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

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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.

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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,¹ complicated manufacturing processes,² rigid and heavy devices,³ and space consuming solutions.⁴ 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,⁵ indicating the features of the proposed approaches for particular applications. For instance in Wei et al,⁶ the state of the art of self-powered systems is introduced, while fibre-shape power devices have been studied in Cai et al.⁷ Similarly, many papers have summarised and discussed the trends and perspectives of the integration concepts.^{8,9} 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.² The developments on nanostructured flexible electrodes and structural designs towards shape-conformable devices have been introduced and summarised in detail.³ 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.¹⁰ Moreover, the current issues and future research directions for various devices that integrate different types of solar cells and SCs technologies have been analysed.^{4,11} Also, in Luo et al¹² and Lee et al,¹³ 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_p). 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	Batteries
	One device	Solar module	Lithium ion
	Combined	Solar panel	Accumulator
	Monolithic	PV module	Electrochemical cell
	Integrated Module	Photovoltaic panel	Supercapacitor
	All in one	Photovoltaic module	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 ⁻²)	η_{sc} (%)	η_{s} (%)	η_{ss} (%)	Capacitance (mF cm ⁻²) [*] (F g ⁻¹) ^{**}
2004	Miyasaka and Murakami ¹⁷	Planar (2E)	DSSC	Activated carbon (LiI-doped)	-	-	80 ^d	-	690 [*]
2005	Murakami et al ¹⁸	Planar (2E,3E)	DSSC	Activated carbon (LiI-doped)	-	-	42 ^d (3E)	-	650 ^g (3E)
2011	Skunik et al ³⁰	Planar (2E)	DSSC	PEDOT(MWCN)/LiCF ₃ SO ₃ (PC)	-	-	-	-	95 ^{**g}
2012	Chen et al ³¹	Coaxial/fibre (2E)	DSSC	CNT/PVA/H ₃ PO ₄ /Ti	-	2.2 ^a	-	1.5 ^e	0.6 [*]
2013	Mini et al ³²	Planar (3E)	DSSC	Ti/TiO ₂ /ZrO ₂ /TiO ₂ /Ti	0.2178 ^b	-	-	-	0.14 [*]
2013	Kulesza et al ³³	Planar (2E,3E)	DSSC	Ag/RuO _x (OH) _y /nafion/FTO (3E)	0.92 ^a	0.92	87.8 ^d (3E)	0.8 ^h	3.26 ^g
2013	Li et al ³⁴	Planar (comb)	DSSC	PET/Ni/Carbon	-	0.27 ^a	-	-	2.89 ^{**f}
2013	Skunik-Nuckowska et al ³⁵	Planar (3E)	DSSC	Ag/RuO _x (-OH) _y /nafion/FTO	2-3 ^a	2-3	87.8 ^d	0.8 ^h	3260 ^{*a}
2013	Yang et al ²⁷	Planar (3E)	DSSC	MWCNT/PVA-H ₃ PO ₄ /FTO	2.31 ^a	2.31 ^a	34	0.79	83 ^{**f}
2013	Zhang et al ³⁶	Planar/fibre (2E)	DSSC	PVDF/ZnO/FTO	2.23-4.36 ^d	7.32 ^{ai,k}	-	3.7 ^e	20 ^{**}
2014	Westover et al ²⁵	Planar(2E)	Si-poly	Porous Si	-	14.8 ^j	84 ^{ai,d}	12.43 ^k	0.014 ^h
2014	Zhang et al ³⁷	Coaxial	OSC	Ti/PVA/H ₃ PO ₄ /MWCNT	1 ^{ai,k}	1.01 ^{ai,k}	65.6 ^f	0.82 ^{ai,k}	0.077 ^h
2014	Chen et al ³⁸	Coaxial	DSSC	Ti/TiO ₂ /PVA/H ₃ PO ₄ /Ti	2.7 ^a	2.73 ^a	75.7 ^h	2.07 ^a	3.32 ^{fi}
2014	Huang et al ³⁹	Planar (3E)	DSSC	Pt/Au/PVDF/FTO	3.3	-	-	1.33-3.38 ^a	0.017 ^{**g}
2014	Yang et al ⁴⁰	Coaxial	DSSC	MWCNT/PVA/H ₃ PO ₄	6.47	6.47 ^a	-	1.83 ^h	18.6 ^{**f}
2014	Bagheri et al ²⁹	Planar	DSSC	Co-doped NiO/AC	5.12	4.9 ^a	54 ^d	0.6	32 ^{**f}
2015	Xu et al ⁴¹	In plane	PVSC	polypyrrole-based	13.6	13.6 ^a	-	10 ^h	572 ^{*f}
2015	Narayanan et al ⁴²	Planar	QDSSC	MWCNT/FTO/Ag/LiCF ₃ SO ₃	-	-	-	3.45 ^c	150 ^{**f}
2015	Shi et al ⁴³	Planar meshed (3E)	QDSSC	carbon/Cu ₂ S/Na ₂ S/S/KCl	-	2.66 ^a	-	-	72.7 ^{**f}
2015	Zhang and Jiang ⁴⁴	Planar(2E)	DSSC	Liquid(l) or quasi-solid electrolyte	-	5.78 ^a (l)	-	-	0.0046 ^{**}
2015	Cohn et al ⁴⁵	Planar(3E)	DSSC	Ionic polymer	4.8 ^r	4.8 ^a	80 ^d	2.1 ^f	3.5 [*]
2015	Chien et al ²²	In plane	OSC	Al/graphene/ITO	-	1.57 ^a	-	-	2.5 ^{*f}
2015	Selvam et al ⁴⁶	Separated	DSSC	b-cyclodextrin/PVP/MnCO ₃	-	5.57 ^a	-	-	202.6 ^{**f}
2015	Reddy et al ⁴⁷	Planar	DSSC	PEDOP/V ₂ O ₅	-	1.4 ^a	-	-	224 ^{**f}
2015	Sun et al ⁴⁸	In plane	P5C	CNT/PVA-H ₃ PO ₄ /PANI	4.3 ^{ai,k}	4.3 ^{ai,k}	72.18 ^{ik}	3.1 ^k	185.2 ^{**h}

Continued

TABLE 2 Continued

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

^aTesting at one sun (1000 W/m²).

