A POWER SIMULATION TOOL FOR THE OPTIMIZATION OF WIRELESS SENSOR NODES

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ABSTRACT

Optimization of system-level power consumption is key in extending battery-life in IoT Wireless Sensor Network (WSN) nodes. Early power analysis aids designers in making informed choices about components, design architectures, communication protocols, and battery capacity. This is particularly important when using Energy Harvesters (EH) to extend a node's battery-life or achieve full power autonomy. This work introduces a simulation tool for solar-powered Asset Tracking (AT) WSN nodes developed in the EU project Energy ECS. Using experimental data from partners CSEM and Net Feasa, the tool performs a step-by-step energy balance for an inter-modal dry container during shipment, predicting the necessary EH and battery sizes for autonomy, while identifying power-hungry processes to optimize performance.

KEYWORDS

Simulation model, Battery life, System-level power consumption, Asset Tracking, Energy Harvesting, IoT, Wireless Sensor Nodes

INTRODUCTION

The interconnectivity of instruments, machinery, user interfaces in the Internet of Things (IoT) can be used to significantly enhance interoperability, controllability and efficiency of real-world systems [1,2]. For example, IoT encompasses applications such as Asset Tracking (AT), performance and health monitoring, etc. An IoT system consists of sensors, data processing units, data transmission units (transceivers) and power supply units. More than 50% of systems are wireless and require a portable power source such as a battery, however, their limited lifespan requires their periodic replacement, thus, they cannot provide a reliable power source in many potential applications [2].

Progress in the design, manufacture and packaging of micro-electronic devices, such as Micro Controller Units (MCUs), has led to the reduction of their average power consumption to the sub mW-range for many applications. This enables the usage of reasonably-sized Energy Harvesters (EH) to achieve a substantial increase in effective battery life, in many cases even leading to power autonomy [3, 4]. A system-level analysis helps in providing an optimum system for IoT sensor nodes before physically implementing them in their operating environment [3]. The work focuses on power estimations of one such IoT node, powered by a photovoltaic (PV) EH, and used to track dry containers (Figure 1). The majority of world trade is transported via intermodal shipping containers [5]. Refrigerated containers (Reefers) comprise of about 8 % of the total whereas 'Dry' (basic steel boxes) containers make up the remaining 92 % of containers.

Figure 1: Commercial Dry Container with Net Feasa IoT Device (IoTPASS™).

Connecting and monitoring intermodal refrigerated containers for shipping is not new, however the digitization of the much larger dry container market remains almost completely unaddressed. Considering that almost 90% of global trade travels via intermodal containers, this represents a massive blind spot for IoT and the digital transformation [6]. The key challenge or problem for connecting dry containers is the lack of available power for IoT Wireless Sensor Network (WSN) nodes to feed off. On refrigerated containers, IoT devices can access power via the refrigeration unit but wireless IoT devices fitted to dry containers must rely on self-contained battery power. The useful lifetime of a container is about 14 years and it is not feasible to frequently replace device batteries due to prohibitive labor costs and operational/logistical constraints (e.g. location of the container when the battery depletes). Accordingly, IoT devices used for tracking and monitoring dry containers must be designed with lowest power consumption in mind. Furthermore, to achieve battery-life extension beyond 2-3 years, the IoT device must be also able to exploit ambient energy sources such as solar, vibrational and/or temperature gradients. Hence, power estimations with energy harvesting discussed in this article is a crucial factor in the design of the nodes [7]. This work is divided into the system-level design, including the IoT device and EH unit, the power estimation tool, and conclusions.

SYSTEM DESIGN

Finding a balance between sustainability, versatility, efficiency, power consumption, size and cost is one of the key goals in the design of IoT sensor system.

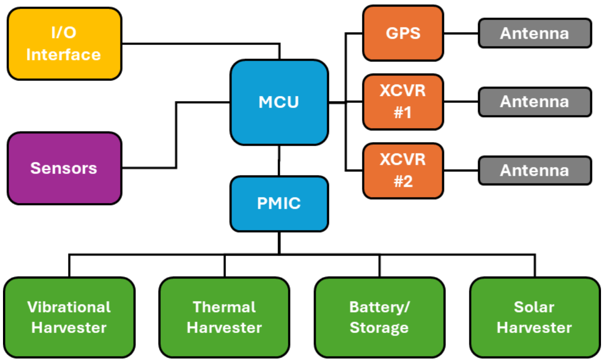

Figure 2: Main HW components of commercialised Net Feasa IoT Device (IoTPASS™)

In order to achieve this, optimized integration of power-efficient hardware entities and protocols is critical to enable the nodes to operate for an extended period of time. System-level design begins with architecture designs supported by a power-aware and adaptive configuration of components and circuits.

