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Physical integration of a photovoltaic-battery system: A thermal analysis

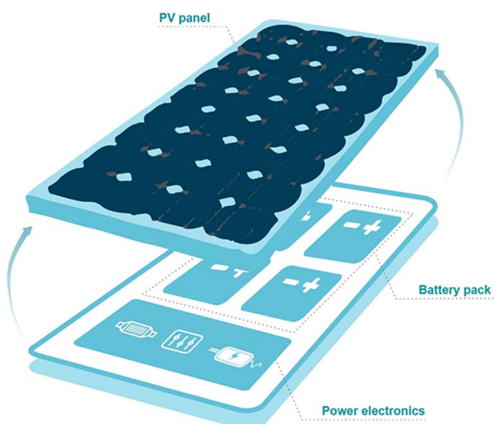
Victor Vega-Garita*, Laura Ramirez-Elizondo, Pavol Bauer

DC Systems, Energy Conversion and Storage at Delft University of Technology, P.O. Box 5031, 2600 GA Delft, Netherlands

HIGHLIGHTS

- The thermal analysis proves the feasibility of the integration concept.
- The battery pack never surpasses the highest temperature of operation.
- Phase change material decreases the maximum battery temperature by 5 °C.
- The experimental results on a prototype validate the thermal model.

GRAPHICAL ABSTRACT



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ABSTRACT

Solar-battery systems are still expensive, bulky, and space consuming. To tackle these issues, we propose a novel device that combines all the components of a solar-battery system in one device. This device might help reduce installation cost compared to the current solar-battery systems as well as provide a *plug-and-play* solution. However, this physical integration means higher temperatures for the components. Therefore, this paper presents a thermal analysis of the physical integration concept to evaluate its feasibility, focusing on the batteries, the most delicate components. The thermal analysis was conducted using a Finite Element Method model and validated with experimental results on a prototype. According to the model, the temperature of the components (battery and converters) reduced drastically by adding an air gap of 5–7 cm between the solar panel and the components. Even under severe conditions, maximum battery temperature never surpassed the highest temperature of operation defined by the manufacturer. Moreover, the maximum battery temperature decreases even further by applying a phase change material as a passive cooling method, reducing it by 5 °C. As a result, the battery pack operates in a safe range when combined with a 265 W_p solar panel, demonstrating the potential of this concept for future solar-battery applications.

1. Introduction

The power produced by a photovoltaic (PV) panel depends on several environmental conditions. A change in either irradiance or ambient temperature, for instance, results in fluctuations of the output power. Therefore, PV panels are not a stable energy source, posing many challenges. A possible solution to cope with these fluctuations is to couple PV panels with energy storage devices. For residential load

* Corresponding author.
E-mail address: v.e.vegagarita@tudelft.nl (V. Vega-Garita).

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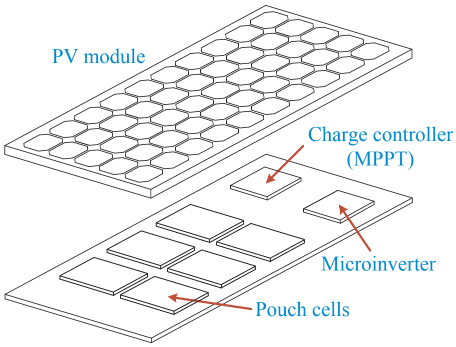

Fig. 1. PV-Battery Integrated Module concept.

levels, batteries are part of PV-storage systems because of their stability, reasonable price, low maintenance cost, and maturity. They provide energy when there is no solar generation, or store energy during moments of high solar generation for later use.

Despite the fact that PV panels and batteries prices are dropping fast [1,2], PV-Battery systems are still expensive. Current PV-Battery systems are complex to design and install. They require extensive technical advice and labour to build the system, impacting the total system cost. In a typical PV-Battery system, PV panels on the roof are usually connected to the power electronics and batteries separately inside the households, making the installation process complicated and time-consuming. The installation cost of solar systems accounts for around 21% of the total cost when other soft costs, not related to hardware (taxes, profit, etc.), are considered [3].