^bParameters estimated from I-V curve.

^cTesting at specific conditions.

^dParameters obtained from a complete charging-discharging process.

^eOverall photo-storage efficiency.

^fParameter calculated using cyclic voltammetry.

^gParameter calculated based only on a charging or discharging process.

^hParameter calculated according to a equation proposed by the authors.

ⁱParameters estimate for one device isolated of the other.

^jParameter given by the manufacturer.

^kParameter obtained for the device with the highest performance.

^lEfficiency calculated by the authors of this paper using Equation 1.

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

^aTesting at one sun (1000 W/m²).

^bParameters estimated from I-V curve.

^cTesting at specific conditions.

^dParameters obtained from a complete charging-discharging process.

^eOverall photo-storage efficiency.

^gParameter calculated based only on a charging or discharging process.

^hParameter calculated according to a equation proposed by the authors.

ⁱParameters estimate for one device isolated of the other.

^jParameter given by the manufacturer.

^kParameter obtained for the device with the highest performance.

^lEfficiency calculated by the authors of this paper using Equation 1.

^mParameter 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_p were considered low-power solutions, whereas devices able to deliver more than 10 W_p were classified as high power, as stated by Apostolou and Reinders.¹⁴ 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).

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

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.

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 (η_{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 η_{sc} is solar cell efficiency and η_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 η_{ss} , making difficult fair comparisons across articles. The η_{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 η_{sc} and η_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.¹⁵ 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 electrode¹¹ 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.

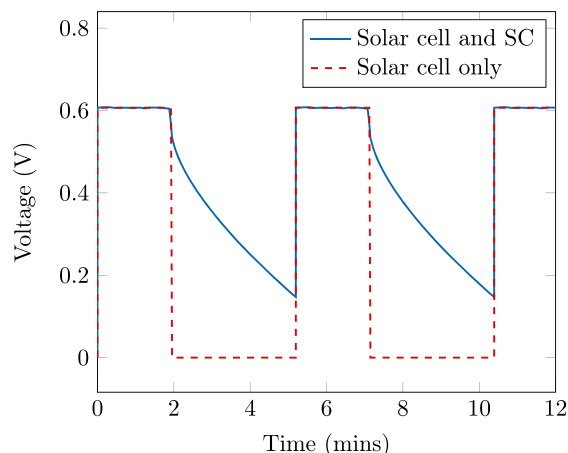


FIGURE 1 Response of a single solar cell and a solar cell coupled with a supercapacitor during intermittent illumination. If light is on, the voltage of a single solar cell is around 0.6, but when light is off, the voltage decreases to 0. In cases where an appropriate SC is used, the system voltage does not decrease to zero intermediately in the absence of light. This figure is based on Ouyang et al,¹⁶ 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]

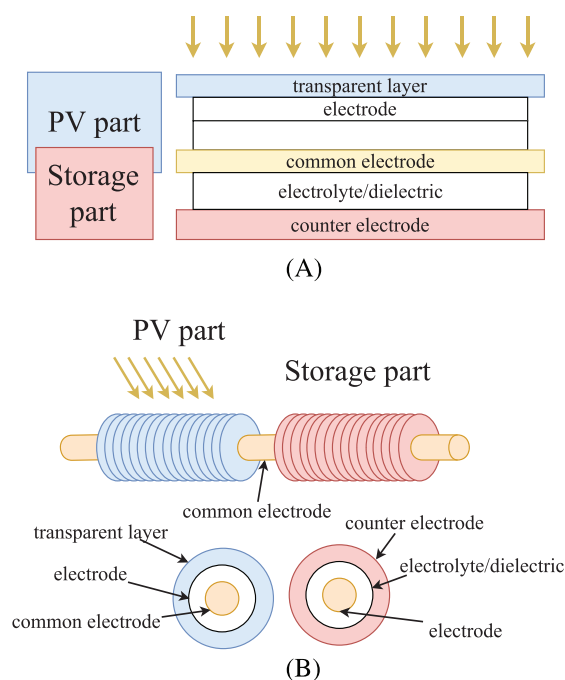


FIGURE 2 A, Planar or monolithic three-electrode structure; B, coaxial fibre parallel structure [Colour figure can be viewed at wileyonlinelibrary.com]

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.¹²

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,¹⁷ 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 TiO₂ 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,¹⁸ 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.⁴ 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.⁷

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 TiO₂. 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 I⁻, are combined with positive dye

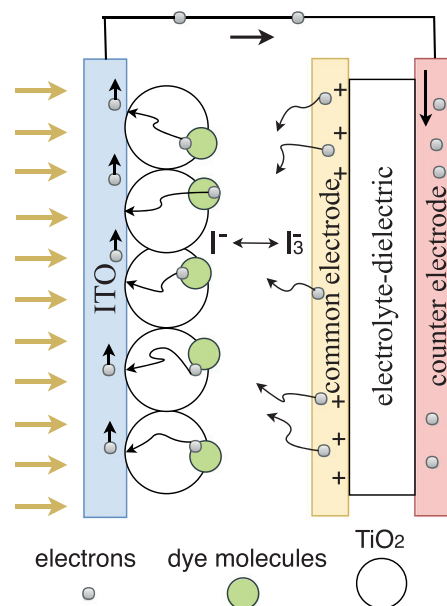


FIGURE 3 Working principle of a dye-sensitized solar cell coupled with a supercapacitor [Colour figure can be viewed at wileyonlinelibrary.com]

molecules allowing its regeneration and keeping the photo-generation process. The charging process continues as the redox reaction (I^-/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.⁴

