applied sciences

Review

Overview and Perspectives for Vehicle-Integrated Photovoltaics

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Abstract: On-board photovoltaic (PV) energy generation is starting to be deployed in a variety of vehicles while still discussing its benefits. Integration requirements vary greatly for the different vehicles. Numerous types of PV cells and modules technologies are ready or under development to meet the challenges of this demanding sector. A comprehensive review of fast-changing vehicle-integrated photovoltaic (VIPV) products and lightweight PV cell and module technologies adapted for integration into electric vehicles (EVs) is presented in this paper. The number of VIPV projects and/or products is on a steady rise, especially car-based PV integration. Our analysis differentiates projects according to their development stage and technical solutions. The advantages and drawbacks of various PV cell and module technologies are discussed, in addition to recommendations for wide-scale deployment of the technologies.

Keywords: photovoltaic; vehicle-integrated photovoltaics; curved PV; flexible PV; light PV

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1. Introduction

The transport sector is one of the main contributors to the emissions of greenhouse gases (close to 25% in Europe). One solution is the electrification of transport via electrical vehicles. However, electric vehicles have limitations despite their purchase price such as limited autonomy and long or frequent recharge times. Vehicle-integrated photovoltaics may help mitigate these downsides. Electrical vehicle-integrated photovoltaics has untapped potential [1] and could accelerate mutual development. On-board photovoltaic energy generation is driven by technological, environmental, and legislative motivations. Among the promises are added range, fewer charging sessions, and a reduced carbon impact. Hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV) may also gain reduced CO_2 emissions as eco-innovation [2] in the future with on-board photovoltaic energy generation.

The integration of photovoltaics into vehicles requires aesthetic, low-weight, and curved modules unlike standard modules used for utility application. Of course, other key metrics such as performance (Wp/m^2), reliability, and safety are still applicable. Materials and technologies should remain cost-competitive to enable large-scale production. In addition to the significant technology change, another drawback is the lack of standards in the field of energy yield calculation from on-board photovoltaics, as well as adapted automotive and photovoltaic standards [3,4].

This paper reviews the state of the art in terms of VIPV performance and available cell and module technologies, as well as module materials to meet the stringent weight and flexibility demands. Firstly, the status of commercial offers and research and development (R&D) projects involving vehicles with on-board PV is presented. Secondly, current flexible and lightweight PV technologies are reviewed, and their potential for integration into EVs is discussed. Nonintegrated PV solutions are outside the scope of this paper.

2. Results and Discussions

2.1. Review of Market Offers and R&D Demonstrators Involving Vehicles with Integrated Photovoltaics (VIPV)

2.1.1. Overall View of the Market Offers and R&D Demonstrators

Commercially available offerings and R&D demonstrators of embedded photovoltaics are found on a variety of vehicle types such as private cars, camper vans, trains, trucks, passenger ships, planes, or spatial vehicles. Some examples of these vehicles (proof-of-concept, prototype, or commercial vehicles) [5–17] are shown in Figure 1.