In an effort to diminish costs and make PV-Battery systems more simple to install, one package including a PV panel and all the balance-of-systems components might result in an attractive solution for the solar energy market [4]. We propose a novel device that combines a battery, charge controller, microinverter, and a PV module in one device (refer to Fig. 1). This device, *PV-Battery Integrated Module* (*PBIM*), is developed to provide a modular *plug-and-play* solution for PV-systems' owners. The *PBIM* can be also utilized for portable solutions or as a building block for standalone systems.

1.1. Literature study

The physical integration of PV devices and storage has been explored previously [5–7]. Advances in mechanical properties of the solar cells and batteries have propitiated their incursion in low power wearable devices [8,9], while fiber-shape devices have been woven into textile [10–13]. The majority of these low power devices lack controllable charging and discharging processes, leading to inefficient solutions [14–17]. For this reason, power electronics is essential to operate the PV cells and batteries at their maximum capacity, in particular for medium-power applications, as intended in this paper.

Although some steps to integrate normal size PV panels (circa 200 W) and balance-of-system components have been reported [18,19], just a few papers have coupled batteries directly with solar panels in one device. A combination of PV panel, battery, and electronic control unit was initially suggested in [20], stating the different advantages, general restrictions, and operational conditions of the so-called *multi-functional module*. Following this, the battery management system was proposed [21], and later, this concept was designed to supply bigger loads. The construction, control, and testing of the prototype were presented in [22]. Moreover, the details of the construction and installation of an integrated module for portable applications were published in [23].

At the time of writing this article, we did not find any paper focusing on the thermal implications derived from the physical integration (PI). Nevertheless, a vast amount of previous papers have investigated the thermal behaviour of PV panel and batteries operating individually [24,25], finding that thermal management systems are necessary to decrease the impact on efficiency and safety [26]. Most of the active cooling solutions (e.g. air or liquid forced convection systems, heat pipe, thermoelectric devices, and cold pipe) are complex to implement and maintain, and therefore costly [27]. Additionally, active cooling consumes a portion of the power generated by the PV panels, decreasing the total efficiency of the system. Instead, phase change materials (PCM) have demonstrated to be a promising option as a passive thermal management system for PV panels and batteries [28]. In comparison to active cooling systems for batteries, PCM achieve higher temperature uniformity [29], prevent temperature peaks [30], provide temperature regulation [31], and keep battery operating under safe temperature thresholds [32]. These are the reasons behind the use of PCM in this study.

1.2. Contribution

While some researchers have developed similar ideas to integrate a PV-Battery system in one device, there are still several gaps to fill regarding the feasibility of the PI concept. In particular, a thorough understanding of the thermal processes that take place when integrating all the components together, and their implications to the battery pack. In this paper, we contribute towards

- build (Section 3) and validate (Section 5) a thermal model for the *PBIM* using the Finite Element Method (FEM),
- understand the effect of directly attaching the components to the PV panel (Section 4.1) or including an air gap between them (Section 4.2),
- estimate the maximum battery temperatures and PV temperatures reached under extreme conditions (Section 4.3),
- evaluate the effectiveness of including a phase change material as thermal management method (Section 4.4), and
- prove that batteries can operate in a safe temperature range, and *PBIM* is technically feasible for solar energy applications (Section 4.3).

2. Physical design

For an optimal design of the *PBIM*, the following criteria must be satisfied:

- Heat has to be dissipated efficiently to avoid overheating.
- The device must prevent the entrance of dust and water from the environment.
- The frame must hold the components to ensure they do not move when installing and operating.
- Total volume and weight of the *PBIM* should be reduced as much as possible.

Given the requirements, pouch cells or prismatic cells are preferred due to their thin profile; they help to achieve high packaging as well as notable storage energy capacity per unit of volume. This sort of cells also provides a more extended surface allowing better heat dissipation than other geometries.

For the model, fifteen $LiFePO_4$ cells (A123 AMP20) are used to store the energy coming from the PV panel (265 W_p from Jinko Solar). The PV panel was chosen after comparing several options, based on efficiency, weight, cost, and temperature coefficients.

Due to the fact that the integration concept is relatively new, the size of the components and other features are assumed similar to the commercial charge controllers and microinverters (see Table 2).

3. Finite element method model

Develop a model that includes the heat generated and dissipated to