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.^{19,20} Furthermore, OSCs low costs and ease of manufacturing (roll-to-roll) underline its potential and interest in physically integrated devices.²¹ 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 al²²; 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 mW cm^{-2}) and capacitance per unit area (572 mF cm^{-2}) is based on union of PVSC and SC. In Kim et al.,²³ 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.^{23,24} Although not so frequently, a-Si and c-Si solar cells have also been researched with acceptable overall efficiencies.^{16,25,26}

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.²⁷

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 TiO_2), the devices perform deficiently due to their high electrical resistance when selected as intermediate electrodes.²⁸

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.²⁹

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.¹⁵

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.¹²

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.¹ 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.⁵⁸

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.,⁵⁹ where a conventional DSSC was modified substituting the I^-/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 WO_3 as a charge storage layer.⁶⁰ For more details, a comprehensive list was developed by Yu et al.,⁶¹ 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.,⁶² 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

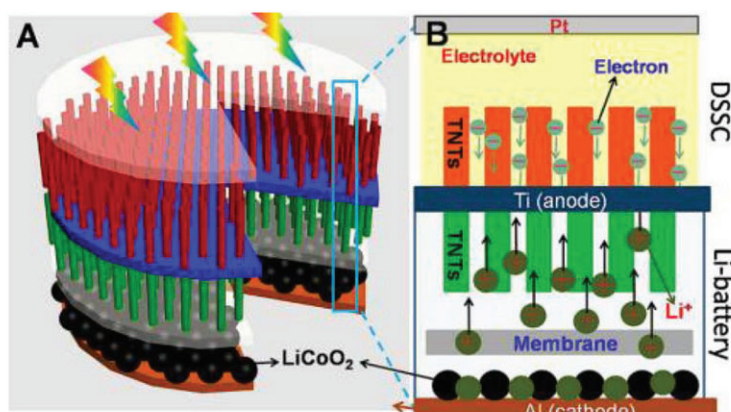
active anode because it results in devices with comparable voltages as individual Li-ion batteries. An example of this was introduced by Paoletta et al.,⁶³ where the delithiation of lithium iron phosphate nanocrystals is produced by its interaction with light, opening the door to photo-rechargeable lithium-ion 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-O₂ light-assisted battery was suggested,⁶⁴ 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.

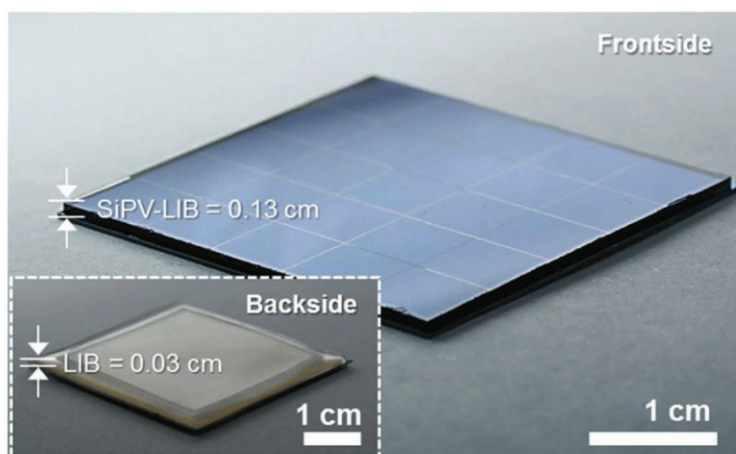
As Si have been intensively used for making solar cells, different types of Si solar cells have been combined with batteries. One remarkable concept was introduced in Chakrapani et al.,⁶⁵ where a nanowire-based multijunction Si PV device shared a Si substrate with a LiCoO₂ battery, which had a Si nanowire 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%.⁶⁶ Moreover, a silicon-on-insulator manufacturing process was introduced to fabricate multiple solar cells and scale up the overall cell voltage⁶⁷; 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.,⁶⁸ 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 TiO₂ nanotubes were grown to be part of the DSSC (orange) and Li-ion battery (green). At the top, the TiO₂ 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 TiO₂ battery anode where they are stored. Also while charging, the Li⁺ move to the anode maintaining the electro-



(A)



(B)

FIGURE 4 A, Three-electrode nanotube based integrated solar battery device. Reprinted with permission from Guo et al.⁶⁹ 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.⁷³ with permission from the The Royal Society of Chemistry [Colour figure can be viewed at wileyonlinelibrary.com]

chemical equilibrium. For this device, the overall efficiency was 0.82% and the battery capacity 38.39 μAh .⁶⁹

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.⁷⁰ 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).⁷¹

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 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 stability⁷²; 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,⁷³ 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 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.⁷⁸

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.⁴ 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.¹⁰

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 decreases⁸⁸; therefore, more developments towards highly conductive electrodes are fundamental. At the same time, new weaving techniques are needed for more stable and powerful devices,⁸⁹ especially considering the increasing complexity of the more recent devices.⁹⁰

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.³ 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.³ 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.³ 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,^{6,35,91} but with the inherent compromise on power density. Although solid electrolyte devices have been already built,⁶⁵ 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.⁶ 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.¹² Consequently, the devices are not as efficient as they could be and their long-term stability is also questionable.^{4,58} 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.⁹⁰