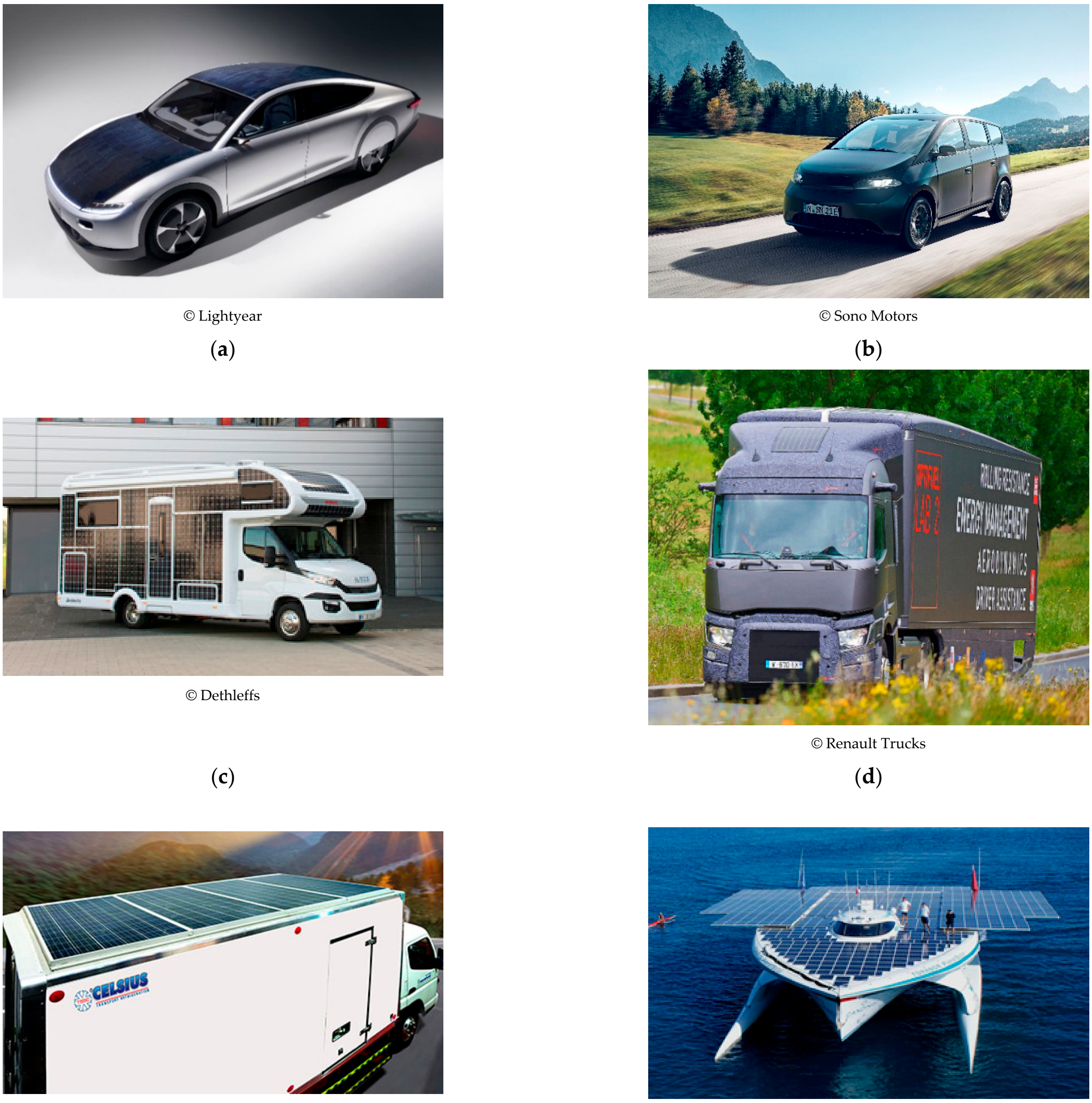

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Figure 1. *Cont.*

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(**g**)

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(**h**)

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(**i**)

Figure 1. (**a**) Proof of concept of the Lightyear One car [5]; (**b**) a car prototype—Sion from Sonomotors [6]; (**c**) Dethleffs motorhome demonstrator: E-home [8]; (**d**) a concept truck from Renault Truck—Optifuel Lab 2 [11]; (**e**) a set for freezer vehicles—TSSC S-Series [12]; (**f**) a ship proof of concept—Tûranor form PlanetSolar [13]; (**g**) a drone prototype from Atlantik Solar [14]; (**h**) a plane proof of concept—Solar Impulse [15]; (**i**) a spatial vehicle prototype: Stratobus [17].

A thorough list of VIPV commercial offerings and R&D projects is shown in Table 1, including information such as module efficiency, cell technology, PV surface or power, model, manufacturer, and use of the PV-generated electricity.

