

**BROADER PERSPECTIVES**

# Integrating a photovoltaic storage system in one device: A critical review

Victor Vega-Garita<sup>1</sup> | Laura Ramirez-Elizondo | Nishant Narayan<sup>2</sup> | Pavol Bauer

DC Systems, Energy Conversion and Storage,  
Delft University of Technology, Delft,  
Netherlands

**Correspondence**

Victor Vega-Garita, PO Box 5031, Delft 2600  
GA, Netherlands.  
Email: v.e.vegagarita@tudelft.nl

**Abstract**

Due to the variable nature of the photovoltaic generation, energy storage is imperative, and the combination of both in one device is appealing for more efficient and easy-to-use devices. Among the myriads of proposed approaches, there are multiple challenges to overcome to make these solutions realistic alternatives to current systems. This paper classifies and identifies previous efforts to achieve integrated photovoltaic storage devices. Moreover, the gaps and future perspectives are analysed to give an overview of the field, paying attention to low-power devices (<10 W) as well as high-power devices (>10 W). We focus on devices that combine solar cells with supercapacitors or batteries, providing information about the structure, materials used, and performance. On the one hand, small power devices must concentrate on including power electronics to increase the efficiency of the system as well as ensuring a safe operation; likewise, more attention should be drawn to validate the feasibility of novel concepts by carrying out more realistic and standardised tests, including long-term testing. On the other hand, high-power devices must be researched thoroughly to evaluate the impact of high temperatures on energy storage and solar module ageing; furthermore, optimum system sizing is a relevant topic that deserves attention and its relation to modular solutions. This critical literature review serves as a guide to understand the characteristics of the approaches followed to integrate photovoltaic devices and storage in one device, shedding light on the improvements required to develop more robust products for a sustainable future.

**KEYWORDS**

battery, one device, PV-storage integration, solar-battery integration, solar energy, supercapacitor

## 1 | INTRODUCTION

Solar photovoltaic (PV) energy generation is highly dependent on weather conditions, making solar power intermittent and many times unreliable. Moreover, energy demand is widespread during the day, and solar energy is available for few hours, provoking a mismatch between demand and supply. These two issues are the driving force behind the use of energy storage (ES) devices, which help decrease the fluctuations from the generation side but also provide the possibility of performing ancillary services. Consequently, it is fundamental to find the most appropriate energy storage device for particular applications and operational conditions.

According to the characteristics of ES devices, the criterion that defines when the energy is stored and utilised may vary, even for the same component. Some ES devices can supply power during extended periods (hours, days), while others are more suitable for shorter periods of operation (seconds, minutes). For instance, rapid changes in PV power due to rapidly changing illumination conditions can be smoothed using supercapacitors (SCs); they deliver power when solar supply is scarce, so the load is still satisfied. For devices with lower self-discharging values like electrochemical cells (batteries), the electrical energy produced by a PV generator could be stored immediately for later use, or the battery could supply the energy accumulated in previous times to complement the generation.

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

© 2018 The Authors. *Progress in Photovoltaics: Research and Applications* Published by John Wiley & Sons Ltd.

Having accepted the fact that solar energy and storage are complementary, there are two forms in which both of them can be combined: via an external circuitry or by physically integrating the components. External connection of components is associated with elevated resistances,<sup>1</sup> complicated manufacturing processes,<sup>2</sup> rigid and heavy devices,<sup>3</sup> and space consuming solutions.<sup>4</sup> By physically integrating a PV-storage system, the current benefits of the synergy solar/storage could be expanded as well as the range of applications for different power levels. The manufacturing process of a complete integrated device is foreseen as one of the main motivations of the physical integration, because it might mean a reduction of the amount of materials and energy in comparison with separately fabricating all components.

Also, integrated devices typically result in higher volumetric and gravimetric energy density devices when compared with solar systems with separated components, due to a reduction on wiring, the sharing of common encapsulation or electrodes, and more compact devices. Another benefit of physically integrated devices is the possibility of having self-sustaining devices and partially self-sustaining devices, opening the door for portable solutions, where no external power sources are required. Furthermore, user-friendly devices that are easy to instal and use are also considered advantages in these sort of applications.

## 1.1 | Related literature

Over the past years, several review papers have explored the combination of solar cells and energy storage in one single component like Xu et al,<sup>5</sup> indicating the features of the proposed approaches for particular applications. For instance in Wei et al,<sup>6</sup> the state of the art of self-powered systems is introduced, while fibre-shape power devices have been studied in Cai et al.<sup>7</sup> Similarly, many papers have summarised and discussed the trends and perspectives of the integration concepts.<sup>8,9</sup> Among them, particular attention has been paid to understand the challenges and advances of printed flexible PV power systems, revising the progress on flexible solar cells, batteries, and power electronics individually.<sup>2</sup> The developments on nanostructured flexible electrodes and structural designs towards shape-conformable devices have been introduced and summarised in detail.<sup>3</sup> Specific interest has been given to the variety of materials that can be combined to build devices that unite dye-sensitised solar

cells (DSSCs) and SCs, where particular attention has been drawn to carefully selecting the materials to achieve components with appropriate performances.<sup>10</sup> Moreover, the current issues and future research directions for various devices that integrate different types of solar cells and SCs technologies have been analysed.<sup>4,11</sup> Also, in Luo et al<sup>12</sup> and Lee et al,<sup>13</sup> the system configuration and working principles of the combination of solar, mechanical, or thermoelectric generator have been reviewed when combined with electrochemical cells or SCs.

However, despite the reviews mentioned above, just a few articles have highlighted the limitations and features that make one of the combinations, solar-battery or solar-SC, better than the other depending on the applications as this review paper intends. As a consequence, this paper gives the opportunity to evaluate both combinations in a common frame. Moreover, to the best of our knowledge, we are presenting the first paper that covers all the relevant efforts related to the physical integration of solar cells and energy storage, from low- to high-power devices (more than 10 W<sub>p</sub>). Especially including high-power devices, which has not been covered before. Additionally, this paper critically analyses the main challenges while indicating future research that should be carried out to enable the development of more robust solutions for high energy applications.

## 1.2 | Contributions

This paper contributes to

- summarise the characteristics of the papers that have implemented PV-storage solutions in a comprehensive manner (Tables 2, 3, and 4),
- analyse the trends and most relevant papers on PV-SCs and PV-batteries for low-power approaches (Sections 3.2.5 and 3.3.3),
- identify general and particular challenges for physically integrating solar and energy storage in low-power applications (Sections 3.4 and 3.5),
- gather the efforts to combine solar and storage devices for high-power solutions (Section 4), and
- identify and analyse the most relevant challenges and gaps for high-power applications (Section 4.5).

**TABLE 1** Searching terms for literature study

Combined with AND		
Combined with OR	Physical Integration	Solar cell
	One device	Batteries
	Combined	Solar module
	Monolithic	Lithium ion
	Integrated Module	Solar panel
	All in one	Accumulator
		Electrochemical cell
		Supercapacitor
		Energy storage
		Photo battery
		Solar battery
		Photo capacitor
		Solar capacitor

**TABLE 2** General characteristics of published research on PSCs

Year	Ref	Structure	PV	SC	PV (mW cm <sup>-2</sup> )	$\eta_{sc}$ (%)	$\eta_s$ (%)	$\eta_{ss}$ (%)	Capacitance (mF cm <sup>-2</sup> )* (F g <sup>-1</sup> )**
2004	Miyasaka and Murakami <sup>17</sup>	Planar (2E)	DSSC	Activated carbon (LiI-doped)	–	–	80 <sup>d</sup>	–	690*
2005	Murakami et al <sup>18</sup>	Planar (2E,3E)	DSSC	Activated carbon (LiI-doped)	–	–	42 <sup>d</sup> (3E)	–	650* <sup>g</sup> (3E)
2011	Skunik et al <sup>30</sup>	Planar (2E)	DSSC	PEDOT(MWCN)/LiCF <sub>3</sub> SO <sub>3</sub> (PC)	–	–	–	–	95** <sup>g</sup>
2012	Chen et al <sup>31</sup>	Coaxial/fibre (2E)	DSSC	CNT/PVA/H <sub>3</sub> PO <sub>4</sub> /Ti	–	2.2 <sup>a</sup>	–	1.5 <sup>e</sup>	0.6*
2013	Mini et al <sup>32</sup>	Planar (3E)	DSSC	Ti/TiO <sub>2</sub> /ZrO <sub>2</sub> /TiO <sub>2</sub> /Ti	0.2178 <sup>b</sup>	–	–	–	0.14*
2013	Kuleszaa et al <sup>33</sup>	Planar (2E,3E)	DSSC	Ag/RuO <sub>x</sub> (OH) <sub>y</sub> /nafion/FTO (3E)	0.92 <sup>a</sup>	0.92	87.8 <sup>d</sup> (3E)	0.8 <sup>h</sup>	3.26* <sup>g</sup>
2013	Li et al <sup>34</sup>	Planar (comb)	DSSC	PET/Ni/Carbon	–	0.27 <sup>a</sup>	–	–	2.89** <sup>f</sup>
2013	Skunik-Nuckowska et al <sup>35</sup>	Planar (3E)	DSSC	Ag/RuO <sub>x</sub> (-OH) <sub>y</sub> /nafion/FTO	2–3 <sup>a</sup>	2–3	87.8 <sup>d</sup>	0.8 <sup>h</sup>	3260* <sup>a</sup>
2013	Yang et al <sup>27</sup>	Planar (3E)	DSSC	MWCNT/PVA-H <sub>3</sub> PO <sub>4</sub> /FTO	2.31 <sup>a</sup>	2.31 <sup>a</sup>	34	0.79	83** <sup>f</sup>
2013	Zhang et al <sup>36</sup>	Planar/fibre (2E)	DSSC	PVDF/ZnO/FTO	2.23–4.36 <sup>a</sup>	7.32 <sup>a,k</sup>	–	3.7 <sup>e</sup>	20**
2014	Westover et al <sup>25</sup>	Planar(2E)	Si-poly	Porous Si	–	14.8 <sup>j</sup>	84 <sup>a,d</sup>	12.43 <sup>k</sup>	0.014* <sup>h</sup>
2014	Zhang et al <sup>37</sup>	Coaxial	OSC	Ti/PVA/H <sub>3</sub> PO <sub>4</sub> /MWCNT	1 <sup>a,k</sup>	1.01 <sup>a,k</sup>	65.6 <sup>f</sup>	0.82 <sup>a,k</sup>	0.077* <sup>h</sup>
2014	Chen et al <sup>38</sup>	Coaxial	DSSC	Ti/TiO <sub>2</sub> /PVA/H <sub>3</sub> PO <sub>4</sub> /Ti	2.7 <sup>a</sup>	2.73 <sup>a</sup>	75.7 <sup>h</sup>	2.07 <sup>a</sup>	3.32* <sup>f</sup>
2014	Huang et al <sup>39</sup>	Planar (3E)	DSSC	Pt/Au/PVDF/FTO	3.3	–	–	1.33–3.38 <sup>a</sup>	0.017** <sup>g</sup>
2014	Yang et al <sup>40</sup>	Coaxial	DSSC	MWCNT/PVA/H <sub>3</sub> PO <sub>4</sub>	6.47	6.47 <sup>a</sup>	–	1.83 <sup>h</sup>	18.6** <sup>f</sup>
2014	Bagheri et al <sup>29</sup>	Planar	DSSC	Co-doped NiO/AC	5,12	4.9 <sup>a</sup>	54 <sup>d</sup>	0.6	32** <sup>f</sup>
2015	Xu et al <sup>41</sup>	In plane	PVSC	polypyrrole-based	13.6	13.6 <sup>a</sup>	–	10 <sup>h</sup>	572* <sup>f</sup>
2015	Narayanan et al <sup>42</sup>	Planar	QDSSC	MWCNT/FTO/Ag/LiCF <sub>3</sub> SO <sub>3</sub>	–	–	–	3.45 <sup>c</sup>	150** <sup>f</sup>
2015	Shi et al <sup>43</sup>	Planar meshed (3E)	QDSSC	carbon/Cu <sub>2</sub> S/Na <sub>2</sub> S/S/KCl	–	2.66 <sup>a</sup>	–	–	72.7** <sup>f</sup>
2015	Zhang and Jiang <sup>44</sup>	Planar(2E)	DSSC	Liquid(l) or quasi-solid electrolyte	–	5.78 <sup>a</sup> (l)	–	–	0.0046**
2015	Cohn et al <sup>45</sup>	Planar(3E)	DSSC	Ionic polymer	4.8 <sup>a</sup>	4.8 <sup>a</sup>	80 <sup>d</sup>	2.1 <sup>f</sup>	3.5*
2015	Chien et al <sup>22</sup>	In plane	OSC	Al/graphene/ITO	–	1.57 <sup>a</sup>	–	–	2.5* <sup>f</sup>
2015	Selvam et al <sup>46</sup>	Separated	DSSC	b-cyclodextrin/PVP/MnCO <sub>3</sub>	–	5.57 <sup>a</sup>	–	–	202.6** <sup>f</sup>
2015	Reddy et al <sup>47</sup>	Planar	DSSC	PEDOP/V <sub>2</sub> O <sub>5</sub>	–	1.4 <sup>a</sup>	–	–	224** <sup>f</sup>
2015	Sun et al <sup>48</sup>	In plane	PSC	CNT/PVA-H <sub>3</sub> PO <sub>4</sub> /PANI	4.3 <sup>a,k</sup>	4.3 <sup>a,k</sup>	72.1 <sup>g,k</sup>	3.1 <sup>k</sup>	185.2** <sup>h</sup>

Continued

TABLE 2 Continued

Year	Ref	Structure	PV	SC	PV (mW cm <sup>-2</sup> )	$\eta_{sc}$ (%)	$\eta_s$ (%)	$\eta_{ss}$ (%)	Capacitance (mF cm <sup>-2</sup> )* (F g <sup>-1</sup> )**
2016	Gao et al <sup>26</sup>	Planar(2E,3E)	a-Si SC	Co-Al LDH/ACT/ACT/graphene	–	22 <sup>j</sup>	3.87 <sup>d</sup>	–	145**g
2016	Li et al <sup>49</sup>	Planar(3E)	PVSC	CuOHNT/KOH/PVA	~ 10.41 <sup>a</sup>	10.41 <sup>a</sup>	–	–	46–67.78* <sup>f</sup>
2016	Lee et al <sup>50</sup>	In plane	DSSC	SWCNT/Buckypaper-based/PVA/KOH	–	0.26 <sup>a</sup>	–	–	62.5–95.25** <sup>f</sup>
2016	Lechêne et al <sup>20</sup>	Planar	OSC	steel/carbon/gel-polymer electrolyte	–	5.2 <sup>i</sup>	–	2.9 <sup>c</sup>	50–130* <sup>i</sup>
2016	Xu et al <sup>51</sup>	Planar (3E)	PVSC	PEDOT-carbon/FTO	–	6.37 <sup>i</sup>	73.77 <sup>h,k</sup>	4.7 <sup>a,k</sup>	10.8–12.8* <sup>f</sup>
2016	Zhou et al <sup>24</sup>	Planar (3E)	PVSC	WO <sub>3</sub> /PVA/H <sub>3</sub> PO <sub>4</sub>	–	–	–	3.73–11.89 <sup>b</sup>	28.7–43.1* <sup>g</sup>
2016	Huang et al <sup>52</sup>	Planar (2E)	DSSC	WO <sub>3</sub> -H <sub>2</sub> O/CNT/PVDF	–	–	–	2.2 <sup>a,k</sup>	195 <sup>f,k</sup> F cm <sup>-3</sup>
2016	Ouyang et al <sup>16</sup>	Planar (3E)	c-Si	Al/MoO <sub>x</sub> /NaSO <sub>4</sub>	–	6.1 <sup>a</sup>	–	–	34* <sup>f</sup>
2016	Wen et al <sup>53</sup>	Coaxial/Fibre	DSSC	PDMS/Cu/PVA/H <sub>3</sub> PO <sub>4</sub>	–	5.64 <sup>a</sup>	–	–	1.9 <sup>f</sup> mF cm <sup>-1</sup>
2016	Chai et al <sup>54</sup>	Coaxial/Fibre	DSSC	Ti/TiN/KOH/PVA	–	0.9 <sup>a</sup>	85 <sup>d</sup>	–	2.28* <sup>f</sup>
2017	Scalia et al <sup>55</sup>	Planar (4E)	DSSC	steel/graphene/PVDF	–	1.38 <sup>a</sup>	73.91	1.02 <sup>h</sup>	10–18** <sup>f,h</sup>
			PVSC		13.2 <sup>a</sup>	80.31	10.97 <sup>h</sup>	142** <sup>g</sup>	
2017	Kim et al <sup>23</sup>	Planar (3E)	OSC	graphene oxide/PVA/H <sub>3</sub> PO <sub>4</sub>	–	9.28 <sup>a</sup>	64.59	5.07 <sup>h</sup>	144** <sup>g</sup>
2017	Zhang et al <sup>56</sup>	Planar (3E)	DSSC	PANI/TiO <sub>2</sub> /PVA/H <sub>3</sub> PO <sub>4</sub> /carbon	–	7.73 <sup>a</sup>	–	6.5 <sup>h</sup>	250–400* <sup>f</sup>
2017	Liu et al <sup>57</sup>	Planar/fibre (3E)	PSC	PANI/CNT	–	2.476 <sup>a</sup>	70.6 <sup>d</sup>	1.74 <sup>h</sup>	422* <sup>f</sup>
2017	Liang et al <sup>28</sup>	Coaxial/fibre	DSSC	CF/TiO <sub>2</sub> /MoS <sub>2</sub>	–	9.5 <sup>a</sup>	–	1.8* <sup>h</sup>	18.51* <sup>f</sup>

<sup>a</sup>Testing at one sun (1000 W/m<sup>2</sup>).<sup>b</sup>Parameters estimated from I-V curve.<sup>c</sup>Testing at specific conditions.<sup>d</sup>Parameters obtained from a complete charging-discharging process.<sup>e</sup>Overall photo-storage efficiency.<sup>f</sup>Parameter calculated using cyclic voltammetry.<sup>g</sup>Parameter calculated based only on a charging or discharging process.<sup>h</sup>Parameter calculated according to a equation proposed by the authors.<sup>i</sup>Parameters estimate for one device isolated of the other.<sup>j</sup>Parameter given by the manufacturer.<sup>k</sup>Parameter obtained for the device with the highest performance.<sup>l</sup>Efficiency calculated by the authors of this paper using Equation 1.<sup>m</sup>Parameter calculated by the authors of this paper based on provided information.