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.² 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,⁸ 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.⁵⁸ 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,¹² 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 F g⁻¹ and a solar cell with an efficiency close to 14%.²³ 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,⁹² with 29.43% reported for c-Si⁹³ 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 mWh g⁻¹,⁹⁴ 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 LiFePO₄, LiCoO₂, and Li₄Ti₅O₁₂ according to Figure 6, with LiFePO₄ 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

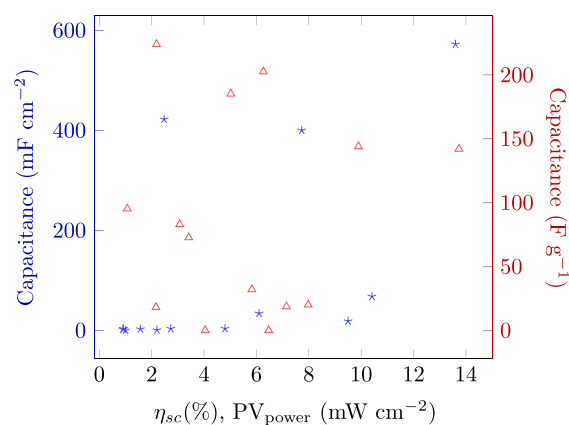


FIGURE 5 Trends in photo-supercapacitors. The data for this graph were taken from Table 2 for devices tested at 1 sun conditions. At the top right, two devices are characterised by high capacitances and solar efficiencies [Colour figure can be viewed at wileyonlinelibrary.com]

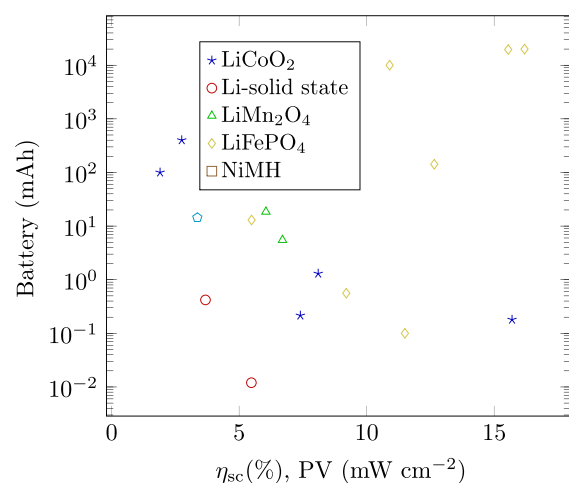


FIGURE 6 Trends in solar battery systems. The data for this graph were taken from Tables 3 and 4 for devices tested at 1 sun conditions. High-power solution are located at the top right of the graph [Colour figure can be viewed at wileyonlinelibrary.com]

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

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.² 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 al²⁶ 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.¹³

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.²

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.⁹⁶ 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,^{66,85} the exploration of electrochemical cells with a lower voltage range of operation,⁷⁰ and the interconnection of single junction solar cell in series to elevate the voltage.^{72,73} 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 options⁹⁷; 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,⁶⁵ TiN is proposed to prevent Li⁺ 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,⁹⁹⁻¹⁰¹ while similar progress has been made to enable flexible storage devices.¹⁰²⁻¹⁰⁷ As a consequence, combined solutions with flexible properties have been reported during the last years, especially in wearable applications,^{108,109} due to their low weight, bendable, and form factor capabilities. Additionally, PI fibre-shape devices have shown potential to be woven in clothing manufacturing.^{89,110,111}

A wearable textile solar battery was developed in Seo et al,⁹⁸ and as a result, the mechanical properties of the battery were modified using textile electrodes. After the changes, the battery with a Li₄Ti₅O₁₂ anode and LiFePO₄ 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.⁷⁷ 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 cm³ 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.¹¹² In addition, another paper assesses the integration of battery and solar cells in a flexible substrate,⁷⁵ making flexible Li-ion batteries a flexible electronics enabler.¹¹³