Table 1. Noncomprehensive chart of VIPV products and R&D initiatives.

Type	Manufacturer	Model/Project	Stage	Year	Vehicule Weight (t)	PV Surface (m^2)	PV Power (kWp)	Cell Technology/Efficiency	PV Use	References
Ship	Eco Ship		Development	2020		12,000	750		Aux.	[18]
Ship	Planet Solar	Tûranor	Proof of concept	2010	89	516.0	93.5	Silicon (Si)	Prop. + Aux.	[13]
Ship	Energy Observer	Energy Observer	Proof of concept	2017	28	130.0	21	Silicon	Prop. + Aux.	[19]
Ship	SoelCat	Catamaran 12	Proof of concept	2017	6		8.6		Prop. + Aux.	[20]
Bus	Fast Concept Car	Starter	Proof of concept			20.5	3.4	Si mono IBC/21.8%	Aux.	[10]
Camper Van	Dethleffs	E-home	Proof of concept	2017	5.6	31.0	3	Silicon mono	Prop. + Aux.	[8,21]
Car	Hyundai	Sonata Hybrid	Commercial	2020		1.3	0.204	Si mono/22.8%	Prop. + Aux.	[22,23]
Car	Skoda	Superb	Commercial	2000					Aux.	[24]
Car	Gaia	Wiseman	Commercial		0.8		0.23	Silicon mono IBC		[25]
Car	Audi	A8, A6, A4	Commercial	1994			0.04		Aux.	[24]
Car	Volkswagen	Touareg, Phaeton, Passat	Commercial	1994			0.04		Aux.	[24]
Car	Mercedes	E class, Maybach	Commercial	1994			0.04		Aux.	[24]
Car	Nissan	Leaf—SL model	Commercial	2014					Aux.	[26]

Table 1. *Cont.*

Type	Manufacturer	Model/Project	Stage	Year	Vehicule Weight (t)	PV Surface (m^2)	PV Power (kWp)	Cell Technology/Efficiency	PV Use	References
Car	Toyota	Toyota—Prius IV	Commercial	2017	1.5	0.9	0.18	HIT	Prop.	[7]
Car	Karma	Karma—Revero	Commercial	2017	2.5		0.2		Prop.	[24]
Car	Karma	Fisker	Commercial	2011			0.12	Silicon mono		[24]
Car	Hyundai/Kia		Development	2018						[27,28]
Car	Tesla	CyberTruck	Development	2019					Prop.	[29]
Car	Fiat	Phylla	Development	2008	0.75		0.34		Prop.	[30,31]
Car	Toyota	Prius Prime	Proof of concept	2019			0.86	Triple junction cells/34.0%	Prop.	[32]
Car	Gazelle Tech	Gazelle	Proof of concept	2020	0.68	4.0		ASCA modules	Prop.	[33,34]
Car	SonoMotors	Sono Motors—Sion	Proof of concept	2018	1.4	7.5	1.2	Si mono IBC/24.0%	Prop.	[6]
Car	Hanergy	Hanergy—Solar R, O, L, and A	Proof of concept	2019	2	3.5 to 7.5	1 to 2	GaAs, III-V flexible/29.0%	Prop.	[35,36]
Car	Ford	C-Max	Proof of concept	2014		1.5	0.3	Silicon mono IBC	Prop.	[37]
Car	Bochum Univ.	Solar racers	Proof of concept	2004–2017	0.25–0.36		1.2	Silicon mono IBC	Prop.	[38]
Car	UNSW	Sunswift solar racers	Proof of concept	1994–2017	0.17–0.43	4.0–7.9	0.8–1.8	Silicon mono IBC/18–23%	Prop.	[39]
Car	Audi	e-tron quattro	Proof of concept	2015		2.5	0.4			[24]
Car	Venturi	Eclectic	Proof of concept	2006	0.35	2.5			Prop.	[40]
Car	Lightyear	One	Proof of concept	2019	2	4.0			Prop.	[5]
Car	Volkswagen	Tiguan GTE	Proof of concept	2015		2.1	0.11			[41]
Car	ISRO		Proof of concept	2017					Prop.	[42]
Car	Peugeot	BB1	Proof of concept	2009				16.0%	Aux.	[43]
Drone	Atlantik Solar		Proof of concept	2017				Si mono IBC/23.0%	Prop.	[14]
Drone	NASA	Helios	Proof of concept	2001–2003	0.8	180.0	35		Prop. + Aux.	[44]
Drone	Airbus DS	Zephyr	Proof of concept	2008	0.05				Prop. + Aux.	[45]
Plane	Solar Stratos	Solar Stratos	Proof of concept	2014	0.45	22.0		Si mono IBC/22.0%	Prop. + Aux.	[46]
Plane	Océan Vital	Eraole	Proof of concept	2015	0.75		5.5	Si mono IBC/24.0%	Prop. + Aux.	[16,47]
Plane		Solar Ship	Proof of concept	2014					Prop.	[48]
Plane	Solar Impulse	Solar Impulse	Proof of concept	2004	2.3	270.0		Si mono IBC/22.6%	Prop. + Aux.	[15]
Spatial	Stratobus	Stratobus	Proof of concept	2018				Si mono IBC/24.0%	Prop. + Aux.	[17]
Bus	FlixBus		Proof of concept	2020				CIGS		[49]
Train	India		Proof of concept	2017				Si	Aux.	[50]
Train	SNCF	TER	Proof of concept	2010		23.0	3.1	Si mono IBC/21.0%	Aux.	[9]