**TABLE 3** General characteristics of published research on solar-batteries

Year	Ref	Structure	PV	Battery	PV (mW cm <sup>-2</sup> )	$\eta_{sc}$ (%)	$\eta_s$ (%)	$\eta_{ss}$ (%)	Capacity (mAh)
				LiMn <sub>2</sub> O <sub>4</sub>					0.8
2002	Raffaella et al <sup>74</sup>	Planar	GaAs	LiNiCoO <sub>2</sub>	–	12.8 <sup>c</sup>	–	–	45
2002	Hauch et al <sup>60</sup>	One device (2E)	DSSC	WO <sub>3</sub> /LiWO <sub>3</sub> /LiI/LiI <sub>3</sub>	–	–	–	–	0.167 <sup>a,h</sup>
2007	Dennler et al <sup>71</sup>	Planar	OSC	LiCoO <sub>2</sub> /graphite	1.9 <sup>a</sup>	1.85 <sup>a</sup>	–	–	100 <sup>l,k</sup>
2009	Kim et al <sup>75</sup>	Planar	a-Si	LiCoO <sub>2</sub> Li-ion solid state	3.68 <sup>j</sup>				0.42 <sup>j</sup>
2010	Krebs et al <sup>76,77</sup>								
2011	Krebs et al <sup>78</sup>	Planar	OSC	LiCoO <sub>2</sub> /graphite	–	1.02–2.75 <sup>a</sup>	–	–	105–400 <sup>a</sup>
2011	Bermejo et al <sup>67</sup>	Parallel	c-Si	SiO <sub>2</sub> /LiMn <sub>2</sub> O <sub>4</sub>	2.07–6.7 <sup>a</sup>	1.5–6.5 <sup>a</sup>	–	–	5.5 <sup>i</sup>
2012	Chakrapani et al <sup>79</sup>	Planar (3E)	Si	Si/LiCoO <sub>2</sub>	–	–	–	–	–
2012	Guo et al <sup>69</sup>	Planar	DSSC	LiCoO <sub>2</sub>	–	–	41	0.82 <sup>h</sup>	0.039 <sup>g</sup>
2012	Liu et al <sup>80</sup>	Planar (3E)	DSSC	carbon/LiClO <sub>4</sub> /PPy/FTO	–	0.1 <sup>a</sup>	–	–	8.3 g <sup>-1</sup> g
2013	Lee et al <sup>81</sup>	Planar	OSC	LiFePO <sub>4</sub> /Li <sub>4</sub> Ti <sub>5</sub> O <sub>12</sub>	–	5.49 <sup>a</sup>	–	–	13
2013	Ye et al <sup>68</sup>	Planar	$\alpha$ -Si	Nb <sub>2</sub> O <sub>5</sub> /LiPON/ LiCoO <sub>2</sub>	–	7.4 <sup>a</sup>	95 <sup>d</sup>	4 <sup>h</sup>	0.215 <sup>g</sup>
2013	Kim et al <sup>82</sup>	Planar	c-Si	Li-solid state	–	5.48 <sup>a</sup>	–	–	0.012 <sup>i</sup>
2014	Rieutort-Louis et al <sup>83</sup>	Planar	a-Si	Li/LiPON/ LiCoO <sub>2</sub>	–	–	–	–	0.3 <sup>j</sup>
2015	Xu et al <sup>72</sup>	Planar/ series	PSC	LiFePO <sub>4</sub> /Li <sub>4</sub> Ti <sub>5</sub> O <sub>12</sub>	–	12.65 <sup>a,i</sup>	–	7.8 <sup>g,h</sup>	142.1 <sup>g</sup> g <sup>-1</sup>
2015	Meister et al <sup>70</sup>	Planar	OSC	NiMH	3.36 <sup>a</sup>	–	–	–	5.5–14.4 <sup>j</sup>
2015	Wang et al <sup>59</sup>	Planar	DSSC	Lead organohalide	–	–	81.5 <sup>d</sup>	8.6 <sup>a</sup>	–
2016	Agbo et al <sup>66</sup>	Planar	a-Si:H	LiFePO <sub>4</sub> /Li <sub>4</sub> Ti <sub>5</sub> O <sub>12</sub>	–	9.2–11.5 <sup>a</sup>	–	8.8 <sup>h,k</sup>	0.1 <sup>g</sup>
2016	Ostfeld et al <sup>84</sup>	Planar	a-Si	graphite/ LiCoO <sub>2</sub>	–	4 <sup>j</sup>	99.9 <sup>d</sup>	–	47.5 <sup>d</sup>
2016	Agbo et al <sup>85</sup>	Planar	a-Si:H	LiFePO <sub>4</sub> /Li <sub>4</sub> Ti <sub>5</sub> O <sub>12</sub>	–	9.2 <sup>a</sup>	–	8 <sup>g,h</sup>	0.56 <sup>d</sup>
2016	Sun et al <sup>86</sup>	Fibre	DSSC	LiMn <sub>2</sub> O <sub>4</sub> /Li <sub>4</sub> Ti <sub>5</sub> O <sub>12</sub>	–	6.05 <sup>a</sup>	95 <sup>g</sup>	5.74 <sup>l</sup>	18.48 <sup>m</sup>
2017	Sandbaumhüter et al <sup>87</sup>	Planar(3E)	a-Si:H/ $\mu$ c-Si:H	Li/LiPON/ LiCoO <sub>2</sub>	–	8.1 <sup>a</sup>	99.9 <sup>d</sup>	8 <sup>l</sup>	1.3 <sup>m</sup>
2017	Um et al <sup>73</sup>	Planar	c-Si	Li <sub>4</sub> Ti <sub>5</sub> O <sub>12</sub> / LiCoO <sub>2</sub> /Al	–	15.7 <sup>a</sup>	–	7.61 <sup>h</sup>	0.18 <sup>g,m</sup>

<sup>a</sup>Testing at one sun (1000 W/m<sup>2</sup>).<sup>b</sup>Parameters estimated from I-V curve.<sup>c</sup>Testing at specific conditions.<sup>d</sup>Parameters obtained from a complete charging-discharging process.<sup>e</sup>Overall photo-storage efficiency.<sup>f</sup>Parameter calculated based only on a charging or discharging process.<sup>g</sup>Parameter calculated according to a equation proposed by the authors.<sup>h</sup>Parameters estimate for one device isolated of the other.<sup>i</sup>Parameter given by the manufacturer.<sup>j</sup>Parameter obtained for the device with the highest performance.<sup>k</sup>Efficiency calculated by the authors of this paper using Equation 1.<sup>l</sup>Parameter calculated by the authors of this paper based on provided information.

### 1.3 | Criteria for classifying papers

For classification purposes, the papers were divided into two categories: high-power and low-power devices. Devices with a PV generation rated power less than 10 W<sub>p</sub> were considered low-power solutions, whereas devices able to deliver more than 10 W<sub>p</sub> were classified as high power, as stated by Apostolou and Reinders.<sup>14</sup> In order to put this value in perspective, charging a cell phone requires from 1 up to 10 W. Accordingly, a low-power-integrated device would barely be capable of charging a midpower cell phone (10 W).

focuses on the integration of PV devices and energy storage technologies, ie, electrochemical cells and SCs. Approaches that include water-splitting devices or bio-inspired concepts are not considered within the scope of this study.

For the searching, databases such as Web of Science, Scopus, and Google Scholar were consulted. The bibliographic references were selected based on quality (highly cited, from renown journals, clear, etc), and novelty (new concepts, high efficiencies, new materials, etc) of the introduced concepts.

## 2 | METHODOLOGY OF THE REVIEW

### 2.1 | Criteria for selecting papers

All the papers collected in this review paper were found using the general searching terms that Table 1 introduces. The literature survey

## 3 | LOW-POWER PV-STORAGE DEVICES

This section introduces various efforts for physically integrating solar cells, SC, and electrochemical cells that result in low-power devices. Here, the general structures followed to combine storage and solar energy is presented along with the main trends and challenges that

both types of devices face. Also, the most promising applications are introduced to describe their level of readiness to become widespread solutions.

### 3.1 | Overall efficiency

To estimate the overall efficiency ( $\eta_{ss}$ ) of an integrated device, a formula that considers the individual efficiencies of the energy sources is written as follows:

$$\eta_{ss} = \eta_{sc}\eta_s, \quad (1)$$

where  $\eta_{sc}$  is solar cell efficiency and  $\eta_s$  energy storage efficiency. By using Equation 1 as a reference, all solutions could be compared using the same expression. This is important because many papers have considered other ways of estimating  $\eta_{ss}$ , making difficult fair comparisons across articles. The  $\eta_{ss}$  values provided by Tables 2 and 3 utilises Equation 1 as long as the information about individual efficiencies is provided. In these tables, the procedure followed to measure or calculate  $\eta_{sc}$  and  $\eta_s$  are also mentioned if details are provided by the authors of the reviewed papers.

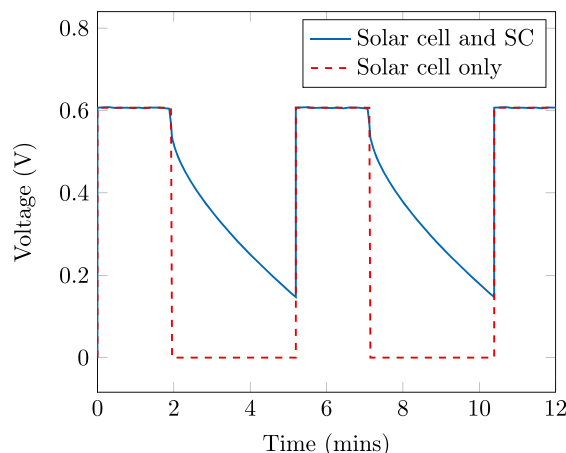
### 3.2 | Solar cells and SC

SCs are capacitors with high values of capacitance but low voltage. In general terms, they are located between electrolytic capacitors and rechargeable batteries in terms of energy density. Among the most important characteristics of SC are low maintenance, high performance, and long cycle life.<sup>15</sup> As mentioned before, SCs are more suitable for power (short-term storage) than for energy applications (long term). Consequently, the devices in this section are mainly designed to make the solar cell output power more stable.

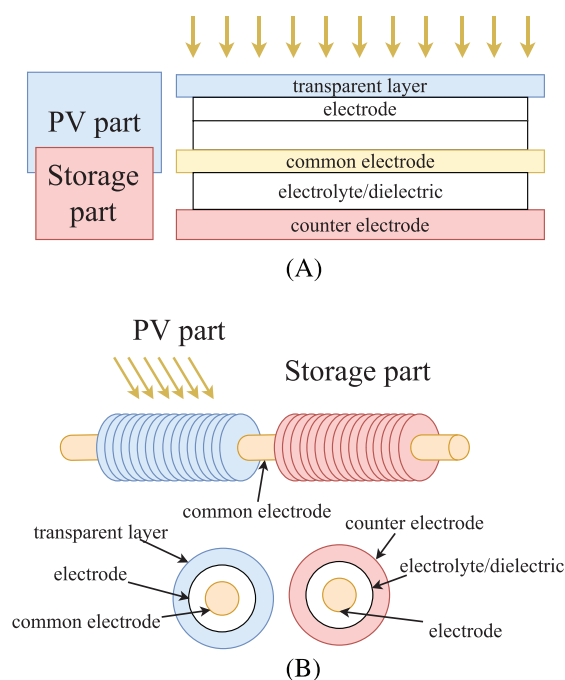
When a solar cell is exposed to light, the voltage increases and as soon as the cell is not illuminated, the voltage returns to zero (Figure 1). However, if the solar cells are connected to a SC, the voltage of the device does not decrease immediately to zero. Therefore, the power delivered is not interrupted when light is not available. Because the power is not interrupted, integrated devices provide more reliable power output, which facilitates its use in a broader range of applications.

#### 3.2.1 | How are SCs and solar cells integrated?

Devices that combine solar cells and SC are referred to as a photo-supercapacitors (PSCs) or solar capacitors. In these devices, multiple solar cells technologies (eg, dye-sensitised, organic, perovskite, and silicon) and SC types (double layer, pseudo-capacitors, and hybrid) have been combined following different approaches. Although previous research has explored the combination of solar cells and SCs when they are connected by external cables, these are not considered entirely integrated solutions. In fully integrated devices, the solar cell and the SC must either share a common electrode<sup>11</sup> or at least the same substrate. This electrode facilitates the charge transfer while reducing resistance losses due to wiring in comparison with not integrated approaches. The majority of these integrated devices exhibit a planar (monolithic) structure or a fibre-shaped configuration as introduced in Figure 2.



**FIGURE 1** Response of a single solar cell and a solar cell coupled with a supercapacitor during intermittent illumination. If light is on, the voltage of a single solar cell is around 0.6, but when light is off, the voltage decreases to 0. In cases where an appropriate SC is used, the system voltage does not decrease to zero intermediately in the absence of light. This figure is based on Ouyang et al,<sup>16</sup> where the illumination period was 2 min followed by a 3-min discharging process at a constant discharging current density of  $40 \mu\text{A cm}^{-2}$  [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 2** A, Planar or monolithic three-electrode structure; B, coaxial fibre parallel structure [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

#### 3.2.2 | Planar structure

In planar or monolithic structures, the solar cell is at the top receiving the incident light, while the SC is placed at the bottom of the device, and as Figure 2A shows, they are typically connected in series. According to the materials and working principle of the solar cell and SC, different ideas of integration can be realised; however, there are three main configurations: two-electrode, three-electrode, and four-electrode modes.<sup>12</sup>



## Two-electrode mode

The two-electrode mode is the most integrated of the approaches because the rear electrode of the solar cell is shared with the SC while reducing materials and increasing the energy density of the device. However, when combining a DSSC and an SC in a two-electrode configuration,<sup>17</sup> the device presented particular issues. One problem occurred during the discharging process because the electrons from the counter electrode were not able to easily cross the  $\text{TiO}_2$  layer towards the shared electrode. The diffusion of iodine ions caused the second problem, as the SC electrolyte shortcircuited or self-discharged the device. These difficulties resulted into a device with lower efficiency in comparison with a three-electrode mode device presented by the same authors,<sup>18</sup> as the two-electrode mode exhibited a higher resistance.

## Three-electrode mode

Due to the problems mentioned above, an intermediate electrode is added to separate the DSSC and the SC, forming a three-electrode structure. By adding this barrier, solar cells and SCs can operate individually or together when supplying the load, which is not possible in the two-electrode case. In a three-electrode configuration, the counter electrode fulfils a double purpose; it functions as a redox electron transfer surface and as charge storage.

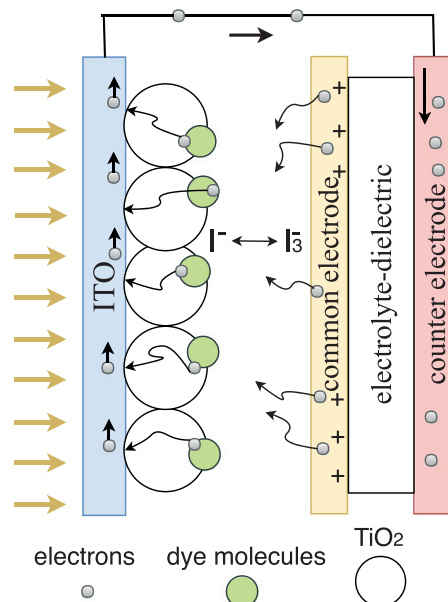
### 3.2.3 | Fibre structure

When compared with a planar structure, fibre-shaped or wire-type devices follow the same physical principles; the difference lies in the arrangement of the components. They are classified as core-shell (or coaxial), twisted, and parallel-like structures.<sup>4</sup> Besides the structure itself, all of these devices share a common substrate in the form of a fibre. Plastic, elastic rubber, and metal wires have been used as mechanical support and to assemble the solar cell part and the SC in cores-shell structures. In the case of twisted devices, the substrate fibres with the solar cell and SC are rolled to achieved the required spiral shape, while for parallel-like structure the mechanical stability normally improved by having the two fibres placed in parallel (Figure 2). While fibre-shaped solutions are less energy efficient when compared with a planar structure, their mechanical properties enable them to be used in wearable and portable low-power applications.<sup>7</sup>

### 3.2.4 | How does a PSC work?

The PV part converts the incident light into electrical energy generating hole-electron pairs while promoting electrons to high-energy levels and holes remain at low-energy level. The exited electrons accumulate at one side of the capacitor and holes in the other electrode until the capacitor saturates.