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.^{114,115}

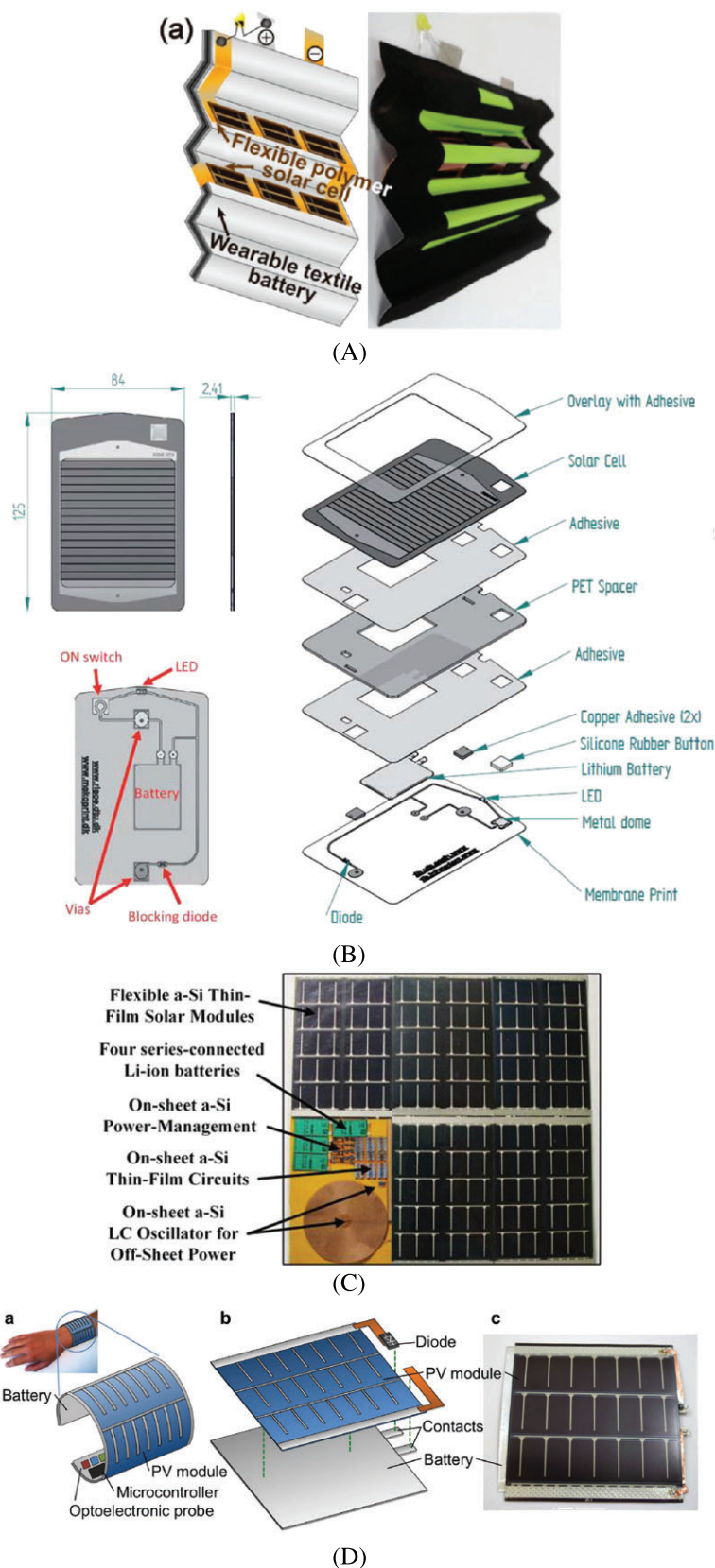


FIGURE 7 A, Wearable textile solar battery. Reprinted with permission from Seo et al.⁹⁸ Copyright 2013, American Chemical Society. B, LED lamp powered by an organic solar cell and polymer Lithium polymer battery. Reproduced from Krebs et al.⁷⁶ with permission of Royal Society of Chemistry. C, Power harvesting,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

To power an 8.75 mm autonomous microsystems for temperature sensing purposes, a thin film battery (12 μ Ah), two 1 mm² solar cells (5.48%), and the power management (dc/dc converter) were built and stuck together as a compact solution.¹¹⁶ 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,¹¹⁷ 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,¹¹⁸ 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,¹¹⁹ 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,⁸³ 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 LiCoO₂ cathode, had a capacity of 47.5 mAh and maximum solar power of around 230 mW.⁸⁴ 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.^{38,120,121}

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,¹²² as lighting is seen as primary need falling in the first tier of household electricity access.¹²³ 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_p.¹²² 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 cm².¹²⁴ A higher-end product from the same company, WakaWaka Power+, includes a 1 W_p 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.¹²⁵

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_p, a 450 mAh lithium iron phosphate battery with 2 LED lights capable of producing up to 60 lumens of light.¹²⁶ Another product called Radiance Lantern from the company Freeplay Energy offers a powerful 2 W_p 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.¹²⁷

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.¹²⁸ Moreover, an integrated power supply has been assessed and found suitable as an autonomous power source for nanosatellites,⁷⁴ 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,^{129,130} 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 _p)	ES Capacity (Wh)	ES Type	Capacity (Ah ^a ,F ^b)
Dede et al ¹³⁹	250	174	Hybrid SC	4285 ^b
Reynaud et al ¹⁴¹⁻¹⁴³	75	480	LiFePO ₄	10 ^a
Grzesiak et al ¹⁴⁴	100	198	LiFePO ₄	19.6 ^a
Vega-Garita et al ¹⁴⁷	265	965	LiFePO ₄	20 ^a
Krauter and Ochs ¹⁴⁰	60	1260	Lead acid	105 ^a
Solpad ¹⁴⁹	72	600	-	-
Hammami et al ¹⁴⁸	-	-	LiFePO ₄	-

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,¹³¹⁻¹³³ or by combining power electronics and energy storage¹³⁴ 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,^{135,136} 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,¹³⁷ 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_p 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_p) has been studied.¹³⁸ To implement this device, several cells are connected to a dc/dc flyback converter that performs MPPT. They are also grouped and attached

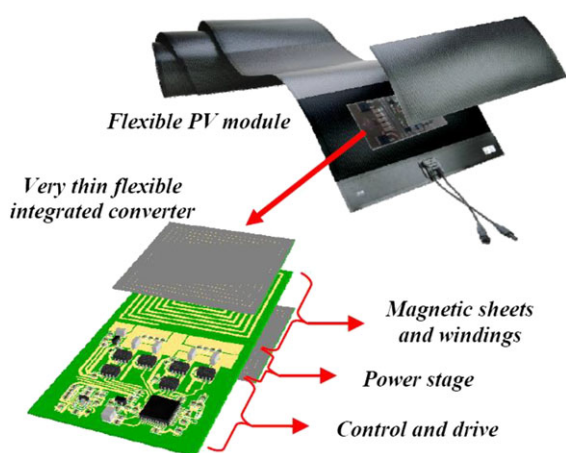


FIGURE 8 Dc/dc converter integrated in a flexible PV module. Reproduced with permission from Acanski et al.¹³⁷ Copyright 2012, IEEE [Colour figure can be viewed at wileyonlinelibrary.com]

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,¹³⁹ 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,¹⁴⁰ 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.¹⁴¹ 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_p 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.