Table 1. *Cont.*

Type	Manufacturer	Model/Project	Stage	Year	Vehiculе Weight (t)	PV Surface (m^2)	PV Power (kWp)	Cell Technology/Efficiency	PV Use	References
Train	Byron Bay		Proof of concept				6.5	Si	Prop.	[51]
Truck	TSSC	TSSC	Commercial			6.4	1.2	Si	Aux.	[12]
Truck	Volvo	SuperTruck Cab	Proof of concept	2014			0.27		Aux.	[24,52]
Truck	Renault	Optifuel Lab 2	Proof of concept	2014		31.1	4.6	Si mono IBC/22.0%	Aux.	[11]
Truck	Renault Volvo Truck		Development					CIGS	Aux.	[53]
Truck	Navistar	Catalyst	Proof of concept	2017		22.4	3.64	Silicon poly	Aux.	[54,55]
Truck	Daimler FreightLiner	SuperTurck	Proof of concept	2015					Aux.	[56]
Truck	Mitsubishi and Nippon	i Cool Solar	Proof of concept	2010			0.9	Organic/4.0%	Aux.	[57]

Note: Prop., propulsion; Aux., powering accessories; Si, silicon; IBC, interdigitated back contact; HIT, heterojunction.

From the data gathered in Table 1, some key information was extracted and is detailed in Figures 2 and 3.