Figure 3 depicts the working principle of a solar SC implemented using a DSSC for a three-electrode configuration. In these devices, photo-excited electrons from the dye reach the conduction band of a semiconductor, generally  $\text{TiO}_2$ . Later, the electrons flow to the transparent conducting electrode, which is externally connected to the SC where they are stored. This process is possible because negative electrolyte ions, frequently  $\text{I}^-$ , are combined with positive dye



**FIGURE 3** Working principle of a dye-sensitized solar cell coupled with a supercapacitor [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

molecules allowing its regeneration and keeping the photo-generation process. The charging process continues as the redox reaction ( $\text{I}^-/\text{I}_3^-$ ) in the electrolyte is sustained by the electrons provided from the shared electrode. The SC can be charged until saturation; however, if light intensity weakens or disappears, the opposite process occurs and the device discharges.

### 3.2.5 | Relevant papers and trends

Table 2 summarises the variety of research carried out when integrating solar cells and SCs; the papers are classified based on the year of publication, solar cells technologies, the structure of the device, type of SC, power, efficiencies, and capacitance. From this table, it is evident that since 2004, when the first paper was published, the articles have focused mainly on the integration of DSSC and different types of SCs. The preference for DSSC over other solar cell technologies lies in its easy manufacturing process, but also because SCs and DSSCs share a similar structure, which facilitates its physical integration.<sup>4</sup>

Later on, organic solar cells (OSC) have also been combined with SCs. OSCs have expanded the range of applications for integrated devices, eg, in portable and wearable solutions. Among the many merits of OSCs, its flexibility, lightweight, and transparency are the most remarkable.<sup>19,20</sup> Furthermore, OSCs low costs and ease of manufacturing (roll-to-roll) underline its potential and interest in physically integrated devices.<sup>21</sup> Although the efficiencies of OSCs need further improvements, the utilisation of OSCs eliminates the need for liquid electrolytes when compared with DSSC concepts, making more stable and robust integrated devices. An OSC and graphene-based SC were combined following an in-plane or parallel structure in Chien et al<sup>22</sup>; the method presented is considered suitable for roll-to-roll manufacture and convenient for future self-sustained application. Nonetheless, after connecting five OSCs in series, the voltage of the device was about 5 V with a low conversion efficiency of almost 1.6%.

In an effort to achieve more efficient and powerful integrated devices, perovskite solar cells (PVSC) and SC have undergone extensive investigation. The result of this combination has produced devices that excel when compared with other devices. As Figure 5 indicates, the device with the highest PV output ( $13.6 \text{ mW cm}^{-2}$ ) and capacitance per unit area ( $572 \text{ mF cm}^{-2}$ ) is based on union of PVSC and SC. In Kim et al.,<sup>23</sup> an OSC- and PVSC-based devices were integrated following the same structure and using SC technology, concluding that as expected PVSC integrated device outperforms OSCs, by a factor of two in this case. As can be seen from Table 2, devices with efficiencies above 10% are possible when high-efficient PVSCs have been combined with conventional SC.<sup>23,24</sup> Although not so frequently, a-Si and c-Si solar cells have also been researched with acceptable overall efficiencies.<sup>16,25,26</sup>

Regarding the materials used as electrodes in the SC part, activated carbon is usually chosen in double-layer capacitors due to its low cost, extensive surface area, and chemical stability. To face the challenges of having a liquid electrolyte, multiwalled carbon nanotubes are used in all-solid integrated devices to achieve a more energetically compact device.<sup>27</sup>

Moreover, pseudo-capacitors made of metal oxides and conductive polymers have been employed as electrodes in various SC coupled to solar cells. Conductive polymers (such as PEDOT and PANI) are selected because they are easy to manufacture and able to reach relatively high capacitance values. In the case of metal oxides (like  $\text{TiO}_2$ ), the devices perform deficiently due to their high electrical resistance when selected as intermediate electrodes.<sup>28</sup>

Although not very often, hybrid SCs have also been investigated as a consequence of its tunable voltage levels and elevated capacitance values. This combination, however, has resulted in devices with low efficiency.<sup>29</sup>

### 3.3 | PV and battery

Unlike SCs, batteries are able to store energy for more extended periods with low self-discharging rates. This feature makes batteries an appropriate technology to manage the mismatch between solar generation and energy demand because the sun shines for a limited time and it is not able to supply power during the night. Batteries can also smooth the output of the solar cell, similarly to the SC, although its response capacity is limited because high-power requirement from the load could damage the batteries. Currently, batteries are part of PV-storage systems because of their stability, reasonable price, low maintenance cost, and maturity.<sup>15</sup>

An electrochemical cell is a device that is able to store energy in a chemical form as a result of electric stimuli. In an electrochemical cell, a material (electrode) reduces while the other electrode oxidises, in which the overall system remains in equilibrium because the electrons flow from one electrode to the other. As the electrodes cannot touch each other, an electrolyte is needed to provide electrical insulation while acting as a medium for the ions to diffuse.

#### 3.3.1 | How are solar cells and batteries integrated?

PV charging devices as well as photocatalytic charging systems have been explored when integrating batteries and solar cells. In PV charging

devices, the battery and solar cells obey independent physicochemical processes, while in photo-catalytic devices, photo-induced interdependent redox reactions occur during the charging process. Integrated devices that contain silicon, organic, or perovskites solar cells are classified as PV charging devices. Conversely, dye-sensitised and quantum DSSCs belong to the category of photo-catalytic devices.<sup>12</sup>

Solar cells and batteries have been integrated following mainly planar structures with differences in the electrode configuration: two-electrode (2E) and three-electrode (3E). In three-electrode devices (Figure 2A), there is a clear distinction between the storage and generation part, although they share a common counter electrode.<sup>1</sup> Alternatively, other articles have introduced devices composed of two electrodes, where one of them works as a photo-electrode and the other functions as an energy storage electrode. Hence, the device is considered as a single entity as there is no physical division in the middle of the generation and storage parts.

#### 3.3.2 | How does a photo-battery work?

In 3E devices, when photons strike the photo-active material, some electrons increase their energy and can reach the conduction band while producing holes. If the voltage provided by the solar cell is enough to activate the electrochemical charging process inside the battery, the electrons from the solar cell move to the battery's anode, where they recombine with the cations released by the cathode. Alternatively, the holes from the solar cell recombine with the electrons generated by the oxidation in the cathode. As soon as the light source is not present, the opposite phenomenon occurs, and the batteries discharge if a load is added to extract the energy accumulated.<sup>58</sup>

However, 2E structured components follow a different working principle. In the photo-electrode material, one chemical element oxidises while in the counter electrode another substance reduces. An example of this kind of devices was explored in Wang et al.,<sup>59</sup> where a conventional DSSC was modified substituting the  $\text{I}^-/\text{I}_3^-$  electrolyte with a lead-organohalide. The device resulted in a dual-function rechargeable solar battery with an overall efficiency close to 7%.

#### 3.3.3 | Relevant papers and trends

2E configurations have been extensively explored, where various combinations of materials for anodes and cathodes were tested in redox cells to evaluate their effectiveness to produce and store solar energy. One of the first attempts at integrating a DSSC and an electrochemical device in one component consisted of using  $\text{WO}_3$  as a charge storage layer.<sup>60</sup> For more details, a comprehensive list was developed by Yu et al.,<sup>61</sup> in which the published papers were classified based on catholyte redox couples, photoelectrode, active anodes, transport ion, solvent, membranes, voltages, and discharged currents. As a consequence of the variety of types of materials, the compatibility of the electrodes and the selection of appropriate electrolytes is fundamental for long-term stability but also to achieve adequate performance. Although few devices have been able to exhibit overall efficiencies above 10% like Licht et al.,<sup>62</sup> the short-term and midterm stability of the devices along with the low voltage output have been considered one of the main problems behind these approaches. One way to increase the voltage is by using Li ions as the



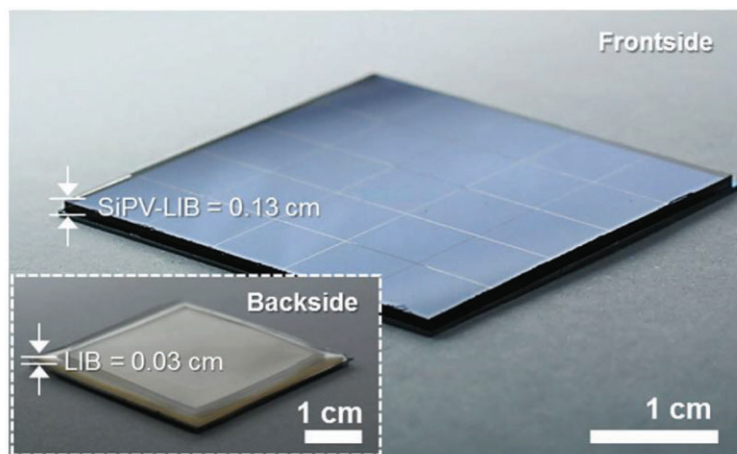
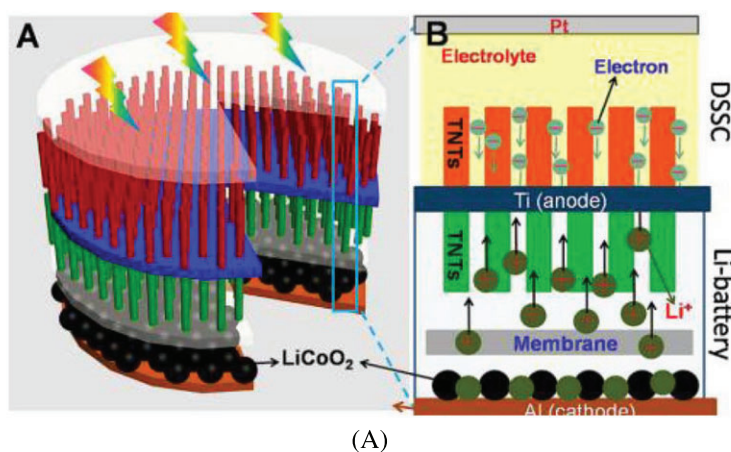
active anode because it results in devices with comparable voltages as individual Li-ion batteries. An example of this was introduced by Paoletta et al.,<sup>63</sup> where the delithiation of lithium iron phosphate nanocrystals is produced by its interaction with light, opening the door to photo-rechargeable lithium-ion batteries, which presents a considerable advance in the field of solar and energy storage. However, the overall efficiency was low, 0.06% to 0.08%. Along the same line, a Li-O<sub>2</sub> light-assisted battery was suggested,<sup>64</sup> with similar voltage values (2.72–2.83 V) and deficient stability.

Because of these limitations, currently, three-electrode configurations have been examined more extensively than two-electrode structures as can be seen in Table 3. In this table, various research papers are classified based on the PV generation technologies, device structure, type of battery, power, storage and generation efficiency, overall efficiency, and battery capacity. Also, based on Tables 3 and 4, Figure 6 summarises while comparing different approaches and battery technologies.

As Si have been intensively used for making solar cells, different types of Si solar cells have been combined with batteries. One remarkable concept was introduced in Chakrapani et al.,<sup>65</sup> where a nanowire-based multijunction Si PV device shared a Si substrate with a LiCoO<sub>2</sub> battery, which had a Si nanowire anode. Another triple-junction solar cells made of amorphous and microcrystalline sil-

icon was used to charge a lithium-ion battery and demonstrate the potential of an integrated solar cell-to-battery cell monolithic device, with a battery capacity of 0.15 mAh and overall efficiency of 8.8%.<sup>66</sup> Moreover, a silicon-on-insulator manufacturing process was introduced to fabricate multiple solar cells and scale up the overall cell voltage<sup>67</sup>; here, an array of 25 cells has been integrated with a micro-battery to act as a mini generator, producing a maximum power of 1.7 mW. The open circuit voltage of the solar cells could be scaled from 3.6 V (nine cells) until 101.5 V if 169 cells are connected in series. Thin film solar cells have also been explored. For instance, in Ye et al.,<sup>68</sup> the fabrication and characterisation of a harvesting device that integrates a thin-film solid-state rechargeable battery was introduced, showing a 0.1%/cycle reduction on battery capacity and a generation-storage efficiency and maximum power point of 7.03% and 150 mW, respectively.

DSSCs have also been combined with batteries following a three-electrode configuration. As presented in Figure 4A, the device has a Ti common electrode in which TiO<sub>2</sub> nanotubes were grown to be part of the DSSC (orange) and Li-ion battery (green). At the top, the TiO<sub>2</sub> nanotubes covered by dye molecules work as electron collectors that when hit by the light transfer excited electrons first to the Ti electrode, and later to the TiO<sub>2</sub> battery anode where they are stored. Also while charging, the Li<sup>+</sup> move to the anode maintaining the electro-



**FIGURE 4** A, Three-electrode nanotube based integrated solar battery device. Reprinted with permission from Guo et al.<sup>69</sup> Copyright 2012, American Chemical Society. B, Monolithic integration of solar cell and solid state Li-ion battery for an more easy manufacturing process. Reproduced from Haddon et al.<sup>73</sup> with permission from the The Royal Society of Chemistry [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

chemical equilibrium. For this device, the overall efficiency was 0.82% and the battery capacity 38.39  $\mu\text{Ah}$ .<sup>69</sup>

Moreover, a few organic solar cells have been physically integrated. A bendable module (1 mm) made utilising an organic PV cell, charging electronics, and a rechargeable battery (NiMH) was introduced in Meister et al.<sup>70</sup> There, two devices with different voltages (6 and 24 V) were tested and charged after 4 hours under 1-sun condition. On the same line, a previous study integrates a thin film solar cell and Li-ion polymer (100 mAh, 3.3 g, <1 mm).<sup>71</sup>

Although not so common, as Table 3 suggests, batteries and PVSC have been studied. Four  $\text{CH}_3\text{NH}_3\text{PbI}_3$  PVSC placed in series have been employed for charging a Li-ion battery made of a  $\text{LiFePO}_4$  cathode and a  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  anode. The device reached an overall efficiency of 7.80% and a good cycling stability<sup>72</sup>; however, the fabrication process must be revised carefully before the device can be implemented in practical applications as indicated by the authors.

In order to improve the manufacturing process of integrated devices, a new method of assembly has been presented to favour an easy and scalable manufacturing process,<sup>73</sup> opening the possibility of using this portable solar batteries for low consumption electronics. The monolithically integrated approach uses 25 c-Si PV cells in series producing a total voltage of 14.1 V (Figure 4B) and a bipolar printed solid-state  $\text{Li}_4\text{Ti}_5\text{O}_{12}$  battery. The complete device has a total area of 9  $\text{cm}^2$  with an overall generation-storage efficiency of 7.61%, while the battery is completely charged in 2 minutes and discharged at 28 C-rate. With the same objective, the roll-to-roll manufacturing process can be used to directly integrate an organic solar cell and pouch li-ion cell, providing a fast manufacturing process.<sup>78</sup>

### 3.4 | General perspectives and gaps

Because batteries and SCs are combined following similar approaches and are integrated with the same PV technologies, they face common challenges to become viable concepts for high-power systems, which are addressed as part of this section.

#### 3.4.1 | Materials compatibility

When building PSCs and solar batteries, the compatibility of active materials is primordial. For instance, their appropriate selection helps reduce electron recombination and increase conversion efficiency.<sup>4</sup> At the same time, the selected materials should not react between them to ensure long-term stability. However, choosing the right redox couple is challenging as only a few of them are available.<sup>10</sup>

#### 3.4.2 | Fibre devices

In the case of fibre-based devices, it is important to outline the interdependency between performance and fibre length. As the device length increases, the performance of the device decreases<sup>88</sup>; therefore, more developments towards highly conductive electrodes are fundamental. At the same time, new weaving techniques are needed for more stable and powerful devices,<sup>89</sup> especially considering the increasing complexity of the more recent devices.<sup>90</sup>

#### 3.4.3 | Binder issue

In some devices, binders are employed to put in contact the solar cells and the storage part. However, the use of binders is normally counterproductive as they are commonly electrical insulators that increases the resistivity of the integrated device.<sup>3</sup> Therefore, other techniques to attach both components must be researched to avoid this problem.

#### 3.4.4 | Mechanical stability

In flexible devices, special attention must be paid to the metallic pieces, because they tend to fail faster than the other pieces.<sup>3</sup> As a result, more light and flexible materials should substitute these materials in order to achieve more stable flexible devices. Another characteristic that should be improved is the structural design of the integrated devices with the objective of ensuring longer functioning times.

#### 3.4.5 | Liquid electrolyte issue

Regular electrochemical cells and DSSC utilise liquid electrolytes to provide a path for the ions to flow, which create potential for possible leakages or evaporation that could compromise the correct functioning of the device.<sup>3</sup> To prevent this problem, there are two possible solutions: improve the capabilities and properties of the encapsulation or focus efforts on the development of devices that operate using solid stated electrolytes,<sup>6,35,91</sup> but with the inherent compromise on power density. Although solid electrolyte devices have been already built,<sup>65</sup> there is still room for improvements on the assembly of the complete device.

#### 3.4.6 | Lack of standardised testing protocols

On several occasions, it is difficult to compare the performance of different devices using a common benchmark because there are no protocols to follow.<sup>6</sup> Consequently, efficiency values like those reported in Tables 2 and 3 are normally not comparable as the test and procedures differ. Protocols for measuring efficiencies, lifetime, and mechanical stability should also be defined to quantify the progress on the field of integration.

#### 3.4.7 | Long-term feasibility

Normally, published papers are merely dedicated to introducing new types of devices using novel materials or structures instead of providing well-developed devices.<sup>12</sup> Consequently, the devices are not as efficient as they could be and their long-term stability is also questionable.<sup>4,58</sup> In particular, there is no information about how ageing affects parameters such as efficiency, capacitances, PV output, and battery capacity. In summary, little information is available about how feasible is a concept to move from lab-scale to practice. This issue is fundamental in not so mature concepts like flexible devices and fibres.<sup>90</sup>

### Indoor vs outdoor

In general, integrated devices can be used for outdoor or indoor conditions; however, indoor testing and applications are more prominent.