IoTPASS Architecture

IoTPASS is a wireless IoT tracking and monitoring device designed to be retrofitted (mounted) onto a (existing) container (Figure 1). The block diagram of the hardware (HW) of the node is shown in Figure 2, while Figure 3 shows a representation of the IoTPASS module developed by Net Feasa with support from CSEM & Tyndall. The device includes multiple sensors, wireless communication modules, a MCU, a Power Management Integrated Circuit (PMIC), a battery and power storage module, plus connectivity for various EH modules such as solar panels, vibrational EHs or Thermo-Electric Generators (TEGs). The device supports LPWAN (Low-Power Wide Area Network) based global connectivity and geolocating capability. It is reliable and robust enough to be mountable on containers with a maintenance-free working life of at least 10 years (with an ultimate target of 14 years). Connectivity is based on a LoRaWAN network that will be deployed as a private network on board vessels and in ports and yards with LTE CAT-M, NB-IoT for 4G and 5G, as RF protocols have been designed specifically for IoT and have much better range that legacy 2G/3G protocols. Public LPWAN cellular networks will be selected and accessed by the IoT device outside of these private network zones e.g. while travelling on roads or by rail [8]. IoTPASS contains a track and monitor circuit board that incorporates sensors and interfaces required temperature, light, barometric pressure, air quality, container door status. It also has a GPS/GNSS independent geo-location function for global tracking of dry containers and the development of transport routing optimization software which includes analysis of location (movement) data and utilization.

Photovoltaic Panel

To facilitate the integration and increase ruggedness of the PV harvester, CSEM has developed a mini-module of amorphous Silicon (a-Si) solar cells deposited on glass substrates via a Plasma-Enhanced Chemical Vapor Deposition (PECVD) process and sealed directly on a Printed Circuit Board (PCB). The mini-module is composed of six laser-scribed a-Si cells connected in series through the PCB (see inset in Figure 4). The figure also reports the measured IV characteristic under standard test conditions AM 1.5 and 25°C. The choice of the underfill and the fabrication process has been crucial to enable good adhesion while protecting the cell against external factors such as humidity. This enabled the mini-modules to pass standard reliability tests, such as light soaking (100 mW/cm^2 at 25°C) and damp heat conditions (1,000-h DH85).

Figure 3: Net Feasa IoTPASS with CSEM Solar Panels

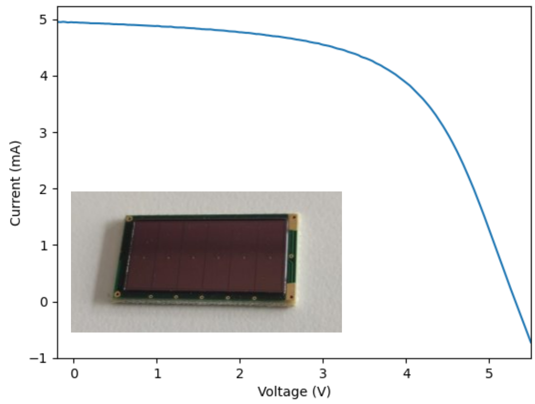

Figure 4: Measured IV characteristic of the 6-cells a-Si solar EH and (inset) photo of the fabricated mini-module.

IoTPASS Power Estimator

System Integrator GUI

The IoTPASS Power estimator is a customizable tool developed in Python and designed to enable system integrators optimize the size of the solar EH and of both primary battery and secondary rechargeable storage (for the harvested energy). Furthermore, it also helps in the selection/comparison of appropriate power management and electronic components. It gives a step-by-step and journey-wide energy consumption analysis. Furthermore, it returns the minimum size of the primary battery required for a single journey as well as the size of the secondary rechargeable battery size (to capture PV energy), along with the resultant battery-life extension.

The tool uses real data from a ship journey, from New York to Rotterdam. For the analysis the journey is subdivided in 19 distinct steps, each corresponding to a specific condition change of the container (e.g. *waiting in stack*, *loading to ship*, …). An average and worst-case PV power availability for each of these steps was recorded in both non-shaded conditions (during travel) and shaded conditions (when stacked on the port). A screenshot of the GUI is shown in Figure 5, and is composed of an Input section and corresponding Outputs.