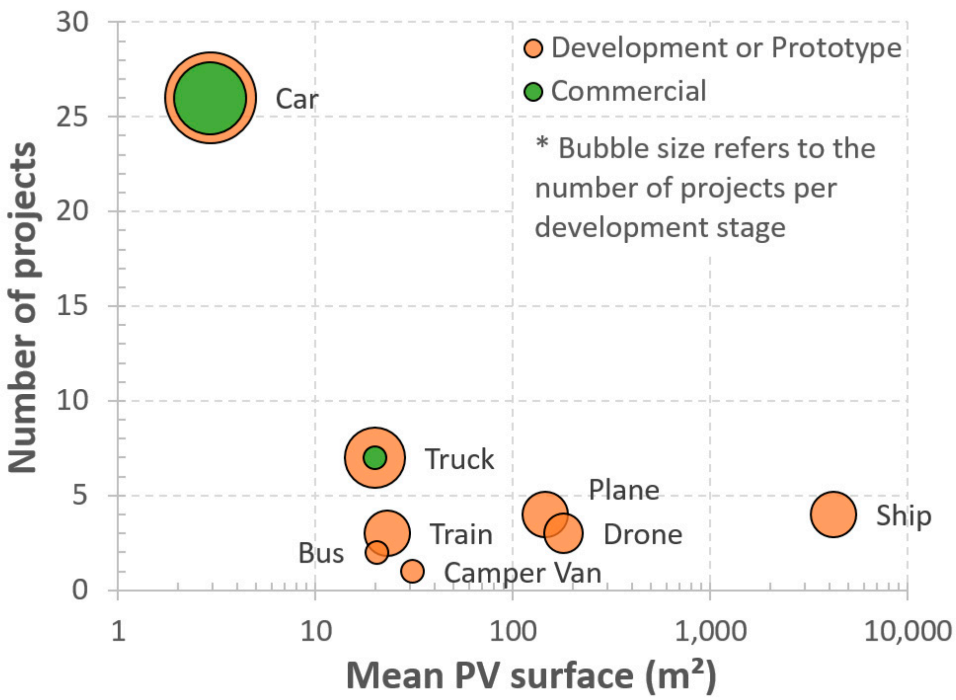


Figure 2. Number of initiatives for several vehicle types and their development stage.

Among the projects listed in Table 1, the majority are car-based (Figure 2). They are mainly proof-of-concept or development vehicles with integrated PV; however, a substantial number of market offerings can be found for cars (Figure 2).

According to the gathered data, the mean PV area for each kind of vehicle is significantly different (Figure 2). The mean embedded PV area ranges from 2.9 m^2 for cars to thousands of square meters for ships. Note that, although passenger cars have the lowest available surface, they have still become the leading application of VIPV. The higher number of passenger cars on the market may explain the higher interest in integrating photovoltaics into passenger cars. The limited surface area raises the demand for high module power density and exploitation of highly curved surfaces.

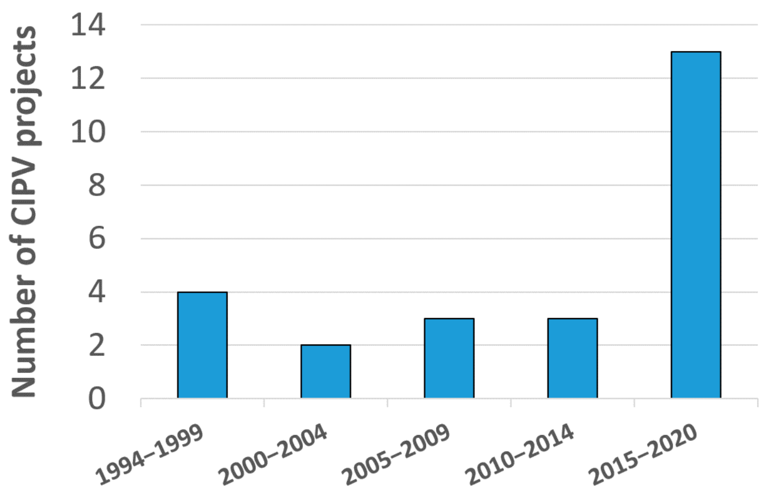


Figure 3. Number of CIPV projects over time.

Aspects such as module curvature and electrical module architecture (series or series–parallel cells, number of bypass diodes, etc.), as well as vehicle system self-consumption, will lower the energy provided by PV during both parking and drive modes. Other aspects can impact the solar kilometers but not the energy provided as vehicle efficiency. The effects of added weight and changes in aerodynamic drag (if any) on the on-board photovoltaic should be considered when evaluating the energy and solar kilometers provided.