This is the rule because, in indoor applications, the operational conditions are not as demanding as in outdoor applications and testing.<sup>2</sup> Outdoor conditions imply higher irradiation and temperature, which affects the performance of the devices making the solar generation more inefficient while increasing the risk of system failure. Furthermore, if long-term testing is performed, the mechanical stresses due to temperature gradients can deteriorate the lifetime of the components and at the same time reduce the energy storage PV generation performance in comparison with indoor cases.

### 3.4.8 | Solar generation and storage mismatch

A notable fact when integrating solar cells and energy storage devices is the mismatch between them,<sup>8</sup> for example, a battery with a capacity much more higher than what the PV cell can provide per charging cycle. The mismatch may occur when the physical dimension of one of the components is imposed on the other component.<sup>58</sup> In planar structures, for instance, the physical size of the electrochemical cell or SC is the same as the solar cell, which often results in electrical undersizing or oversizing of the storage part. This mismatch again provokes low-efficient concepts,<sup>12</sup> especially when power electronic conversion stages are not utilised.

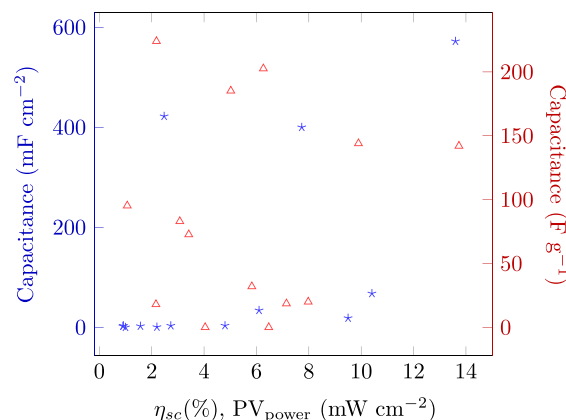
An example of this problem can be seen in Figure 5, where the power produced by the solar cell increases but capacitances remain almost constant (blue star markers). In the same figure, one device clearly outperforms the rest, due to its appropriate PV efficiency and high capacitance (star marker at the top right corner). When considering gravimetric capacitance as a reference, one integrated device presents outstanding features almost  $150 \text{ F g}^{-1}$  and a solar cell with an efficiency close to 14%.<sup>23</sup> Although according to this metric various devices exhibited acceptable values of gravimetric capacitance (top left red triangles), the efficiency of the solar part needed further improvements.

### 3.4.9 | Constant strife for higher energy density and efficiency

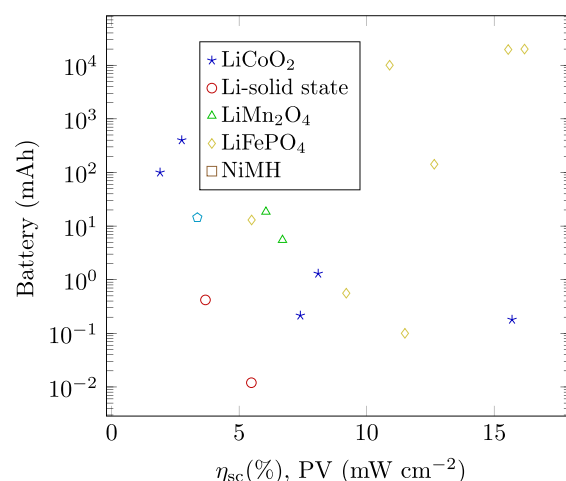
PV materials are getting closer to the theoretical maximums,<sup>92</sup> with 29.43% reported for c-Si<sup>93</sup> under 1-sun condition. However, these highly efficient materials have not been integrated with SC or electrochemical cells. Additionally, as Figures 5 and 6 suggest, solar cells with efficiency bigger than 15% have not been explored.\*

From the battery's point of view, appropriate materials to achieve high energy storage capacity and efficiency also need further improvements. Particularly for Li-ion batteries, a goal has been set to double the average energy density to  $250 \text{ mWh g}^{-1}$ ,<sup>94</sup> a goal that has not been achieved yet. Therefore, there is significant room for improvement for Li-ion batteries, from which the more commonly used are LiFePO<sub>4</sub>, LiCoO<sub>2</sub>, and Li<sub>4</sub>Ti<sub>5</sub>O<sub>12</sub> according to Figure 6, with LiFePO<sub>4</sub> being the most selected in high-power applications.

The increase in power and energy density is needed to prove its feasibility in practical applications, in particular, for low-power devices by being able to supply energy to basic loads. In general terms, a



**FIGURE 5** Trends in photo-supercapacitors. The data for this graph were taken from Table 2 for devices tested at 1 sun conditions. At the top right, two devices are characterised by high capacitances and solar efficiencies [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 6** Trends in solar battery systems. The data for this graph were taken from Tables 3 and 4 for devices tested at 1 sun conditions. High-power solution are located at the top right of the graph [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

low-power device should be at least able to supply power to a single white LED, where values of 60 mW are the minimum.<sup>95</sup>

### 3.4.10 | Relevance of power electronics

As mentioned before, there is a natural mismatch between solar cells and storage devices. Even if in theory the voltages of both of them are comparable, the system efficiency can be improved by incorporating power electronics units in order to control the storage charging and discharging process. Additionally, the possibility to perform maximum power point tracking (MPPT) is fundamental to obtain appropriate solar-battery efficiency values, but most importantly in solar-SC systems where the efficiency reduce by half if MPPT is not implemented.<sup>2</sup> In the case of solar-battery systems, the absence of MPPT can be compensated by selecting a PV cell with a voltage similar to the expected nominal voltage of the cell.

Moreover, power electronics conversion stages can aid increasing lifetime of components like batteries by avoiding overcharging and

\* Gao et al<sup>26</sup> was not included, as details about solar cell testing were not provided.

overcharging issues while ensuring a safe operation. Another important feature of power electronics is that the charging and discharging processes can be decoupled, and the power flows can be managed to perform energy management increasing flexibility of integrated devices.<sup>13</sup>

In cases where including power electronics cannot be implemented, a basic electric component, the blocking diode, is crucial as it impedes the discharging of the storage unit to the PV cell that could be seen as a load during dark instances.<sup>2</sup>

### 3.5 | Particular challenges

Although batteries and SCs are classified as energy storage devices, their natures are different; therefore, their integration with the variety of PV technologies leads to particular issues that are presented as follows.

#### 3.5.1 | Solar cells and SC

When integrating solar cells and SCs, there is a consensus that the higher the possible capacitance values, the better. Therefore, plenty of papers focus on optimising the design to fulfil this goal. On the other hand, most of the integrated devices are characterised by their low voltages. A device with low voltage is not able to meet the voltage requirements to power even small electronics devices. The relatively low voltage of a photo-capacitor is given by the intrinsic low voltage of both, individual solar cells and SCs. A possible solution to this problem is to connect multiple solar cells in series to increment the voltage, and at the same time more SCs could be connected in series and parallel, in parallel to increase the total capacitance of the device, and in series to also increase the voltage.

#### 3.5.2 | Solar cells and batteries

Single junction solar cells exhibit a nominal voltage lower than the voltage of the electrochemical cells. The operational voltage depends on many factors, but the concentration of electrons and holes in the junction primarily defines the PV voltage along with the semiconductor bandgap.<sup>96</sup> The concentration of holes, electrons, and bandgap is tightly related to the semiconductor material of the cells, where the open circuit voltage of single junction cells is usually around 0.2 to 1.5 V. While in many cases Li-ion cells have a nominal voltage above 3 V, solar cells are not able to match this voltage, and as a consequence, the charging process does not occur unless a power electronic conversion stage is involved to step up the voltage. Three approaches have been explored previously, the usage of multijunction solar cells,<sup>66,85</sup> the exploration of electrochemical cells with a lower voltage range of operation,<sup>70</sup> and the interconnection of single junction solar cell in series to elevate the voltage.<sup>72,73</sup> However, even if the voltage mismatch is handled, the relatively low-power density of the combination of PV and electrochemical cells must be improved, as presented in Table 3 and Figure 6.

With the more recent attention dedicated to other electrochemical cells inside the family of Li-ion cells, new opportunities have arisen, and new concepts may be developed shortly. In particular, Li-air and Li-S stand out among the multiple options<sup>97</sup>; although, these are still technologies under development.

Additionally, in devices with shared electrodes and interfaces among the solar cell part and the electrochemical cell, it is a challenge to contain the Li-ions in the electrochemical cell part, so they do not interfere with the normal functioning of the solar cell. In Chakrapani et al,<sup>65</sup> TiN is proposed to prevent Li<sup>+</sup> diffusion to the PV part. This kind of device results in typically low-power devices along with low efficiencies.

### 3.6 | Applications

Due to the advances in combining PV and energy storage technologies, some integrated devices have been dedicated for applications such as flexible power devices, microsystems, and aerospace applications. The most important features of relevant devices are introduced in this section.

#### 3.6.1 | Flexible devices

Advances in the mechanical properties of solar cells have propitiated its incursion in flexible electronics applications,<sup>99-101</sup> while similar progress has been made to enable flexible storage devices.<sup>102-107</sup> As a consequence, combined solutions with flexible properties have been reported during the last years, especially in wearable applications,<sup>108,109</sup> due to their low weight, bendable, and form factor capabilities. Additionally, PI fibre-shape devices have shown potential to be woven in clothing manufacturing.<sup>89,110,111</sup>

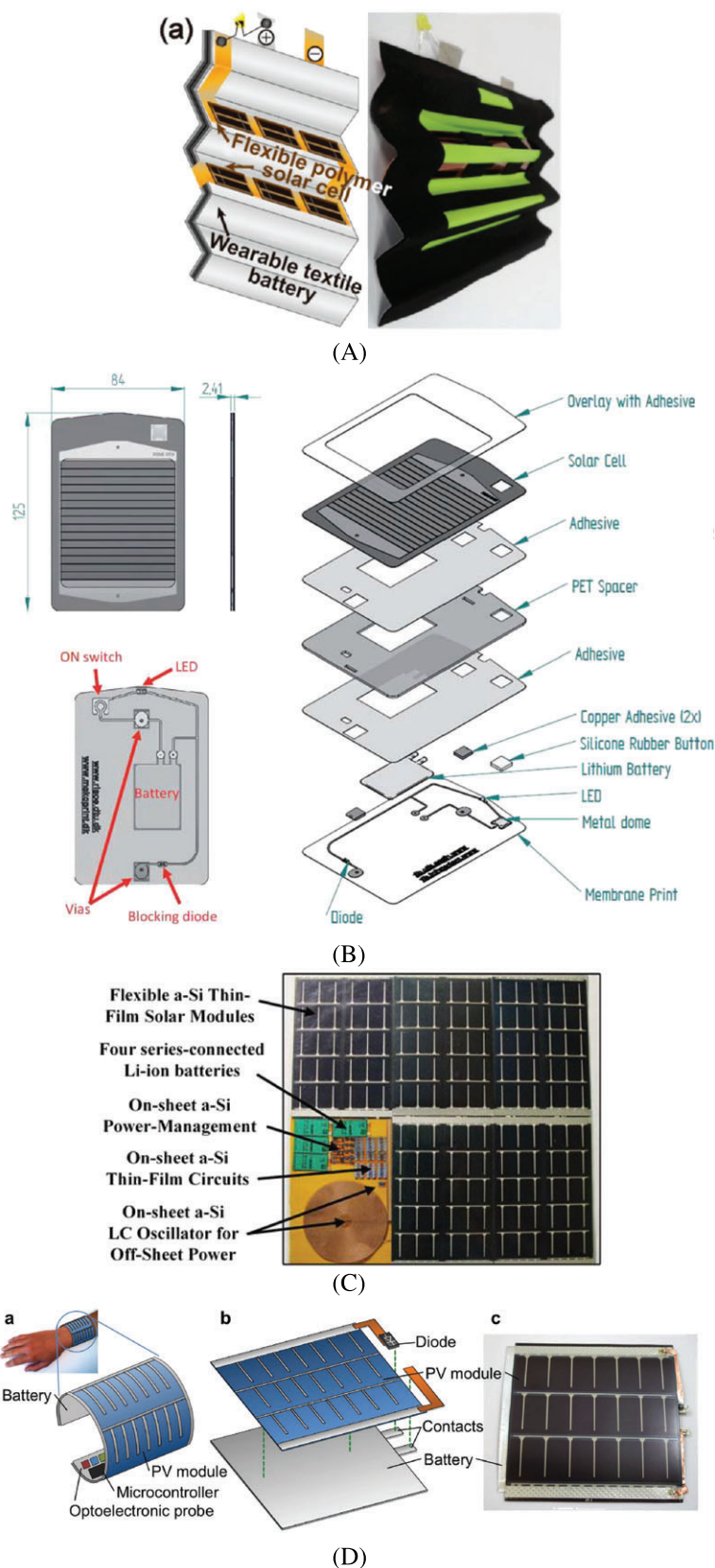
A wearable textile solar battery was developed in Seo et al,<sup>98</sup> and as a result, the mechanical properties of the battery were modified using textile electrodes. After the changes, the battery with a Li<sub>4</sub>Ti<sub>5</sub>O<sub>12</sub> anode and LiFePO<sub>4</sub> cathode performed similarly to a conventional metal foil-based battery. Six solar cells in series were connected to the textile battery and supplied a LED load that consumed 4.2 mW (Figure 7A). A direct relationship between mechanical endurance and battery capacity was also observed. This because an increase in electrode thickness (directly related to battery capacity) negatively affected the mechanical stability, limiting the design.

Furthermore, semitransparent flexible polymer solar cells were integrated with small pouch batteries and white light LEDs to form a solar lamp.<sup>77</sup> This lamp was created to provide light in places with limited access to electricity. As presented in Figure 7B, the completed device consisted of a front cover and a back cover, which give mechanical stability to the device. The battery, solar cell, connections, and components were attached using adhesive layers. This solar lamp was 12.5 × 8.8 × 2.4 cm<sup>3</sup> and weighted 50 g, proving to be a more sustainable solution compared with conventional lighting system when evaluating its environmental impact the rural communities studied.<sup>112</sup> In addition, another paper assesses the integration of battery and solar cells in a flexible substrate,<sup>75</sup> making flexible Li-ion batteries a flexible electronics enabler.<sup>113</sup>

#### 3.6.2 | Microsystems

With the development of self-sustainable solutions by combining storage and solar cells, it is possible to elaborate new device that performs specific functions such as monitoring and sensing.<sup>114,115</sup>





**FIGURE 7** A, Wearable textile solar battery. Reprinted with permission from Seo et al.<sup>98</sup> Copyright 2013, American Chemical Society. B, LED lamp powered by an organic solar cell and polymer Lithium polymer battery. Reproduced from Krebs et al.<sup>76</sup> with permission of Royal Society of Chemistry. C, Power harvesting, management, storage, and delivery concept. Reproduced with permission from Rieutort-Louis et al.<sup>83</sup> Copyright 2014, IEEE. D, High-performance flexible energy storage and harvesting system for wearable electronics. Reproduced with permission from Ostfeld et al.<sup>84</sup> Copyright 2016, Nature Publishing Group [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

To power an 8.75 mm autonomous microsystems for temperature sensing purposes, a thin film battery (12  $\mu$ Ah), two 1 mm<sup>2</sup> solar cells (5.48%), and the power management (dc/dc converter) were built and stuck together as a compact solution.<sup>116</sup> In the same line, a dual-band wearable textile antenna for on-body medical applications composed of a flexible solar cell and energy storage was introduced in Lemey et al,<sup>117</sup> where the maximum solar production could reach 53 mW.

As mentioned before, SCs are used to stabilise solar cells output power for reduced periods as in Cai et al,<sup>118</sup> where an LCD clock was connected and powered uninterruptedly under intermittent light conditions. Moreover, the preliminary design of a Bluetooth Low Energy Beacon was introduced in Jeon et al,<sup>119</sup> wherein a coin cell battery was integrated along with a solar cell to deliver power.

Furthermore, a flexible system that combined an amorphous silicon solar module, Li-ion thin-film batteries, and battery management was introduced in Rieutort-Louis et al,<sup>83</sup> and it is presented in Figure 7C. This device can supply load directly integrated into the device as well as external loads via wireless power transfer. It is important to mention that all the circuitry needed for the operation of the system was also integrated on the flexible sheet. The system was able to provide 5 mW to the internal loads (60% efficiency), while up to 8 mW via the wireless power system with an efficiency of 21%.

For a wearable health monitoring device, flexible energy storage and an amorphous Si solar cell were monolithically combined as Figure 7D shows. The printed battery, with a graphite anode and LiCoO<sub>2</sub> cathode, had a capacity of 47.5 mAh and maximum solar power of around 230 mW.<sup>84</sup> This device was made for indoor lighting conditions and tested under electrical and mechanical stress cycles, showing good capacity retention. Here, the battery powered a pulse oximeter. Other wearable textile devices have been reported as a prominent application.<sup>38,120,121</sup>

### 3.6.3 | Off-grid electrification

Recent years have seen a meteoric rise in the use of integrated PV-battery devices for off-grid lighting applications,<sup>122</sup> as lighting is seen as primary need falling in the first tier of household electricity access.<sup>123</sup> These products have a small, portable form factor with integrated PV and battery storage and potentially some power electronics. These products are known as picosolar products in the solar off-grid appliance market and are classified in the power rating of up to 11 W<sub>p</sub>.<sup>122</sup> These products usually include integrated PV-battery and LED lights and sometimes also include USB-charging options for higher-rated devices.