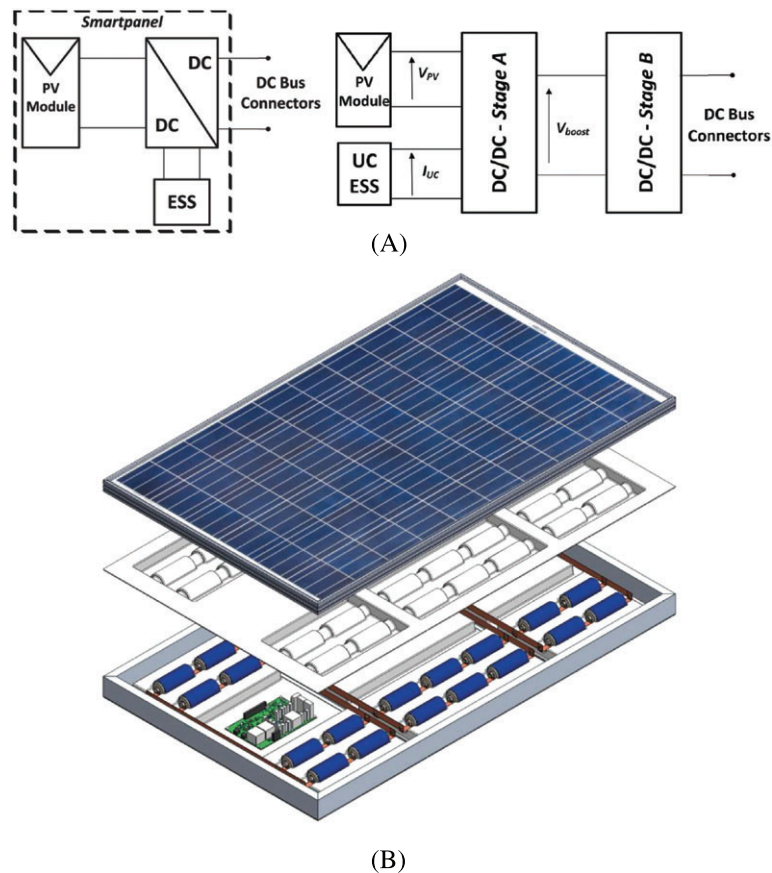


FIGURE 9 A, System components (left), power conversion stages (right); B, complete integrated system. Reproduced with permission with Dede et al.¹³⁹ Copyright 2016, IEEE [Colour figure can be viewed at wileyonlinelibrary.com]

As a continuation, a prototype of the MPPT circuit board and battery management system board were presented and individually tested in Reynaud et al.¹⁴² 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,¹⁴³ 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_p PV panel coupled with a battery pack of 15 LiFePO₄ (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.¹⁴⁴ 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_p, 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,⁴² the pronounced thermal stresses that the components of a fully integrated solution must handle deserve to be further explored.^{145,146}

In Vega-Garita et al,¹⁴⁷ 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-

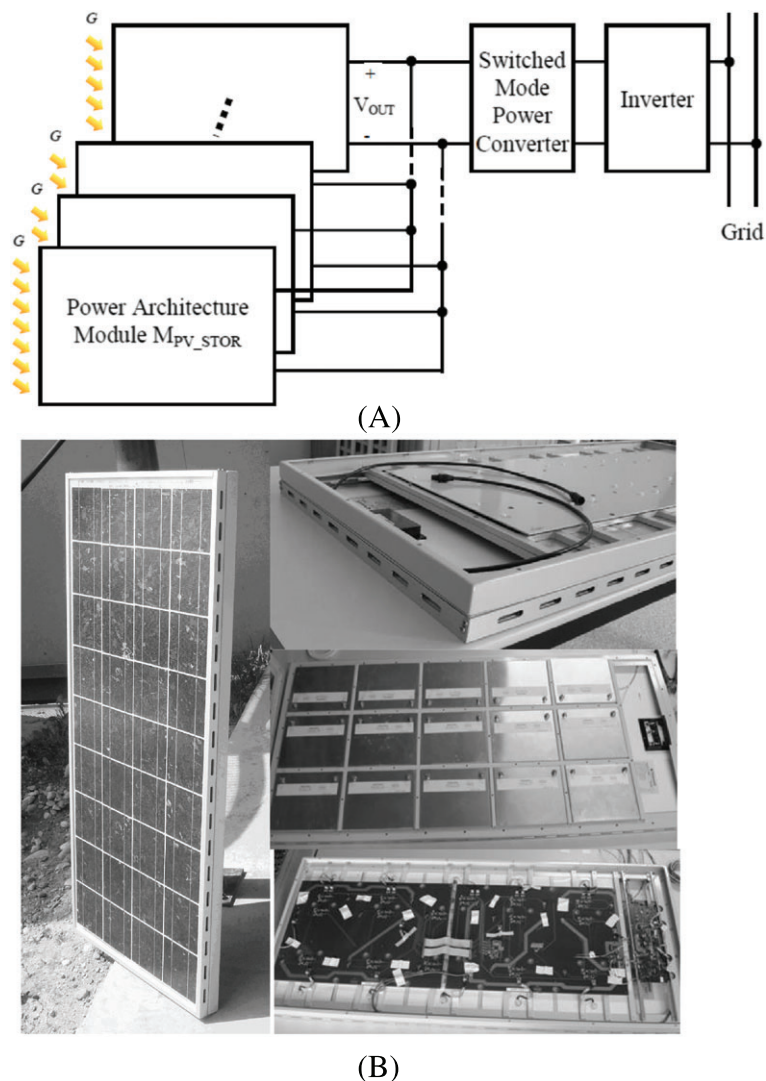


FIGURE 10 A Distributed architecture and B prototype. Reproduced with permission from Reynaud et al.¹⁴³ Copyright 2010, IEEE [Colour figure can be viewed at wileyonlinelibrary.com]