2.1.2. Car-Integrated Photovoltaics and Constraints Related to the Automotive Sector

It was found that the number of car-integrated photovoltaic (CIPV) projects has increased since 2015 (Figure 3). This increase may be linked to the reduction in PV price and increase in EV sales. Advantages such as increased range or lower recharge frequency, especially in summer, have led to a decrease in cost and increased market share.

For these developments, the following regulatory constraints are demanding [58–65]:

- The safety of the vehicle, verified through mechanical calculations, crash tests, static mechanical tests, impact, electrostatic discharge safety, and vibration or fatigue tests.
- Acoustic emissions, in order to limit noise pollution, particularly in cities. They can be limited by the choice of vibration-absorbing materials, the development of quieter engines, etc.
- Particle and greenhouse gas emissions, which can be reduced by developing fuel-efficient engines and particle filters or even eliminated in the case of electric vehicles, at least during the vehicle's use phase [66].
- Recycling of the vehicle, with a recovery rate of 85% by weight, including a minimum recycling and reuse rate of 80% (European Directive on end-of-life vehicles (ELV); Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000).

In addition to these competitive and regulatory requirements, a car manufacturer must meet the following expectations of its end-users, which can be broken down according to different criteria:

- Safety: normally assured by standards, in addition to a feeling of safety. The interior must be protective, and the vehicle must be reliable in case of an accident. PV modules integrated in the roof and/or car body need to meet the relevant automotive safety standards.
- Reliability, robustness, durability: the purchase of a vehicle is an investment for 10 to 15 years [67]. It must remain in good condition in terms of performance and aesthetics without excessive maintenance throughout its life. If maintenance is required, it must be at an acceptable cost.

- Purchase cost or lifetime profitability of the product: If the vehicle has a particular technology that increases the cost of the vehicle, it must have an important functionality for the user or pay back its cost in the long run. For example, for a solar panel, one could set a constraint that the additional cost of the technology should be translated into fuel savings, which would pay back the technology in a few years.
- Functionality: every user expects a product to fulfill certain functionalities. For example, for a photovoltaic module, the functionality is provided by the production of energy used either to propel the vehicle or to supply on-board equipment. We can also expect ease of use and a limitation of the constraints linked to its use (PV allows for example to reduce the time or the number of charging sessions on the grid, in addition to range extension). Another functionality could be the possibility to power auxiliary functions.
- Aesthetics for passenger cars similarly to building-integrated photovoltaics (BIPV) is critical although existing coloring technologies will reduce performance, leading to a tradeoff.

2.1.3. Other Vehicles with On-Board PV

Motor homes and coaches are often equipped with a PV module of about 100 Wp to keep the lead–acid battery full for auxiliaries or to start the engine.

On coaches, trains, and trucks, PV is employed to power the auxiliaries even if no reason is given for this limitation. A few kWp of photovoltaics can be integrated on these vehicles where the mean PV area is about 20–23 m^2. On vehicles, the commercial offers are mainly limited to installed PV kits.

Buses, drones, planes, and spatial vehicles have the largest available surface area for integrated PV, ranging from hundreds of square meters to even thousands of square meters on ships. The generated electricity is used for propulsion and/or auxiliaries, but no market offerings could be found.

The increased range offered by the photovoltaics embedded on a vehicle will depend heavily on the real energy generated by the PV, as well as on the vehicle performance in terms of system and motor efficiency, drag coefficient, weight, etc.

2.2. Examination and Outlook of PV Technologies for PV-Powered Vehicles

2.2.1. Review of the PV Technologies and Their Performance

A large number of PV cell concepts and technologies exist. The evolution of cell efficiency in research was presented by NREL [68].