A prominent example is WakaWaka light, the most basic in the WakaWaka company's product portfolio. It has an integrated lithium polymer (Li-Po) battery of 500 mAh, LED lights up to 25 lumens, and monocrystalline silicon-based PV cell with 18% efficiency and surface area of 11 × 6 cm<sup>2</sup>.<sup>124</sup> A higher-end product from the same company, WakaWaka Power+, includes a 1 W<sub>p</sub> monocrystalline-based PV cell with 22% efficiency, 3000 mAh of Li-Po battery, LED of up to 70 lumens, and additional USB outlet for charging of USB-power appliances with a max current of 2.1 A.<sup>125</sup>

Another example is the company d.light design, which offers a variety of such picosolar products as well. The product d.light S30, for instance, includes a monocrystalline silicon-based PV cell rated 0.33 W<sub>p</sub>, a 450 mAh lithium iron phosphate battery with 2 LED lights capable of producing up to 60 lumens of light.<sup>126</sup> Another product called Radiance Lantern from the company Freeplay Energy offers a powerful 2 W<sub>p</sub> PV panel integrated with 2600 mAh Li-ion battery, electronics for USB-based charging, and LED lighting (up to 200 lumens) with an additional integrated feature of an 85 dB safety siren.<sup>127</sup>

### 3.6.4 | Aerospace applications

In aerospace applications, the challenge for reducing launch mass and the assembly process is identified as the main benefits of the physical integration. A monolithic structure using a flexible PV layer, flexible solid-state battery, and a flexible power management unit has been proposed and tested for space applications.<sup>128</sup> Moreover, an integrated power supply has been assessed and found suitable as an autonomous power source for nanosatellites,<sup>74</sup> where a monolithic package supply continuous power during space missions.

## 4 | HIGH-POWER PV-STORAGE DEVICES

The prices of solar panels and batteries are decreasing faster than expected,<sup>129,130</sup> which is helping to minimise the cost of PV-storage solutions. However, further improvement can be made from the balance of system components point of view but also from the soft cost side (ie, installation cost and designing costs). More integrated and simple manufacturing process would aid in achieving this goal.

Apart from reducing systems costs, ancillary services such as energy balance, peak shaving, backup energy, and power stability for the distribution grid are also perceived as beneficial. Therefore, the possibility of PV-storage units is essential for low and medium voltage levels.

**TABLE 4** Features of PV panel and storage integrated devices for high-power concepts

Article	PV Power (W <sub>p</sub> )	ES Capacity (Wh)	ES Type	Capacity (Ah <sup>a</sup> , F <sup>b</sup> )
Dede et al <sup>139</sup>	250	174	Hybrid SC	4285 <sup>b</sup>
Reynaud et al <sup>141-143</sup>	75	480	LiFePO <sub>4</sub>	10 <sup>a</sup>
Grzesiak et al <sup>144</sup>	100	198	LiFePO <sub>4</sub>	19.6 <sup>a</sup>
Vega-Garita et al <sup>147</sup>	265	965	LiFePO <sub>4</sub>	20 <sup>a</sup>
Krauter and Ochs <sup>140</sup>	60	1260	Lead acid	105 <sup>a</sup>
Solpad <sup>149</sup>	72	600	–	–
Hammami et al <sup>148</sup>	–	–	LiFePO <sub>4</sub>	–



As a consequence, integrated devices are able to produce power at higher values are fundamental in this context.

This section presents a comprehensive analysis of the published high-power integrated solutions while analysing the issues that must be solved as well as giving an indication of future trends and perspectives. A summary of the main features of these devices can be seen in Table 4. Also an indication of an ideal integrated device is introduced and graphically described in Figure 15.

#### 4.1 | Integration of power electronics

While some prototypes or existent products do not include all the components of the PV-storage system, previous efforts have been made either by integrating PV and power electronics converters,<sup>131-133</sup> or by combining power electronics and energy storage<sup>134</sup> in one device.

Dc/dc optimisers and microinverters are already available in the solar market. The main advantages of these solutions are reductions on installation time and improvements in system efficiency in comparison with PV systems with central inverters. They are placed close to the solar panel,<sup>135,136</sup> implementing MPPT. However, the connection between them and the panel is made during the installation process, which is not an entirely integrated solution.

A more integrated approach is achieved by combining the dc/dc converter with the PV module. In Acanski et al,<sup>137</sup> a thin flexible converter is directly coupled with the PV panel in the same flexible substrate (Figure 8). Here, a boost converter 2 mm thick is designed to match the characteristics of a 124 W<sub>p</sub> flexible solar panel, operating with a switching frequency between 0.1 and 1 MHz and input voltage range of 25 to 45 V. The design procedure for such thin flexible converter is presented, highlighting the challenges when finding flexible and thin materials for the core. The efficiency was 84% for the rated power.

Another approach that consists of controlling groups of individual solar cells of the PV module (235 W<sub>p</sub>) has been studied.<sup>138</sup> To implement this device, several cells are connected to a dc/dc flyback converter that performs MPPT. They are also grouped and attached

to an H-bridge inverter that produces a 120/240 Vac voltage. By extracting the maximum power from a group of PV cells, the maximum possible PV power for a particular module can be obtained. A solution like this is especially suitable for PV systems placed on curved surfaces, where gradients on irradiation might have a considerable influence on performance.

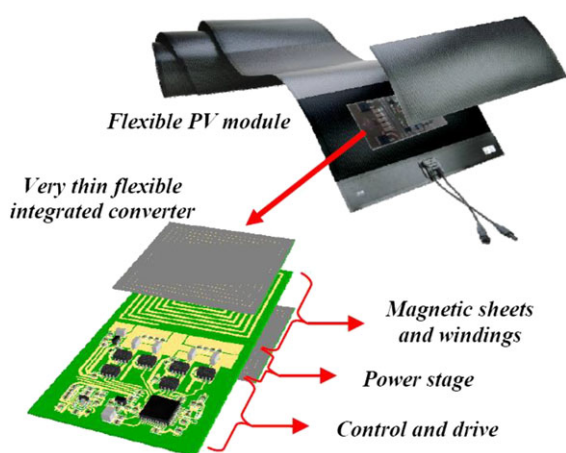
#### 4.2 | PV and SC

An SC bank of 28 units was integrated with a PV panel and power electronics interface in Dede et al,<sup>139</sup> with the purpose of providing services such as power support to distribution networks to account for the intermittent and uncertain nature of PV generation. The output of the so-called smart PV module is dc (Figure 9A left), and when various modules are connected in parallel to the dc bus, the modules are coupled with a central inverter for ac applications. Two dc/dc conversion stages are also proposed (Figure 9A right), in order to boost the voltage of the PV panel (around 30 V) to the voltage of the dc bus (400 V). The complete system is shown in Figure 9B, there the SC bank is placed at the back of the PV panel as well as the power electronics interface unit. Because this solution is developed for microgrids, the following modes of operation are defined: (a) PV and SCs provide the power available as requested by the microgrid, (b) when PV power must lessen, the remaining power will be transferred to the SCs, and (c) the SCs are operated for a minimal impact on lifetime. The power electronics interface keeps the module operating in four states: charge, discharge, standby, and float. The decision of the state is based on the instantaneous voltage and its comparison with reference voltages. The testing of the buck-boost converter for the first conversion stage and the flyback converter for the second stage conversion is performed using a test bench. A maximum efficiency of 92.5% was reached for a PV power of around 160 W. The specifications of this solution are presented in Table 4, where it is also compared with other solutions.

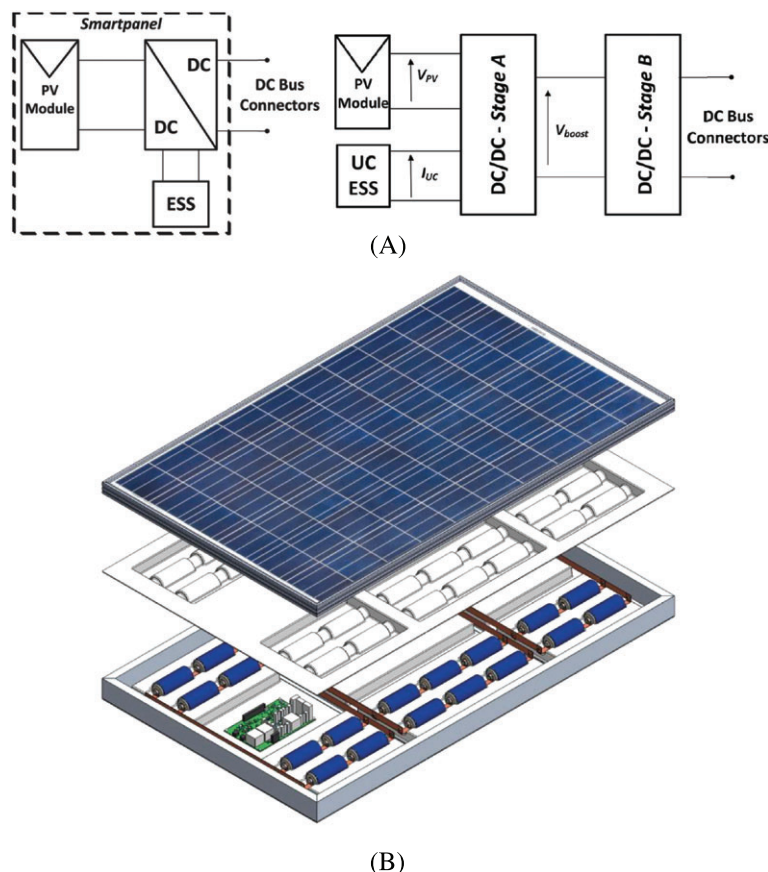
#### 4.3 | PV and battery

First attempts of integration consisted of voluminous concepts, as presented in Krauter and Ochs,<sup>140</sup> with a significant structure combining a PV panel, active cooling system, lead-acid battery, and inverter as an all-in-one solution. However, improvements in battery technology and power electronics have made possible less space-consuming solutions.

A compact integration of a PV panel, battery pack, and an electronic control unit for relatively high power was suggested initially in Reynaud et al.<sup>141</sup> This solution proposed multiple configurations: dc connection, ac connection, and grid-tied. According to the defined specifications, a solar module with a rated output power of 70 W<sub>p</sub> is proposed, where the weight of the complete device should not exceed 15 kg and last for at least 15 years. The temperature range in which the PV panel, battery pack, and power electronics will operate are as follows: 85° C to -40° C, 60° C to -20° C, and 85° C to -40° C, respectively. The electronic control unit of the so-called multifunctional module has a converter that performs MPPT, a charge controller to take care of power flowing in and out of the battery pack, and a battery balancing system for monitoring and controlling individual cells of the pack.



**FIGURE 8** Dc/dc converter integrated in a flexible PV module. Reproduced with permission from Acanski et al.<sup>137</sup> Copyright 2012, IEEE [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 9** A, System components (left), power conversion stages (right); B, complete integrated system. Reproduced with permission with Dede et al.<sup>139</sup> Copyright 2016, IEEE [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

As a continuation, a prototype of the MPPT circuit board and battery management system board were presented and individually tested in Reynaud et al.<sup>142</sup> The battery management system (BMS) was designed to keep the cell operating safely and to reduce the impact on lifetime. The BMS limits the charging and discharging process by monitoring the voltage and comparing it with predefined thresholds, calculating the rate of discharging and charging, implementing specific charging or discharging method (ie, constant current or constant voltage), and determining battery state of health (SoH). It also enables cell balancing to avoid overcharging or overdischarging of the weakest cell. To ensure the protection of the battery system, a set of alarm signals were defined, eg, for a temperature higher than maximum, low SoH, maximum current reached, a voltage higher than maximum/minimum, and short-circuit protection.

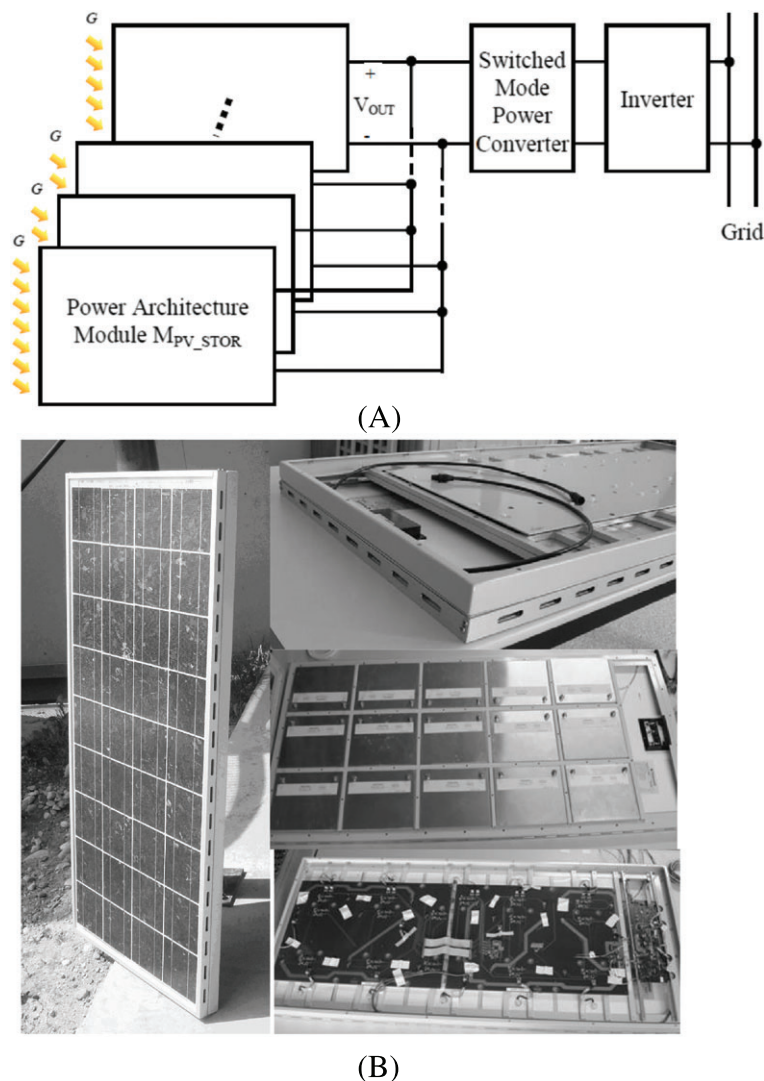
The same concept was proposed as a building block to scale up the grid-connected system by connecting modules in parallel,<sup>143</sup> as it is illustrated in Figure 10A. In such a system, all the integrated modules are connected to a central dc/dc converter, and this converter is linked to a single-phase inverter attached to the grid. A model to show the dynamic behaviour of two multifunctional modules in parallel was built, and the parameter of the boost converter was also reported. To test the idea of integration, a prototype with a 75 W<sub>p</sub> PV panel coupled with a battery pack of 15 LiFePO<sub>4</sub> (3.2 V, 10 Ah) cells in series was tested (Figure 10B). The efficiency of the converter used was 90% when the system operates at rated power. Regarding the energy management system, battery charging is the priority. However, in some cases if the

battery is above the minimum voltage and PV power is not enough to satisfy the load, the PV production will go directly to the load and the battery discharges. On the contrary, if the PV is at some time higher than the load, the power demanded is provided entirely by the PV, and the battery charge again. Experiments were performed, and the performance was presented for two particular cases.

Another approach was introduced in Grzesiak et al.<sup>144</sup> This paper focuses on portable applications for places with no connection to the electricity grid (Figure 11). The proposed integrated solution uses a PV panel of 100 W<sub>p</sub>, and a battery pack placed (13.2 V, 19.6 Ah) at the rear side of the PV module frame. The selection of commercial components that matched the specification of the PV and batteries are suggested; one element controls the charging while another the discharging process; for both devices, the schematics are provided. Finally, the authors recommend the proposed solution for camping, monitoring systems, and mobile systems.

Although previous papers have studied the optimal design and implementation of power electronics to ensure proper operation of the battery pack,<sup>42</sup> the pronounced thermal stresses that the components of a fully integrated solution must handle deserve to be further explored.<sup>145,146</sup>

In Vega-Garita et al,<sup>147</sup> a thermal model that considers all heat generation sources was introduced in order to find an optimum placement of the components. This model was validated by testing a prototype (Figure 12A) in a solar simulator, where the temperature of the components was monitored during a 120-minute test, and the IR pho-



**FIGURE 10** A Distributed architecture and B prototype. Reproduced with permission from Reynaud et al.<sup>143</sup> Copyright 2010, IEEE [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

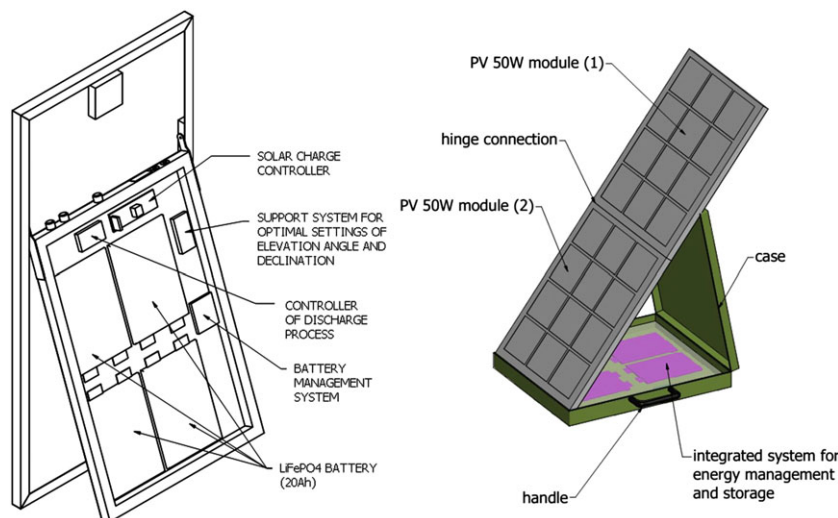
tograph was taken for validation purposes as illustrated in Figure 12B. The thermal effect over the battery pack is the focus of this paper, as it is the most delicate component. By means of the model, it was determined that attaching the battery pack directly to the solar panel results in extreme temperature (Figure 12C). As a consequence, an air gap was found necessary, finding that the battery pack and other components must be placed at a distance of 5 to 7 cm from the solar panel to ensure a safe operation (Figure 12D). By including this air gap, even under severe conditions, the maximum battery temperature never surpassed 39° C. Moreover, an additional decrease of 5° C in the maximum battery temperature was achieved using a phase change material as a passive cooling method.