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.¹⁴⁸ 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.¹⁴ lead acid and Li-ion being the most popular. However, just a few products have targeted applications with loads higher than 40 W_p 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_p), 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*,¹⁴⁹ which

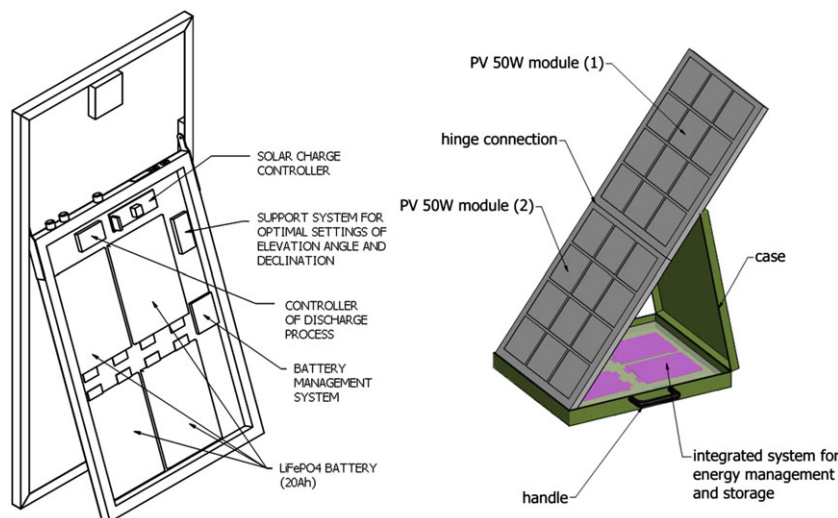


FIGURE 11 System for off-grid (left) and portable solutions (right). Reproduced with permission from Grzesiak et al.¹⁴⁴ Copyright 2016, Elsevier [Colour figure can be viewed at wileyonlinelibrary.com]

is designed to provide an ac output (115/230 V_{ac}) 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.¹⁴⁷ 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^{147,148} 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.¹⁵¹

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.¹⁵² 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.

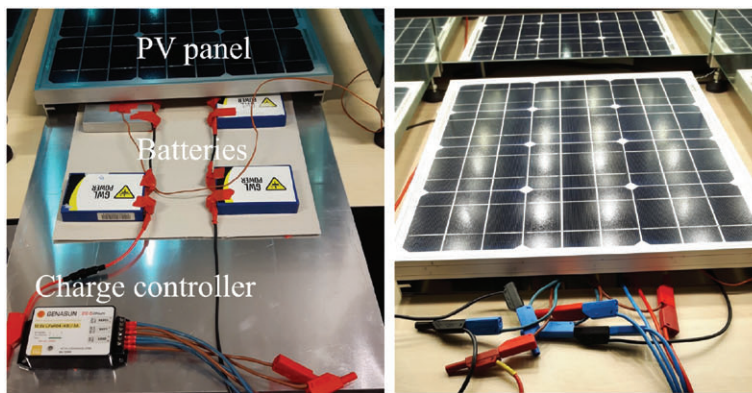
The widespread Li-ion batteries are composed of liquid electrolytes, which in cases of intensive operation can leak causing sudden failures that could lead to a potential explosion or malfunction. Consequently, with the recent advent of solid-electrolyte-batteries is convenient to start incorporating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

4.5.3 | Quest for the ideal system

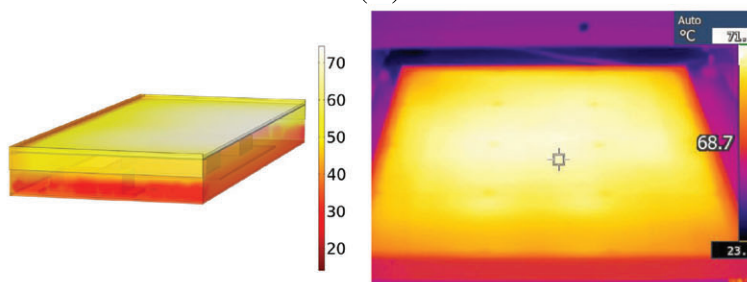
Due to the more accelerated ageing expected in integrated devices when compared with a conventional discrete PV-storage system, the components will fail faster; therefore, failing components must be replaced in an easy manner. To achieve this, the high-power integrated devices have to be designed to 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

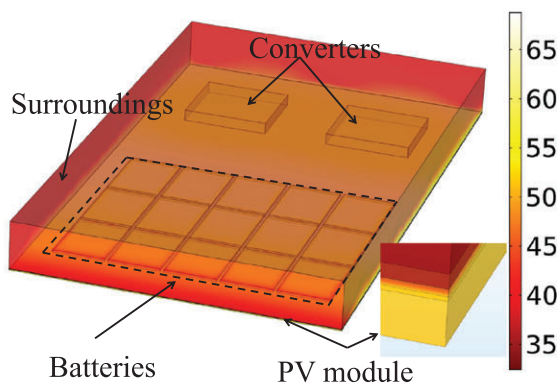
For integrated devices, an optimum electrical system sizing is crucial considering both cost and space constraints. Batteries, for instance, are the most costly component, and there is a consensus that battery