GaAs single-junction cells and multijunction cells have the best efficiencies but also highest costs. Crystalline Si-based cells present a good reliability and the best compromise between performance and price. Thin-film technologies have lower efficiencies but a better flexibility and lower weight. Lastly, emerging PV technologies such as perovskite cells present high promise to simultaneously achieve high efficiency, low price, ultralow weight, and flexibility. Today, this technology still has limited trustworthiness, longevity, and yield compared to large-scale crystalline silicon cell-based modules (Figure 4).

The main commercial PV technologies are c-Si-based with PERx cells for example. The ITRPV 2021 roadmap estimated the market to be split across PERx/TOPCON, SHJ, IBC, and tandem cells in 2031 [70]. Interconnection technologies using cut cells have numerous advantageous for EV applications. The cells can embrace a curved shape. In addition, smaller cells allow higher parallel sections of cells in series to be established for the same module voltage. As the voltage follows a logarithmic relationship with the irradiance while the current is proportional to the irradiance, such architectures would help to reduce the impact of partial shadowing. A large number of main commercial PV modules are not adapted for integration into EVs as they are planar, nonflexible, and heavy [71].

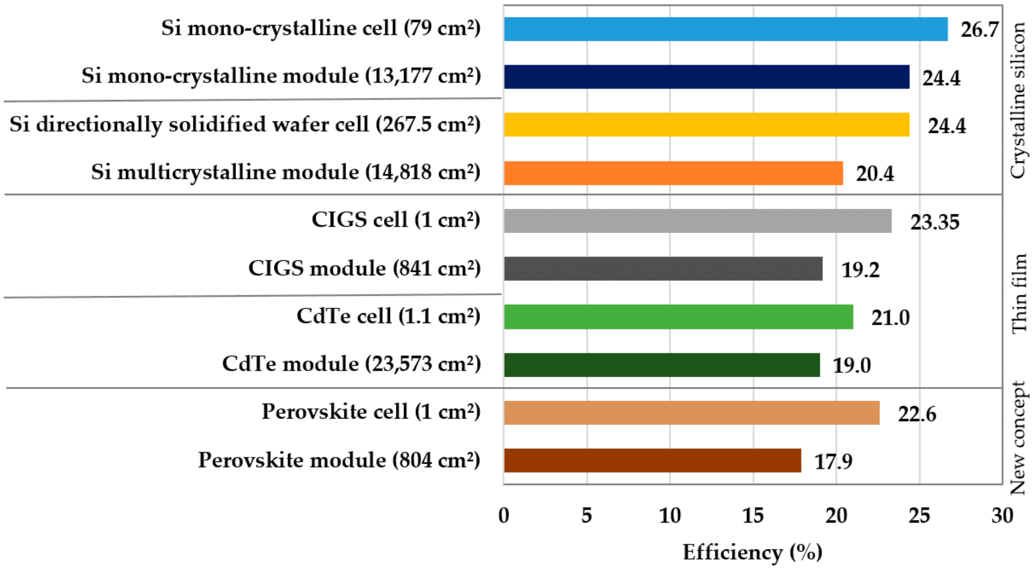
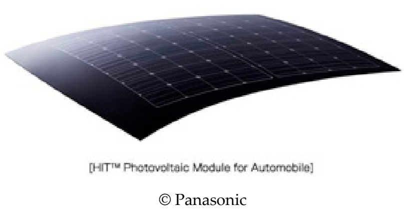


Figure 4. Best cell and module efficiencies found in the literature. Data from Green et al. [69].

2.2.2. Perspectives of the PV Technologies and Their Performance for Implementation in EVs

Different types of lightweight and/or flexible/curved PV modules already exist, including curved PV modules with a similar structure to a flat panel (2–3 mm thick front glass), flexible PV modules which are lightweight (often glass free), or light PV modules with a rigid structure. Examples of such PV technologies are presented in Figure 5. The characteristics of PV technologies vary depending on the application. Integration of the module-level electronics (usually bypass diodes or MOSFETs) into the module laminate could facilitate the placement of modules in/on EVs. An electrical architecture more resilient to shadowing is recommended for EV applications due to the higher frequency of partial shadowing compared to a power plant. One possibility is to increase the number of bypass diodes in a module of cells in series, whereas an alternative layout could include a parallel connection. Numerous solutions are under investigation for BIPV, which could inspire module design for EVs [72,73].