Moreover, the thermal effect of the solar panel was also analysed in Hammami et al.<sup>148</sup> In this research, the batteries were mounted on the back side of a PV panel at 2 cm from it, as can be seen in Figure 13B. The PV temperature and battery temperature were measured using an infrared camera, finding localised hotspots caused by the proximity of the battery to the PV panel, which impede an efficient heat dissipation, as can be noticed in the PV panel in the centre (Figure 13A). By analysing the results from experiments, a

thermal model was set, and its results were validated with the aim of being used to estimate the thermal behaviour of the module under various conditions. Consequently, it was found that in average, the PV panel with batteries integrated is 10 to 15° C hotter than PV panel without batteries; as a consequence, the battery integrated PV panel is 6% less efficient for a defined scenario.

#### 4.4 | Integrated products

Among the PV products already in the market, the majority of them include batteries according to Apostolou et al.<sup>14</sup> lead acid and Li-ion being the most popular. However, just a few products have targeted applications with loads higher than 40 W<sub>p</sub> in one single unit. One of them is for solar street lighting applications. The solar lamp is shown in Figure 14A includes a solar module (60 W<sub>p</sub>), a charge controller, Li-ion battery pack, and a LED array. This kind of lighting solutions have been implemented since several years ago, and it is expected to grow as the prices of PV modules, LED lighting systems, and batteries continue to reduce. Another solution is the product *Solpad*,<sup>149</sup> which



**FIGURE 11** System for off-grid (left) and portable solutions (right). Reproduced with permission from Grzesiak et al.<sup>144</sup> Copyright 2016, Elsevier [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

is designed to provide an ac output (115/230 V<sub>ac</sub>) and plug-and-play solution for portable purposes.

## 4.5 | Challenges and perspectives

For high-power devices, some of the challenges found in low-power concepts still hold; for instance, the importance of developing solid-state-electrolyte storage devices. However, new problems have come out such as thermal stability and its relation with battery, solar cells, and power electronics ageing, the importance of system sizing, and modularity. While facing these problems, it is also relevant to pay attention to the economic considerations that could make these solutions feasible for the solar systems.

### 4.5.1 | Thermal effects of integration

As supported in Vega-Garita et al.<sup>147</sup> the battery pack operates at a higher temperature in integrated devices when compared with batteries operating inside buildings or households in nonintegrated systems. Therefore, it is fundamental to study how these additional thermal stresses impact the dynamic functioning of the batteries. Moreover, the PV panel also operates at a more elevated temperature in integrated devices than when no components are attached at its rear side<sup>147,148</sup> with the unavoidable consequence of having a solar panel operating at lower efficiency. How much the temperature of the PV panel can be reduced and what is the optimum placement for all the components inside the casing are still open questions. Additionally, the effect of high temperature over the power electronics must be analysed as suggested in Narayan et al.<sup>151</sup>

### 4.5.2 | Ageing in integrated devices

As stated above, all components of the integrated device are subject to a higher temperature than usual, accelerating their ageing mechanisms. In the case of batteries, because they are electrochemical cells, the instantaneous capacity of the battery increases following temperature rises, but in the long term, it results in faster degradation rates across

battery technologies.<sup>152</sup> This degradation is due to the increase in battery electrochemical activity, which accelerates the intercalation process in Li-ion batteries but at the same time foster undesired side reactions, which result on losses of active material (Li).

From the PV panel perspective, the rise in temperature of operation has detrimental consequences, lowering the lifespan, although a precise indication of its magnitude must be clarified in the future. Future research should contemplate which failure mechanisms are promoted in Si solar cells as it is the most widely used solar cells technology. At the same time, the impact on power electronics ageing must be addressed.

The widespread Li-ion batteries are composed of liquid electrolytes, which in cases of intensive operation can leak causing sudden failures that could lead to a potential explosion or malfunction. Consequently, with the recent advent of solid-electrolyte-batteries is convenient to start incorporating and testing its feasibility to cope with the ageing and safety issues previously described.

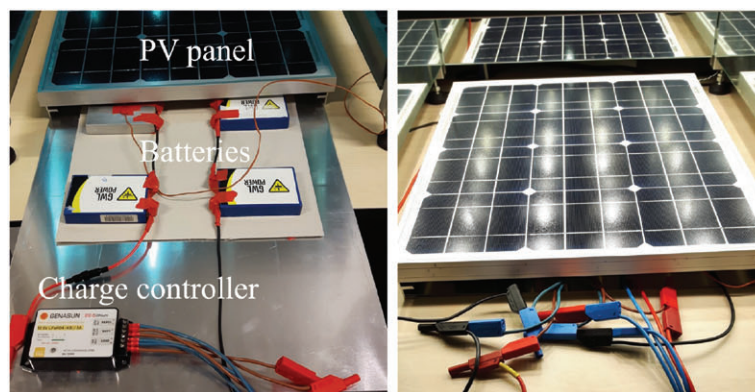
### 4.5.3 | Quest for the ideal system

Due to the more accelerated ageing expected in integrated devices when compared with a conventional discrete PV-storage system, the components will fail faster; therefore, failing components must be replaced in an easy manner. To achieve this, the high-power integrated devices have to be designed to account for these replacements while also maintaining a high level of integration. Accordingly, an ideal PV-storage system can be seen as a system that combines the benefits of actual low-power integrated devices, which are characterised by its high level of integration and state-of-the-art discrete PV-storage systems, where the components can be substituted easily. The ideal system is introduced in Figure 15 as the green box at the top right.

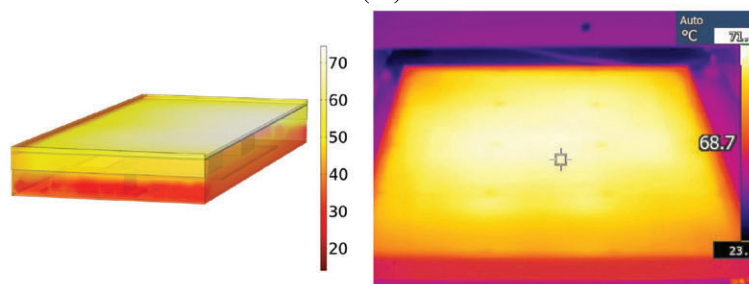
### 4.5.4 | System sizing

For integrated devices, an optimum electrical system sizing is crucial considering both cost and space constraints. Batteries, for instance, are the most costly component, and there is a consensus that battery

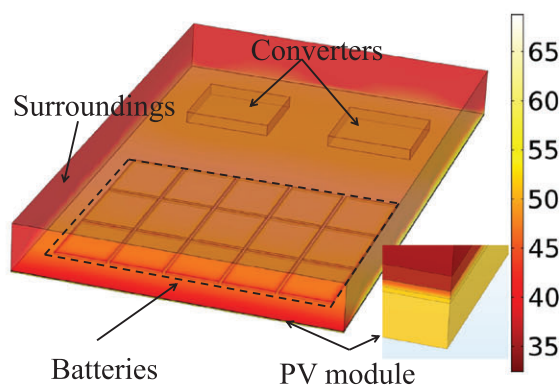




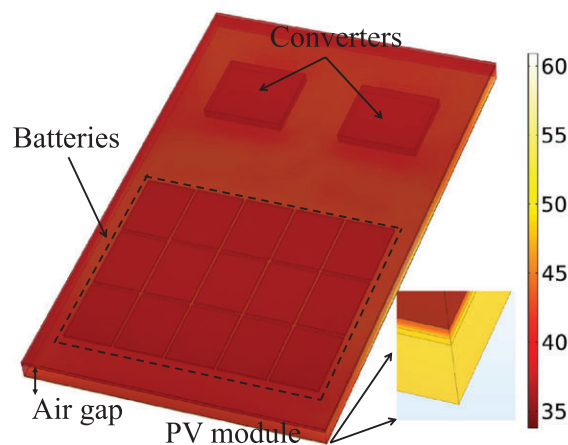
(A)



(B)

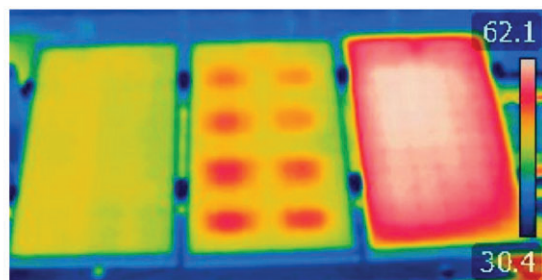


(C)

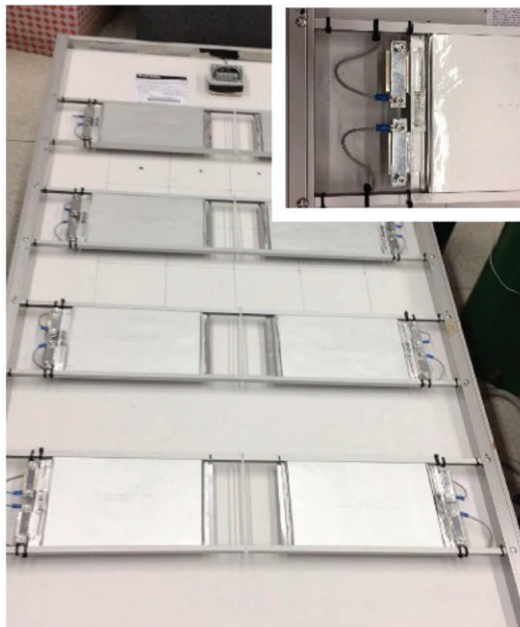


(D)

**FIGURE 12** A, Prototype components placement (left) and prototype under testing (right); B, simulation result (left) and IR image (right); C, PV-battery Integrated Module with an optimum air gap; D, PV-battery Integrated Module completely attached to the PV panel. Reproduced with permission from Vega-Garita et al.<sup>147</sup> Copyright 2017, Elsevier [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



(A)



(B)

**FIGURE 13** A, Thermal image of the module with batteries attached; B, placement of batteries. Reproduced with permission from Hammami et al.<sup>148</sup> Copyright 2017, MDPI [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

capacity should be kept as low as possible. Nonetheless, the relationship between battery size and subsequent battery cycling must be considered, as the depth and velocity of charging/discharging is linked closely to its end of life.

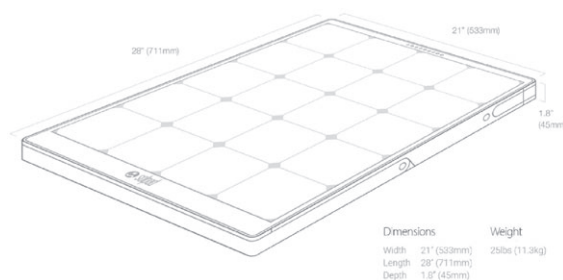
The adequate combination of energy storage and solar generation is part of an appropriate sizing methodology. The battery capacity and PV panel rating depends on the application and relates to the criteria that control the power flow of the system. The approach that the controller of the system follows is called an energy management system, and it is another aspect to consider during the sizing as it determines the cycling, depth of discharge, and C-rates. Additionally, the power electronics take care of controlling the power flow inside the integrated device, and its size (power rating) and architecture must be established considering the EMS system.

#### 4.5.5 | Importance of modularity

When the energy needs augment, having a system that can be scaled up without a total reconstruction of the system is ideal.<sup>145</sup> In these lines, a modular solution provides flexibility, acting as a building block when energy demand changes.<sup>143</sup> Hence, it is essential to incorporate

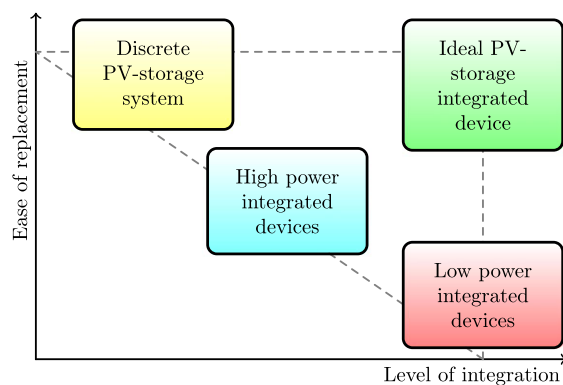


(A)



(B)

**FIGURE 14** A, A Solar street lamp. Reproduced with permission from Ciriminna et al.<sup>150</sup> Copyright 2016, John Wiley & Sons. B, Solpad integrated module.<sup>149</sup> Reproduced with permission of Solpad



**FIGURE 15** Comparison of existing approaches in terms of level of integration and ease of replacement; an ideal integrated device shown in green [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

the possibility of developing modular solutions in the design via power electronic enabler platform. Later on, if a modular solution is developed, next steps towards how to optimised the modular growing of the system could become a promising research area.

#### 4.5.6 | Economic analysis

As the integrated solutions intend to become an alternative to conventional PV-storage systems, aspects such as cost and possible benefits derived from the use of integrated devices deserve to be put under scrutiny. For instance, new studies are required to quantify the ten-



tative reduction on cost due to more simple and easy manufacturing processes for integrated devices, when compared to conventional systems. A similar analysis is needed for high power integrated devices, where possible reduction on installation cost is foreseen in comparison to standard PV-storage systems.

## 5 | CONCLUSION

This paper summarises the efforts when combining PV panels, power electronics, and energy storage components in one device. The gaps to fill and challenges to tackle are introduced and analysed. For the low-power-integrated concepts, it is essential to incorporate the benefits obtained by means of power electronics to achieve higher efficiencies and ensure safe operation of components. While novel ideas of integration are promising, long-term testing including cycling analysis is fundamental when validating the feasibility of the approaches. In the case of high-power devices, the thermal stresses induced by outdoor conditions and its relation to ageing must be investigated in more detail. Additionally, the electrical system sizing is fundamental as integrated concepts experience space-, economic-, and application-related constraints. This article describes the progress on the integration on solar energy and energy storage devices as an effort to identify the challenges and further research to be done in order achieve more stable power-integrated devices for PV systems, to move from the laboratory or proof of concept to practical applications.

## ACKNOWLEDGEMENT

The authors thank the financial support of the Universidad de Costa Rica, Ministerio de Ciencia y Tecnología y Telecomunicaciones of Costa Rica and Consejo Nacional para Investigaciones Científicas y Tecnológicas.