Input Section

The input GUI, shown in Figure 5(a), takes the following inputs from the user:

- The *size* (in cm^2) and *efficiency* (in %) of the EH.
- The *average power* (in W) consumed by the IoTPASS module.
- The '*context switching*' parameter.

Context switching refers to stages of the container journey (identified by the system integrator) where the 'static' power consumption can be lowered. For example, entering the value as 0.3, reduces the power consumption to 30% of the static value for journey steps configured in the tool.

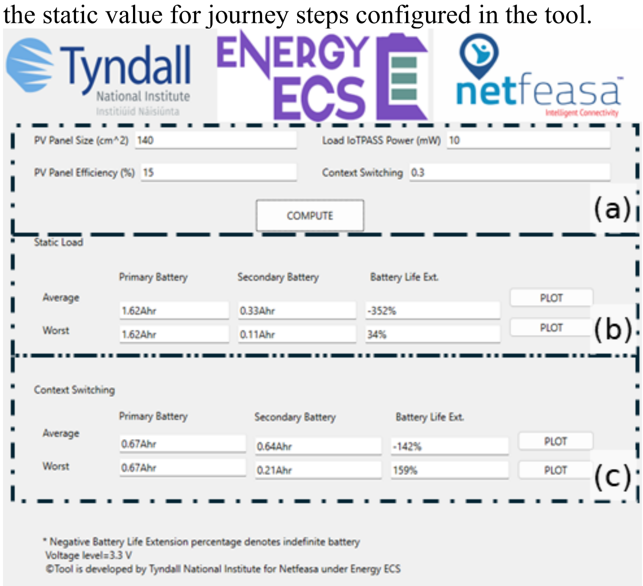

Figure 5: The IoTPASS Power Estimator (a) input, (b) 'static-load' output, and (c) 'context-aware' output.

This percentage figure and the stages for which it is applied can be determined via discussions between the stakeholders. They can agree whether sensing, processing or tranceiving of data can be done less often (especially during the power hungry steps) and what is the resultant reduction in power consumption for this stage. For instance, when the device detects that the dry container sits in a shaded area in a dock (limited PV energy and no motion underway), the detection and communication of the device's location may be carried out less frequently, until such time as container movement is detected.

Output GUI

The tool provides a simplified output section, for users only interested in the system integration, shown in Figure 5(b) and Figure 5(c). The tool computes the size for the primary and secondary battery, as well as the percentage extension of battery life under 'static-load' condition (see Figure 5(b)). It should be noted that a negative number for battery life indicates autonomous operation (i.e. available energy exceeds that needed). The tool can also re-calculate the parameter if context switching loading can be applied. Due to context switching the overall power consumption of the load can be decreased, hence, more energy from the harvester is available to be stored, leading to a larger secondary battery. The same calculations are performed under a worst-case analysis. The input dataset used from CSEM, displayed that the worst-case available energy is only 5% of the average.

Advanced GUI

The tool also provides the simulated step-by-step power and energy analysis of the system during the journey as an aid to system designers. The data in Figure 6 shows the energy balance, together with the energy harvested and consumed for the input parameters, during each of the 19 steps of the journey. When analyzed, the graph shows the presence of opportunities to optimize the power in some steps.

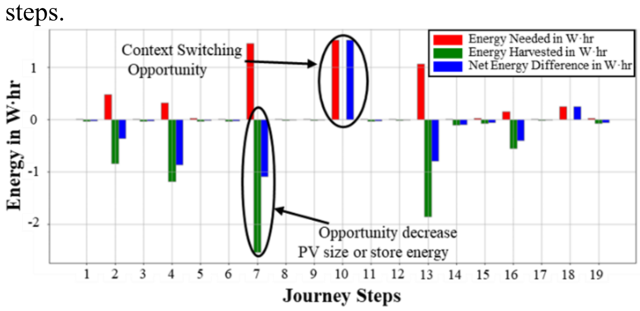

Figure 6: Average Power budget for static-load condition.

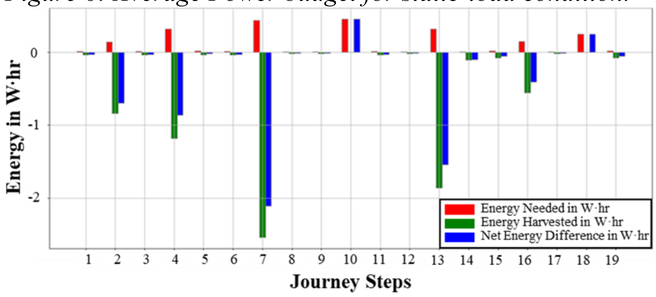

Figure 7: Average Power budget for context-aware load.

