text{cons}} \) | \( E_{\text{stor}} \) | \( \eta \) |
|--------|----------------|--------|----------------|----------------|--------|
| #1     | 190.3 J        | 10.5%  | 107.1 J        | 38.8 J         | 68.6%  |
| #2     | 192.4 J        | 9.5%   | 105.4 J        | 19.8 J         | 58.9%  |
| #3     | 184.7 J        | 13.1%  | 108.0 J        | 33.5 J         | 66.6%  |
| #4     | 186.9 J        | 12.1%  | 107.0 J        | 11.2 J         | 55.6%  |

4. Discussion

Although the stored energy \( E_{\text{stor}} \) differs significantly between the four experiments, it is not that obvious in the calculated system efficiency. The efficiency can represent quite extreme cases: an \( \eta = 0\% \) represents a system where no load is supplied and no storage is charged, whereas \( \eta = 100\% \) represents a perfect system, where all excess energy can be stored. Moreover, both input power converters operate in their supposed operating region. An under- or overdimensioned converter will reduce the system efficiency significantly. Furthermore, the storage was large enough. A too small storage (< 100 J) reduces the capability of storing excess energy, which then reduces the system efficiency further.

Nevertheless, a clear difference of 10 percentage points of higher system efficiency is notable between buck converter and LDO as voltage supply. Especially during noon, where the storage voltage is high, the LDO conversion efficiency is low which is visible in a steeper slope for \( t > 18 \) h in Fig. 7. The mismatch of \( E_{\text{harv.}} \) to the \( 212.6 \) J is assumed to arise from the FOCV method. A system efficiency of max. 69% seems to be low but it is due to permitting all possible system losses and not due to the testbed.

5. Conclusion and outlook

Four different configurations of \( \mu \)PM where tested. The fixed boundary condition generate reproducible results and the proposed system efficiency makes it possible compare different systems. The approach is adaptable to other types of harvesters, such as thermoelectric and vibration harvesters. Further research will focus on varying the input power and storage capacity.

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