## ORCID

Victor Vega-Garita  <https://orcid.org/0000-0003-2133-5830>

Nishant Narayan  <https://orcid.org/0000-0002-1534-0679>

## REFERENCES

- Zhong Y, Xia X, Mai W, Tu J, Fan HJ. Integration of energy harvesting and electrochemical storage devices. *Adv Mater Technol*. 2017;2(12):1-14. <https://doi.org/10.1002/admt.201700182>
- Ostfeld AE, Arias AC. Flexible photovoltaic power systems: integration opportunities, challenges and advances. *Flex Print Electron*. 2017;2(1):013001. <https://doi.org/10.1088/2058-8585/aa5750>
- Li L, Wu Z, Yuan S, Zhang X-BB. Advances and challenges for flexible energy storage and conversion devices and systems. *Energy Environ Sci*. 2014;7(7):2101. <https://doi.org/10.1039/c4ee00318g>
- Sun Y, Yan X. Recent advances in dual-functional devices integrating solar cells and supercapacitors. *Solar RRL*. 2017;1(3-4):1700002. <https://doi.org/10.1002/solr.201700002>
- Xu J, Wang X, Wang X, et al. Three-dimensional structural engineering for energy-storage devices: from microscope to macroscope. *ChemElectroChem*. 2014;1(6):975-1002. <https://doi.org/10.1002/celec.201400001>
- Wei H, Cui D, Ma J, et al. Energy conversion technologies towards self-powered electrochemical energy storage systems: the state of the art and perspectives. *J Mater Chem A*. 2017;5(5):1873-1894. <https://doi.org/10.1039/C6TA09726J>
- Cai X, Zhang C, Zhang S, Fang Y, Zou D. Application of carbon fibers to flexible, miniaturized wire/fiber-shaped energy conversion and storage devices. *J Mater Chem A*. 2017;5(6):2444-2459. <https://doi.org/10.1039/C6TA07868K>
- Pu X, Hu W, Wang ZL. Toward wearable self-charging power systems: the integration of energy-harvesting and storage devices. *Small*. 2017;17(28):1-19. <https://doi.org/10.1002/smll.201702817>
- Pan S, Zhang Z, Weng W, Lin H, Yang Z, Peng H. Miniature wire-shaped solar cells, electrochemical capacitors and lithium-ion batteries. *Mater Today*. 2014;17(6):276-284. <https://doi.org/10.1016/j.mattod.2014.04.024>
- Ng CH, Lim HN, Hayase S, Harrison I, Pandikumar A, Huang NM. Potential active materials for photo-supercapacitor: a review. *J Power Sources*. 2015;296:169-185. <https://doi.org/10.1016/j.jpowsour.2015.07.006>
- Liu R, Liu Y, Zou H, Song T, Sun B. Integrated solar capacitors for energy conversion and storage. *Nano Research*. 2017;10(5):1545-1559. <https://doi.org/10.1007/s12274-017-1450-5>
- Luo B, Ye D, Wang L. Recent progress on integrated energy conversion and storage systems. *Adv Sci*. 2017;4(9):1-15. <https://doi.org/10.1002/advs.201700104>
- Lee J-H, Kim J, Kim TY, Al Hossain MS, Kim S-W, Kim JH. All-in-one energy harvesting and storage devices. *J Mater Chem A*. 2016;4(21):7983-7999. arXiv:1612.08814, <https://doi.org/10.1039/C6TA01229A>
- Apostolou G, Reinders AHME. Overview of design issues in product-integrated photovoltaics. *Energy Technol*. 2014;2(3):229-242. <https://doi.org/10.1002/ente.201300158>
- Vega-Garita V, Ramirez-Elizondo L, Mouli GRC, Bauer P. Review of residential PV-storage architectures. In: 2016 IEEE International Energy Conference (ENERGYCON); 2016April; Leuven, Belgium:1-6. <https://doi.org/10.1109/ENERGYCON.2016.7514039>
- Ouyang Z, Lou SN, Lau D, et al. Monolithic integration of anodic molybdenum oxide pseudocapacitive electrodes on screen-printed silicon solar cells for hybrid energy harvesting-storage systems. *Adv Energy Mater*. 2016;7:1602325. <https://doi.org/10.1002/aenm.201602325>
- Miyasaka T, Murakami TN. The photocapacitor: an efficient self-charging capacitor for direct storage of solar energy. *Appl Phys Lett*. 2004;85(17):3932-3934. <https://doi.org/10.1063/1.1810630>
- Murakami TN, Kawashima N, Miyasaka T. A high-voltage dye-sensitized photocapacitor of a three-electrode system. *Chem Commun*. 2005;26:3346. <https://doi.org/10.1039/b503122b>
- Su Y-W, Lan S-C, Wei K-H. Organic photovoltaics. *Mater Today*. 2012;15(12):554-562. [https://doi.org/10.1016/S1369-7021\(13\)70013-0](https://doi.org/10.1016/S1369-7021(13)70013-0)
- Lechêne BP, Cowell M, Pierre A, Evans JW, Wright PK, Arias AC. Organic solar cells and fully printed super-capacitors optimized for indoor light energy harvesting. *Nano Energy*. 2016;26:631-640. <https://doi.org/10.1016/j.nanoen.2016.06.017>
- Krebs FC, Espinosa N, Hösel M, Søndergaard RR, Jørgensen M. 25th anniversary article: Rise to power - OPV-based solar parks. 2014. <https://doi.org/10.1002/adma.201302031>
- Chien CT, Hiralal P, Wang DY, et al. Graphene-based integrated photovoltaic energy harvesting/storage device. *Small*. 2015;11(24):2929-2937. <https://doi.org/10.1002/smll>
- Kim J, Lee SM, Hwang Y-H, et al. A highly efficient self-power pack system integrating supercapacitors and photovoltaics with an area-saving monolithic architecture. *J Mater Chem A*. 2017;5:1906-1912. <https://doi.org/10.1039/C6TA09117B>
- Zhou F, Ren Z, Zhao Y, et al. Perovskite photovoltaic chromic supercapacitor with all-transparent electrodes. *ACS Nano*. 2016;10(6):5900-5908. <https://doi.org/10.1021/acsnano.6b01202>

25. Westover AS, Share K, Carter R, Cohn AP, Oakes L, Pint CL. Direct integration of a supercapacitor into the backside of a silicon photovoltaic device. *Appl Phys Lett*. 2014;104(21):1-4. <https://doi.org/10.1063/1.4880211>
26. Gao Z, Bumgardner C, Song N, Zhang Y, Li J, Li X. Cotton-textile-enabled flexible self-sustaining power packs via roll-to-roll fabrication. *Nature Commun*. 2016;7(May):11586. <https://doi.org/10.1038/ncomms11586>
27. Yang Z, Li L, Luo Y, et al. An integrated device for both photoelectric conversion and energy storage based on free-standing and aligned carbon nanotube film. *J Mater Chem A*. 2013;1(3):954-958. <https://doi.org/10.1039/C2TA00113F>
28. Liang J, Zhu G, Wang C, et al. MoS<sub>2</sub>-based all-purpose fibrous electrode and self-powering energy fiber for efficient energy harvesting and storage. *Adv Energy Mater*; 7(3):1601208. arXiv:<https://onlinelibrary.wiley.com/doi/pdf/10.1002/aenm.201601208>, doi: <https://onlinelibrary.wiley.com/doi/abs/10.1002/aenm.201601208>
29. Bagheri N, Aghaei A, Ghotbi MY, et al. Combination of asymmetric supercapacitor utilizing activated carbon and nickel oxide with cobalt polypyridyl-based dye-sensitized solar cell. *Electrochimica Acta*. 2014;143:390-397. <https://doi.org/10.1016/j.electacta.2014.07.125>
30. Skunik M, Kulesza PJ, Vlachopoulos N, et al. Development of hybrid organic-inorganic materials for efficient charging/discharging in electrochemical and photoelectrochemical capacitors. *ECS Transactions*. 2011;35(25):93-102. <https://doi.org/10.1149/1.3655515>
31. Chen T, Qiu L, Yang Z, et al. An integrated "energy wire" for both photoelectric conversion and energy storage. *Angewandte Chemie - International Edition*. 2012;51(48):11977-11980. <https://doi.org/10.1002/anie.201207023>
32. Mini PA, Nair SV, Subramanian KRV. Design and development of an integrated device consisting of an independent solar cell with electrical. *Prog Photovolt Res Appl*. 2013;May 2012:1153-1157. <https://doi.org/>
33. Kulesza PJ, Skunik-Nuckowska M, Grzeszczuk K, Vlachopoulos N, Yangb L, Haggmanb L, Hagfeldt A. Development of solid-state photo-supercapacitor by coupling dye-sensitized solar cell utilizing conducting polymer charge relay with proton-conducting membrane based electrochemical capacitor. 2013;50(43):235-244.
34. Li H, Zhao Q, Wang W, et al. Novel planar-structure electrochemical devices for highly flexible semitransparent power generation/storage sources. *Nano Lett*. 2013;13(3):1271-1277. <https://doi.org/10.1021/nl4000079>
35. Skunik-Nuckowska M, Grzeszczuk K, Kulesza PJ, et al. Integration of solid-state dye-sensitized solar cell with metal oxide charge storage material into photoelectrochemical capacitor. *J Power Sources*. 2013;234:91-99. <https://doi.org/10.1016/j.jpowsour.2013.01.101>
36. Zhang X, Huang X, Li C, Jiang H. Dye-sensitized solar cell with energy storage function through PVDF/ZnO nanocomposite counter electrode. *Advanced Materials*. 2013;25(30):4093-4096. <https://doi.org/10.1002/adma.201301088>
37. Zhang Z, Chen X, Chen P, et al. Integrated polymer solar cell and electrochemical supercapacitor in a flexible and stable fiber format. *Adv Mater*. 2014;26(3):466-470. <https://doi.org/10.1002/adma.201302951>
38. Chen X, Sun H, Yang Z, Guan G, Zhang Z, Qiu L, Peng H. A novel energy fiber by coaxially integrating dye-sensitized solar cell and electrochemical capacitor. *J Mater Chem A*. 2014;2(6):1897. <https://doi.org/10.1039/c3ta13712k>
39. Huang X, Zhang X, Jiang H. Energy storage via polyvinylidene fluoride dielectric on the counterelectrode of dye-sensitized solar cells. *J Power Sources*. 2014;248:434-438. <https://doi.org/10.1016/j.jpowsour.2013.09.094> Short communication
40. Yang Z, Deng J, Sun H, Ren J, Pan S, Peng H. Self-powered energy fiber: energy conversion in the sheath and storage in the core. *Adv Mater*. 2014;26(41):7038-7042. <https://doi.org/10.1002/adma.201401972>
41. Xu X, Li S, Zhang H, et al. A power pack based on organometallic perovskite solar cell and supercapacitor. *ACS Nano*. 2015;9(2):1782-1787. <https://doi.org/10.1021/nn506651m>
42. Narayanan R, Kumar PN, Deepa M, Srivastava AK. Combining energy conversion and storage: a solar powered supercapacitor. *Electrochimica Acta*. 2015;178:113-126. <https://doi.org/10.1016/j.electacta.2015.07.121>
43. Shi C, Dong H, Zhu R, et al. An "all-in-one" mesh-typed integrated energy unit for both photoelectric conversion and energy storage in uniform electrochemical system. *Nano Energy*. 2015;13:670-678. <https://doi.org/10.1016/j.nanoen.2015.03.032>
44. Zhang X, Jiang H. Scattering-layer-induced energy storage function in polymer-based quasi-solid-state dye-sensitized solar cells. *Appl Phys Lett*. 2015;106(10):103903. <https://doi.org/10.1063/1.4914585>
45. Cohn AP, Erwin WR, Share K, et al. All silicon electrode photocapacitor for integrated energy storage and conversion. *Nano Letters*. 2015;15(4):2727-2731. <https://doi.org/10.1021/acs.nanolett.5b00563>
46. Selvam S, Balamuralitharan B, Karthick SN, et al. Novel high-temperature supercapacitor combined dye sensitized solar cell from a sulfated  $\beta$ -cyclodextrin/PVP/MnCO<sub>3</sub> composite. *J Mater Chem A*. 2015;3(19):10225-10232. <https://doi.org/10.1039/C5TA01792K>
47. Reddy BN, Mukkabl R, Deepa M, Ghosal P. Dual purpose poly(3,4-ethylenedioxythiophene)/vanadium pentoxide nanobelt hybrids in photoelectrochromic cells and supercapacitors. *RSC Adv*. 2015;5(40):31422-31433. <https://doi.org/10.1039/C5RA05015D>
48. Sun H, Jiang Y, Qiu L, et al. Energy harvesting and storage devices fused into various patterns. *J Mater Chem A*. 2015;3(29):14977-14984. <https://doi.org/10.1039/C5TA03235K>
49. Li C, Islam MM, Moore J, et al. Wearable energy-smart ribbons for synchronous energy harvest and storage. *Nature Commun*. 2016;7(May):13319. <https://doi.org/10.1038/ncomms13319>
50. Lee F-W, Ma C-W, Lin Y-H, Huang P-C, Su Y-L, Yang Y-J. A micromachined photo-supercapacitor integrated with CDS-sensitized solar cells and buckypaper. *Sens Mater*. 2016;28(7):749-756. <https://doi.org/10.18494/SAM.2016.1166>
51. Xu J, Ku Z, Zhang Y, Chao D, Fan HJ. Integrated photo-supercapacitor based on PEDOT modified printable perovskite solar cell. *Adv Mater Technol*. 2016;1:1-5. <https://doi.org/10.1002/admt.201600074>
52. Huang X, Zhang X, Jiang H. Photovoltaically self-charging cells with WO<sub>3</sub> · H<sub>2</sub>O/CNTs/PVDF composite. *RSC Adv*. 2016;6(99):96490-96494. <https://doi.org/10.1039/C6RA21303K>
53. Wen Z, Yeh M-H, Guo H, et al. Self-powered textile for wearable electronics by hybridizing fiber-shaped nanogenerators, solar cells, and supercapacitors. *Sci Adv*. 2016;2(10):e1600097-e1600097. <https://doi.org/10.1126/sciadv.1600097>
54. Chai Z, Zhang N, Sun P, et al. Tailorable and wearable textile devices for solar energy harvesting and simultaneous storage. *ACS Nano*. 2016;10(10):9201-9207. <https://doi.org/10.1021/acsnano.6b05293>
55. Scalia A, Bella F, Lamberti A, Bianco S. A flexible and portable powerpack by solid-state supercapacitor and dye-sensitized solar cell integration. *J Power Sources*. 2017;359:311-321. <https://doi.org/10.1016/j.jpowsour.2017.05.072>
56. Zhang F, Li W, Xu Z, et al. Transparent conducting oxide- and Pt-free flexible photo-rechargeable electric energy storage systems. *RSC Advances*. 2017;7(83):52988-52994. <https://doi.org/10.1039/c7ra11246g>

57. Liu R, Liu C, Fan S. A photocapacitor based on organometal halide perovskite and PANI/CNT composites integrated using a CNT bridge. *J Mater Chem A*. 2017;5:23078-23084.
58. Schmidt D, Hager MD, Schubert US. Photo-rechargeable electric energy storage systems. *Adv Energy Mater*. 2016;6(1):1-11. <https://doi.org/10.1002/aenm.201500369>
59. Wang Q, Chen H, McFarland E, Wang L. Solar rechargeable batteries based on lead-organohalide electrolyte. *Adv Energy Mater*. 2015;5(24):1-6. <https://doi.org/10.1002/aenm.201501418>
60. Hauch A, Georg A, KraslŇovec UO, Orel B, Opara Krašovec U, Orel B. Photovoltaically self-charging battery. *J Electrochem Soc*. 2002;149(9):A1208. <https://doi.org/10.1149/1.1500346>
61. Yu M, McCulloch WD, Huang Z, et al. Solar-powered electrochemical energy storage: an alternative to solar fuels. *J Mater Chem A*. 2016;4(8):2766-2782. <https://doi.org/10.1039/C5TA06950E>
62. Licht S, Hodes G, Tenne R, Manassen J. A light-variation insensitive high efficiency solar cell. 1987;326(6116):863-864. <https://doi.org/10.1038/326863a0>
63. Paoletta A, Faure C, Bertoni G, et al. Light-assisted delithiation of lithium iron phosphate nanocrystals towards photo-rechargeable lithium ion batteries. *Nature Commun*. 2017;8:1-10. <https://doi.org/10.1038/ncomms14643>
64. Yu M, Ren X, Ma L, Wu Y. Integrating a redox-coupled dye-sensitized photoelectrode into a lithium-oxygen battery for photoassisted charging. *Nature Commun*. 2014;5(May):5111. <https://doi.org/10.1038/ncomms6111>
65. Chakrapani V, Rusli F, Filler MA, Kohl PA. A combined photovoltaic and Li ion battery device for continuous energy harvesting and storage. *J Power Sources*. 2012;216:84-88. <https://doi.org/10.1016/j.jpowsour.2012.05.048>
66. Agbo SN, Merdzhanova T, Yu S, et al. Photoelectrochemical application of thin-film silicon triple-junction solar cell in batteries. *Phys Status Solidi A Appl Mater Sci*. 2016;213(7):1926-1931. <https://doi.org/10.1002/pssa.201532918>
67. Bermejo PR, Genoe J, Heremans P, Poortmans J. Light harvesting photovoltaic mini-generator. *Prog Photovolt Res Appl*. 2011;15(August 2011):967-974. arXiv: 1303.4604, <https://doi.org/10.1002/pip>
68. Ye RB, Yoshida K, Ohta K, Baba M. Integrated thin-film rechargeable battery on  $\alpha$ -Si thin-film solar cell. *Adv Mater Res*. 2013;788: 685-688. <https://doi.org/10.4028/www.scientific.net/AMR.788.685>
69. Guo W, Xue X, Wang S, Lin C, Wang ZL. An integrated power pack of dye-sensitized solar cell and Li battery based on double-sided TiO<sub>2</sub> nanotube arrays. *Nano Lett*. 2012;12:2520-2523. <https://doi.org/10.1021/nl3007159>
70. Meister T, Ishida K, Shabanpour R, et al. Bendable energy-harvesting module with organic photovoltaic, rechargeable battery, and a-IGZO TFT charging electronics. In: 2015 European Conference on Circuit Theory and Design (ECCTD); 2015; Trondheim, Norway:1-4. <https://doi.org/10.1109/ECCTD.2015.7300095>
71. Dennler G, Bereznev S, Fichou D, et al. A self-rechargeable and flexible polymer solar battery. *Solar Energy*. 2007;81(8):947-957. <https://doi.org/10.1016/j.solener.2007.02.008>
72. Xu J, Chen Y, Dai L. Efficiently photo-charging lithium-ion battery by perovskite solar cell. *Nat Commun*. 2015;6(May):1-7. arXiv:1011.1669v3, <https://doi.org/10.1038/ncomms9103>
73. Handon Um, Choi K-H, Hwang I, Kim S-H, Seo K, Lee S-Y. Monolithically integrated, photo-rechargeable portable power sources based on miniaturized Si solar cells and printed solid-state lithium-ion batteries. *Energy Environ Sci*. 2017;10(4):931-940. <https://doi.org/10.1039/C6EE03266D>
74. Raffaele RP, Hepp AF, Landis GA, Hoffman DJ. Mission applicability assessment of integrated power components and systems. *Prog Photovolt Res Appl*. 2002;10(6):391-397. <https://doi.org/10.1002/pip.445>
75. Kim HS, Kang JS, Park JS, Hahn HThomas, Jung HC, Joung JW. Inkjet printed electronics for multifunctional composite structure. *Combust Sci Technol*. 2009;69(7-8):1256-1264. <https://doi.org/10.1016/j.compscitech.2009.02.034>
76. Krebs FC, Fyenbo J, Jørgensen M. Product integration of compact roll-to-roll processed polymer solar cell modules: methods and manufacture using flexographic printing, slot-die coating and rotary screen printing. *J Mater Chem*. 2010;20(41):8994. <https://doi.org/10.1039/c0jm01178a>
77. Krebs FC, Nielsen TD, Fyenbo J, Wadstrom M, Pedersen MS. Manufacture, integration and demonstration of polymer solar cells in a lamp for the "Lighting Africa" initiative. *Energy Environ Sci*. 2010;3(5):512-525. <https://doi.org/10.1039/b918441d>
78. Krebs FC, Fyenbo J, Tanenbaum DM, et al. The OE-A OPV demonstrator anno domini 2011. *Energy Environ Sci*. 2011;4(10):4116. <https://doi.org/10.1039/c1ee01891d>
79. Chakrapani V, Rusli F, Filler MA, Kohl PA. A combined photovoltaic and Li ion battery device for continuous energy harvesting and storage. *J Power Sources*. 2012;216:84-88. <https://doi.org/10.1016/j.jpowsour.2012.05.048>
80. Liu P, Yang HX, Ai XP, Li GR, Gao XP. A solar rechargeable battery based on polymeric charge storage electrodes. *Electrochem Commun*. 2012;16(1):69-72. <https://doi.org/10.1016/j.elecom.2011.11.035>
81. Lee YH, Kim JS, Noh J, et al. Wearable textile battery rechargeable by solar energy. *Nano Letters*. 2013;13(11):5753-5761. <https://doi.org/10.1021/nl403860k>
82. Kim J, Kim C, Fojtik M, et al. A millimeter-scale energy-autonomous sensor system with stacked battery and solar cells. *IEEE J Solid-State Circ*. 2013;48(3):801-813. <https://doi.org/10.1109/JSSC.2012.2233352>
83. Rieutort-Louis W, Huang L, Hu Y, et al. A complete fully thin-film PV harvesting and power-management system on plastic with on-sheet battery management and wireless power delivery to off-sheet loads. *IEEE J Photovoltaics*. 2014;4(1):432-439. <https://doi.org/10.1109/JPHOTOV.2013.2285959>
84. Ostfeld AE, Gaikwad AM, Khan Y, Arias AC. High-performance flexible energy storage and harvesting system for wearable electronics. *Sci Rep*. 2016;6(April):26122. <https://doi.org/10.1016/j.jpowsour.2016.07.073>
85. Agbo SN, Merdzhanova T, Yu S, Tempel H. Development towards cell-to-cell monolithic integration of a thin-film solar cell and lithium-ion accumulator. *J Power Sources*. 2016;327:340-344. <https://doi.org/10.1016/j.jpowsour.2016.07.073>
86. Sun H, Jiang Y, Xie S, et al. Integrating photovoltaic conversion and lithium ion storage into a flexible fiber. *J Mater Chem A*. 2016;4(20):7601-7605. <https://doi.org/10.1039/C6TA01514J>
87. Sandbaumhüter F, Agbo SN, Tsai CL, et al. Compatibility study towards monolithic self-charging power unit based on all-solid thin-film solar module and battery. *J Power Sources*. 2017;365:303-307. <https://doi.org/10.1016/j.jpowsour.2017.08.103>
88. Pan S, Ren J, Fang X, Peng H. Integration: An effective strategy to develop multifunctional energy storage devices. *Adv Energy Mater*. 2016;6(4):1-19. <https://doi.org/10.1002/aenm.201501867>
89. Song T, Sun B. Towards photo-rechargeable textiles integrating power conversion and energy storage functions: can we kill two birds with one stone? *ChemSusChem*. 2013;6(3):408-410. <https://doi.org/10.1002/cssc.201200889>
90. Chen T, Yang Z, Peng H. Integrated devices to realize energy conversion and storage simultaneously. *ChemPhysChem*. 2013;14(9):1777-1782. <https://doi.org/10.1002/cphc.201300032>
91. Lu X, Yu M, Wang G, Tong Y, Li Y. Flexible solid-state supercapacitors: design, fabrication and applications. *Energy Environ Sci*. 2014;7(7):2160. <https://doi.org/10.1039/c4ee00960f>
92. Green MA, Hishikawa Y, Dunlop ED, Levi DH, Hohl-Ebinger J, Ho-Baillie AW. Solar cell efficiency tables (version 52). *Prog Photovolt*