For instance, step 7 displays a strong availability of harvested energy that can be stored for later use. Similarly, step 10 shows a power consumption much higher than the harvested, indicating energy-saving strategies, such as context switching, should be considered. Similarly, context switching can also be applied to step 13. The data in Figure 7 shows the context-aware switching concept applied to steps (2, 7, 10, and 13) where it is considered viable. It should also be noted that with context awareness, in addition to reducing peak load deficits, there is more net energy being stored. To this end some cumulative energy as well as power analysis is required. Both of these plots can be easily shown by clicking on the 'PLOT' button in front of various working conditions. The cumulative energy balance output for respectively the static and context-aware loads are plotted as shown in Figure 8 and Figure 9. These energies are plotted for different panel sizes for both static and context-aware conditions (Figure 8(a) and Figure 9(a)). After the end of the journey steps, the leftover energy for a given PV panel size is plotted in the form of a bar chart (Figure 8(b) and Figure 9(b)). This chart shows the "line of autonomy", the point where the energy harvested during the full journey is equal to the energy consumed. The GUI assumes that the secondary battery is adequately sized to store all of the excess energy harvested during a given stage. This can be validated via the System Integrator GUI described earlier. Hence, for any specific panel size it can be determined if the point of autonomy can be reached or exceeded, i.e. if the energy harvested from the PV panel is enough to power the IoTPASS device throughout the journey without the need of a primary battery. These plots are essential in determining a minimum PV panel size required to power the IoTPASS load throughout the journey as well as optimizing the size of the secondary storage device (battery).

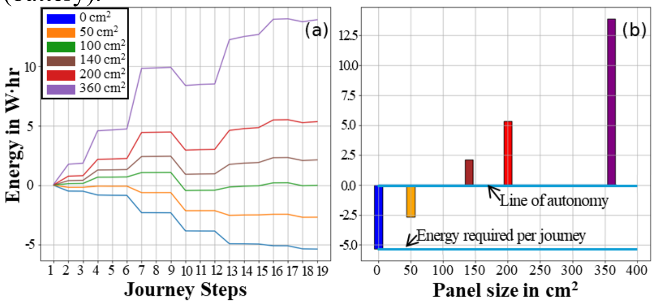

Figure 8: Cumulative Energy (a) vs step and (b) at end of journey for various panel sizes, for static-load condition.

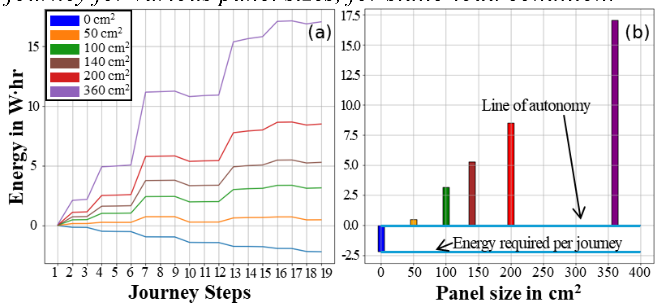

Figure 9: Cumulative Energy (a) vs step and (b) at end of journey for various panel sizes, for context-aware load.

These GUIs indicate that under static-load and average condition, the minimum PV panel size required to autonomously power the IoTPASS is 100 cm^2, while under context-aware load condition the minimum PV panel size required is reduced by 50% to 50 cm^2. Thus, the context switching technique helps not only to manage power, but also to provide significant information about the minimum panel size requirement for the journey.

CONCLUSIONS

The IoTPASS Power Estimator tool provides help for system designers and integrators by determining the size of the primary and secondary batteries, and the PV Panel. It provides the option to demonstrate the potential to reduce primary battery size and/or extend battery life on pre-configured steps. It also helps to identify the minimum PV Panel size necessary to achieve a fully-autonomous system. Both average and worst case conditions help understand the potential deficit for a given combination of journeys. Future iterations will provide improved data visualization, as well as a more accurate and flexible description of the node behavior. Practical testing of the tool would help in improving its estimations, thus making it more accurate and reliable. Still, the architecture of our tool is quite flexible and adaptable to other use cases with relative ease. A new version of our model is under development, which will achieve greater flexibility and granularity through the combined power simulation of the single hardware components, including batteries and harvesters, in a simulated environmental context.

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