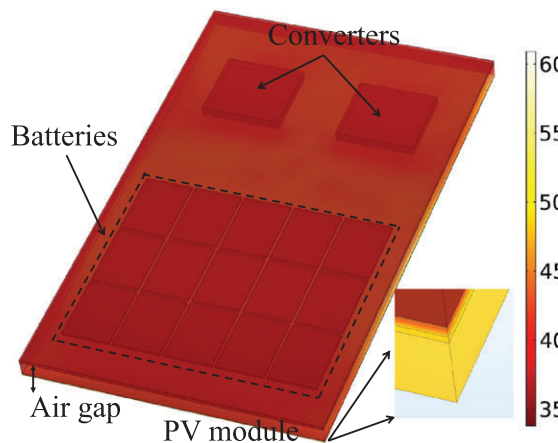
(A)



(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.¹⁴⁷ Copyright 2017, Elsevier [Colour figure can be viewed at wileyonlinelibrary.com]

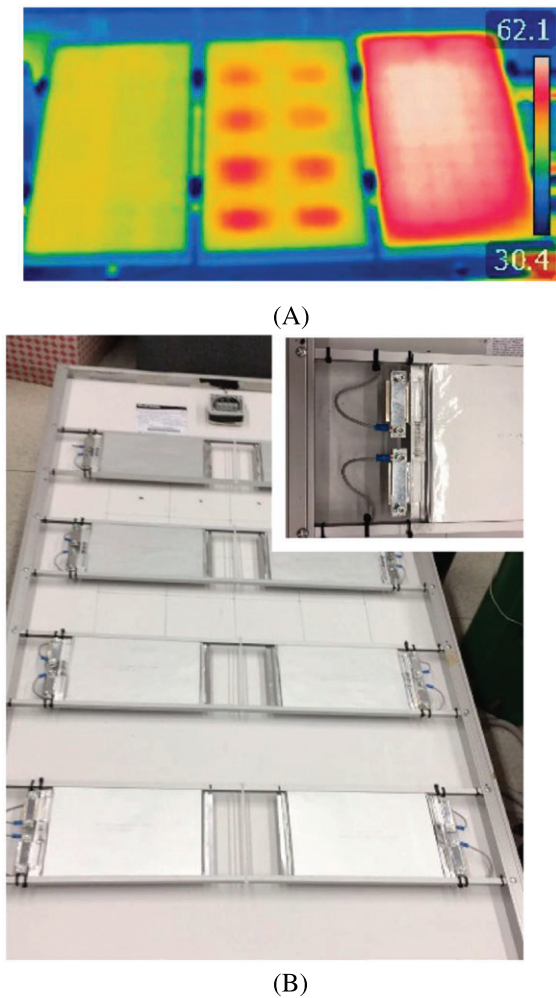


FIGURE 13 A, Thermal image of the module with batteries attached; B, placement of batteries. Reproduced with permission from Hammami et al.¹⁴⁸ Copyright 2017, MDPI [Colour figure can be viewed at wileyonlinelibrary.com]

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

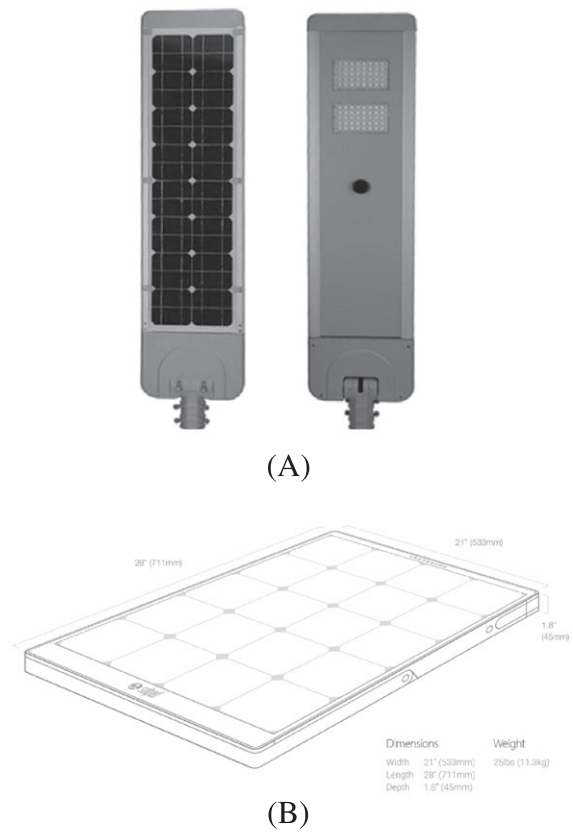


FIGURE 14 A, A Solar street lamp. Reproduced with permission from Ciriminna et al.¹⁵⁰ Copyright 2016, John Wiley & Sons. B, Solpad integrated module.¹⁴⁹ Reproduced with permission of Solpad

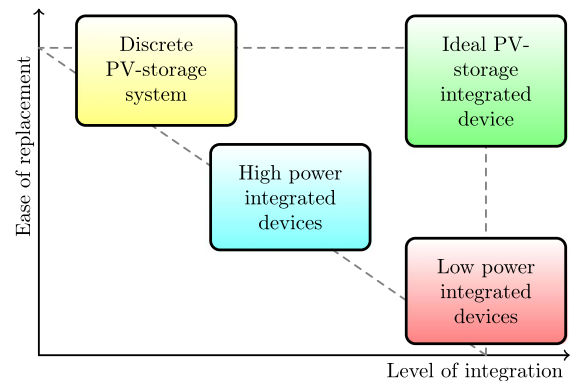


FIGURE 15 Comparison of existing approaches in terms of level of integration and ease of replacement; an ideal integrated device shown in green [Colour figure can be viewed at wileyonlinelibrary.com]

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 to achieve more stable power-integrated devices for PV systems, to move from the laboratory or proof of concept to practical applications.

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