- Res Appl.* 2018;26(7):427-436. arXiv:1303.4604, <https://doi.org/10.1002/pip.3040>
93. Richter A, Hermle M, Glunz SW. Crystalline silicon solar cells reassessment of the limiting efficiency for crystalline silicon solar cells. *IEEE J Photovoltaics*. 2013;3(4):1184-1191. <https://doi.org/10.1109/JPHOTOV.2013.2270351>
  94. Thielmann A, Sauer A, Isenmann R, Wietschel M. Development of solid-state photo-supercapacitor by coupling dye-sensitized solar cell utilizing conducting polymer charge relay with proton-conducting membrane based electrochemical capacitor. Tech. Rep. 1, Technology Roadmap Energy storage for Electric mobility 2030; 2013.
  95. Everlight. Technical data sheet, 5 mm Round White LED (T-1 3/4); 2007.
  96. Smets AH, Jager K, Isabella O, van Swaaij R, Zeman M. *Solar Energy*. Cambridge: UIT CAMBRIDGE; 2016. <http://doi.org/tkisolarenergy.nl/nl/zonne-energie/>
  97. Vlad A, Singh N, Galande C, Ajayan PM. Design considerations for unconventional electrochemical energy storage architectures. *Adv Energy Mater*. 2015;5(19):1-53. <https://doi.org/10.1002/aenm.201402115>
  98. Seo J, Jeon S, Kim TS, Lee JY, Choi JW. Wearable textile battery rechargeable by solar energy. *Nano letters*. 2013;13:5753-5761.
  99. Kim JS, Ko D, Yoo DJ, et al. A half millimeter thick coplanar flexible battery with wireless recharging capability. *Nano Letters*. 2015;15(4):2350-2357.
  100. Di Giacomo F, Fakharuddin A, Jose R, Brown TM. Progress, challenges and perspectives in flexible perovskite solar cells. *Energy Environ Sci*. 2016;9(10):3007-3035. <https://doi.org/10.1039/C6EE01137C>
  101. Li G, Zhu R, Yang Y. Polymer solar cells. *Nature Photonics*. 2012;6(3):153-161. <https://doi.org/10.1038/nphoton.2012.11>
  102. Xie K, Wei B. Materials and structures for stretchable energy storage and conversion devices. *Adv Mater*. 2014;26(22):3592-3617. <https://doi.org/10.1002/adma.201305919>
  103. Zhou G, Li F, Cheng H-M. Progress in flexible lithium batteries and future prospects. *Energy Environ Sci*. 2014;7(4):1307-1338. <https://doi.org/10.1039/C3EE43182G>
  104. Lee S-Y, Choi K-H, Choi W-S, et al. Progress in flexible energy storage and conversion systems, with a focus on cable-type lithium-ion batteries. *Energy Environ Sci*. 2013;6(8):2414. <https://doi.org/10.1039/c3ee24260a>
  105. Song Z, Wang X, Lv C, et al. Kirigami-based stretchable lithium-ion batteries. *Sci Rep*. 2015;5(1):10988. <https://doi.org/10.1038/srep10988>
  106. Song Z, Ma T, Tang R, et al. Origami lithium-ion batteries. *Nature Commun*. 2014;5:1-6. <https://doi.org/10.1038/ncomms4140>
  107. Singh N, Galande C, Miranda A, et al. Paintable battery. *Sci Rep*. 2012;2:6-10. <https://doi.org/10.1038/srep00481>
  108. Jost K, Dion G, Gogotsi Y. Textile energy storage in perspective. *J Mater Chem A*. 2014;2(28):10776. <https://doi.org/10.1039/c4ta00203b>
  109. Wang X, Jiang K, Shen G. Flexible fiber energy storage and integrated devices: recent progress and perspectives. *Mater Today*. 2015;18(5):265-272. <https://doi.org/10.1016/j.mattod.2015.01.002>
  110. Lv T, Yao Y, Li N, Chen T. Wearable fiber-shaped energy conversion and storage devices based on aligned carbon nanotubes. *Nano Today*. 2016;11(5):644-660. <https://doi.org/10.1016/j.nantod.2016.08.010>
  111. Zhai S, Karahan HE, Wei L, et al. Textile energy storage: structural design concepts, material selection and future perspectives. *Energy Storage Mater*. 2016;3:123-139. <https://doi.org/10.1016/j.enstm.2016.02.003>
  112. Espinosa N, García-Valverde R, Krebs FC. Life-cycle analysis of product integrated polymer solar cells. *Energy Environ Sci*. 2011;4(5):1547. <https://doi.org/10.1039/c1ee01127h>
  113. Kim BJ, Kim DH, Lee Y-Y, et al. Highly efficient and bending durable perovskite solar cells: toward a wearable power source. *Energy Environ Sci*. 2015;8(3):916-921. <https://doi.org/10.1039/C4EE02441A>
  114. Oshima S, Matsunaga K, Morimura H, Harada M. 3D integration techniques using stacked PCBs and small dipole antenna for wireless sensor nodes. 2012:3-6. <https://doi.org/10.1109/ICSJ.2012.6523438>
  115. Horiguchi F. Integration of series-connected on-chip solar battery in a triple-well CMOS LSI. *IEEE Trans Electron Devices*. 2012;59(6):1580-1584. <https://doi.org/10.1109/TED.2012.2189116>
  116. Chen G, Fojtik M, Kim D, et al. A millimeter-scale nearly perpetual sensor system with stacked battery and solar cells. 2010;48(June 2009):166-167. <https://doi.org/10.1109/JSSC.2012.2233352>
  117. Lemey S, Declercq F, Rogier H. Dual-band substrate integrated waveguide textile antenna with integrated solar harvester. *IEEE Antennas Wirel Propag Lett*. 2014;13:269-272. <https://doi.org/10.1109/LAWP.2014.2303573>
  118. Cai J, Lv C, Watanabe A. Laser direct writing of high-performance flexible all-solid-state carbon micro-supercapacitors for an on-chip self-powered photodetection system. *Nano Energy*. 2016;30:790-800. <https://doi.org/10.1016/j.nanoen.2016.09.017>
  119. Jeon K. E., Tong T, She J. Preliminary design for sustainable BLE Beacons powered by solar panels. *Proc - IEEE INFOCOM*. 2016;2016-Sept:103-109. <https://doi.org/10.1109/INFOCOMW.2016.7562054>
  120. Li C, Islam M, Moore J, Sleppy J, Morrison C, Konstantinov K. Energy harvest and storage. *Nat Publ Group*. 2016;7(May):1-10. <https://doi.org/10.1038/ncomms13319>
  121. Dong X, Chen L, Su X, Wang Y, Xia Y. Flexible aqueous lithium-ion battery with high safety and large volumetric energy density. *Angew Chem Int Ed*. 2016;55(26):7474-7477. <https://doi.org/10.1002/anie.201602766>
  122. Global Off-Grid Lighting Association. Global off-grid solar market report - semi-annual sales and impact data. Tech. Rep., GOGLA, Lighting Global and Berenschot; 2018.
  123. Bhatia M, Nicolina A. *Capturing The Multi-dimensionality of Energy Access*. Washington, DC: Live Wire, 2014/16. World Bank; 2014. ©World Bank, <https://doi.org/openknowledge.worldbank.org/handle/10986/18677License:CCBY3.0IGO>
  124. Wakawaka. Datasheet. Waka Waka Light - solar-powered LED flashlight; 2014.
  125. Wakawaka. Datasheet. 2015. Waka Waka Power+ - solar-powered charger + light.
  126. D.Light Design. Datasheet. D.light S30 solar lantern; 2016.
  127. Freeplay Energy. Datasheet. Radiance - solar-powered lantern; 2016.
  128. Clark C, Summers J, Armstrong. Innovative flexible lightweight thin-film power generation and storage for space applications. In: Collection of Technical Papers. 35th Intersociety Energy Conversion Engineering Conference and Exhibit (IECEC) (CAT. No.00CH37022), Vol. 1, 2000, Vol. 1; 2000July:692-698. <https://doi.org/10.1109/IECEC.2000.870854>
  129. Nykvist B, Nilsson M. Rapidly falling costs of battery packs for electric vehicles. *Nat Clim Change*. 2015;5(April):329-332. <https://doi.org/10.1038/nclimate2564>
  130. Jäger-waldau A. PV Status Report 2016. no. October, <https://doi.org/10.2790/749737>; 2016.
  131. Swiegers W, Enslin JHR. An integrated maximum power point tracker for photovoltaic panels. In: IEEE International Symposium on Industrial Electronics. Proceedings. ISIE'98 (Cat. No.98TH8357), Vol. 1.

- Pretoria, South Africa, South Africa; 1998. <https://doi.org/10.1109/ISIE.1998.707746>
132. Wills RH, Krauthamer S, Bulawka A, Posbic JP. The AC Photovoltaic Module Concept. In: Proceedings of the 32nd Intersociety Energy Conversion Engineering Conference (IECEC); 1997; Honolulu, Hawaii:1562-1563. <https://doi.org/10.1109/IECEC.1997.656653>
  133. Enslin JHR, Wolf MS, Snyman DB, Swiegers W. Integrated photovoltaic maximum power point tracking converter. *IEEE Trans Ind Electron*. 1997;44(6):769-773. <https://doi.org/10.1109/41.649937>
  134. Kim RY, Lim CS, Jung HJ, Cho SB. A general-purpose integrated battery energy module for non-isolated energy storage system applications. In: 2012 IEEE Vehicle Power and Propulsion Conference, VPPC 2012; 2012; Beijing, China:1503-1507.
  135. Femto grid. Datasheet, Solar Power Optimizer - English; 2017.
  136. Enphase. Datasheet, Microinverter: Enphase Inverter Technology; 2017.
  137. Acanski M, Ouyang Z, Popovic-Gerber J, Ferreira B. Very thin flexible coupled inductors for PV module integrated GaN converter. In: Conference Proceedings - 2012 IEEE 7th International Power Electronics and Motion Control Conference - ECCE Asia, IPEMC 2012, Vol. 1; 2012; Harbin, China:693-697. <https://doi.org/10.1109/IPEMC.2012.6258780>
  138. Mazumdar P, Enjeti PN, Balog RS. Analysis and design of smart PV modules. *IEEE J Emerg Sel Top Power Electron*. 2014;2(3):451-459. <https://doi.org/10.1109/JESTPE.2013.2294640>
  139. Dede A, Giustina DD, Massa G, Pasetti M, Rinaldi S. A smart PV module with integrated electrical storage for smart grid applications. In: 2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM 2016, Vol. 40545387; 2016; Anacapri, Italy:895-900. <https://doi.org/10.1109/SPEEDAM.2016.7525997>
  140. Krauter S, Ochs F. All-in-one solar home system. In: Conference Record of the IEEE Photovoltaic Specialists Conference. New Orleans, LA, USA; 2002:1668-1671. <https://doi.org/10.1109/PVSC.2002.1190938>
  141. Reynaud JF, Alonso C, Aloisi P, et al. Multifunctional module lithium-ion storage and photovoltaic conversion of solar energy. In: Conference Record of the IEEE Photovoltaic Specialists Conference. San Diego, CA, USA; 2008:1-5.
  142. Reynaud JF, Gantet O, Aloisi P, Estibals B, Alonso C. New adaptive supervision unit to manage photovoltaic batteries. In: IECON Proceedings (Industrial Electronics Conference). Porto, Portugal; 2009:664-669.
  143. Reynaud JF, Gantet O, Aloisi P, Estibals B, Alonso C. A novel distributed photovoltaic power architecture using advanced Li-ion batteries; 2010:6-12. <https://doi.org/10.1109/EPEPMC.2010.5606548>
  144. Grzesiak W, Mackow P, Maj T, et al. Innovative system for energy collection and management integrated within a photovoltaic module. *Solar Energy*. 2016;132:442-452. <https://doi.org/10.1016/j.solener.2016.03.043>
  145. Vega-Garita V, Harsarapama AP, Ramirez-Elizondo L, Bauer P. Physical integration of PV-battery system: advantages, challenges, and thermal model. In: 2016 IEEE International Energy Conference, ENERGYCON 2016; 2016; Leuven, Belgium. <https://doi.org/10.1109/ENERGYCON.2016.7514038>
  146. Ačanski M, Popović-Gerber J, Ferreira B. Thermal modeling of the module integrated DC-DC converter for thin-film PV modules. In: Proceedings of EPE-PEMC 2010 - 14th International Power Electronics and Motion Control Conference; 2010; United States:160-165. <https://doi.org/10.1109/EPEPMC.2010.5606523>
  147. Vega-Garita V, Ramirez-Elizondo L, Bauer P. Physical integration of a photovoltaic-battery system: a thermal analysis. *Appl Energy*. 2017;208(June):446-455. <https://doi.org/10.1016/j.apenergy.2017.10.007>
  148. Hammami M, Torretti S, Grimaccia F, Grandi G. Thermal and performance analysis of a photovoltaic module with an integrated energy storage system. *Appl Sci*. 2017;7(11):1107. <https://doi.org/10.3390/app7111107>
  149. Solpad. Datasheet, SolPad - The smart home solar solution is here; 2017.
  150. Ciriminna R, Meneguzzo F, Albanese L, Pagliaro M. Solar street lighting: a key technology en route to sustainability. Wiley Interdisciplinary Reviews: Energy and Environment. 2016 <https://doi.org/10.1002/wene.218>; .
  151. Narayan N, Vega-Garita V, Qin Z, Popovic-Gerber J, Bauer P, Zeman M. A modeling methodology to evaluate the impact of temperature on solar home systems for rural electrification. In: 2018 IEEE International Energy Conference (ENERGYCON); 2018; Limassol, Cyprus:1-6. <https://doi.org/10.1109/ENERGYCON.2018.8398756>
  152. Palacin MR, de Guibert A. Why do batteries fail? *Science*. 2016;351(6273):1253292-1253292. <https://doi.org/10.1126/science.1253292>

**How to cite this article:** Vega-Garita V, Ramirez-Elizondo L, Narayan N, Bauer P. Integrating a photovoltaic storage system in one device: A critical review. *Prog Photovolt Res Appl*. 2019;27:346-370. <https://doi.org/10.1002/ppp.3093>