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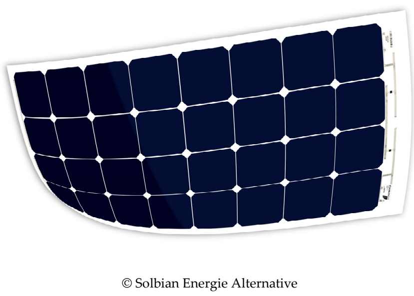

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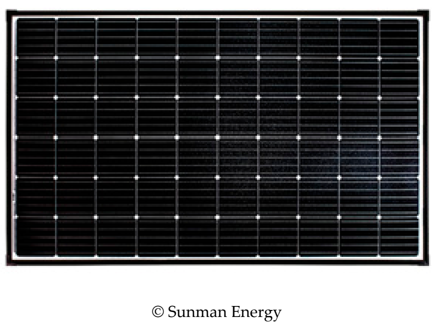

(c)

Figure 5. (a) Curved Panasonic module for Toyota Prius [74]; (b) Solbian flexible solar panels [75]; (c) Sunman light solar panel [76].

A noncomprehensive list of commercially available low-weight and/or bendable modules is presented in Table 2, including information such as module yield, cell technology, weight, model, and manufacturer.

Table 2. Non-comprehensive chart of light rigid and/or flexible PV technologies and their performances.

Type	Manufacturer	Model/ Project	Stage	Year	Cell Technology	Cell Efficiency	Module Efficiency	P_Surf Wc/m²	P_Mass Wc/kg	Weight kg/m²	Thickness (mm)	References
Curved	Panasonic		On the market	2017	HIT							[74]
Curved	A2Solar		On the market	2013	Silicon							[77]
Curved	Fuyao		On the market									[78]
Curved	Sunpower		On the market		Sunpower							[79]
Curved	CEA / IPC		Prototype	2020	Silicon mono							[80]
Curved	LG	Neon 2 CELLO cells (6 × 9)	Prototype	2018	LG cell 12BB	23.0%		167				[81,82]
Curved	LG	Neon R IBC cells (6 × 9)	Prototype	2018	LG cell BC	25.0%		193				[81,82]
Curved	Fraunhofer		Prototype	2019	366 Si mono shingle cells							[83]
Flexible PV	Gochermann		On the market	2014	Si mono IBC		22.9%	229	327	0.70		[84]
Flexible PV	SinoSola	SASF	On the market		Si mono IBC	22.0%	18.7%	187	56	3.36	3.00	[85]
Flexible PV	Solbian	Flex SP	On the market		Si mono IBC	23.0%	17.7%	177	76	2.34	2.00	[75]
Flexible PV	Sacred Solar		On the market		Si mono IBC	23.0%	17.4%	174	51	3.45	3.00	[86]
Flexible PV	DAS Energy	Project Series	On the market	2017	Si mono 5 BB		17.1%	171	50	3.42	2.00	[87]
Flexible PV	HighFlex	HF315	On the market		Si mono 3 BB	19.2%	16.5%	165	88	1.89	1.50	[88]
Flexible PV	Armor	ASCA	On the market		Organic							[89]
Flexible PV	Heliatek	HeliaSol	On the market		Organic							[90]
Flexible PV	Opvius		On the market		Organic							[91]
Flexible PV	Hanergy Miasolé	02WS	On the market	2018	CiGS	17.0%	15.1%	151	56	2.69	2.50	[92]
Flexible PV	Sunport Power	S-FLEX	On the market		Silicon mono		20.1%	201	61.1	3.29	2.5	[93]
Flexible PV	Sunware	20 series	On the market	2017	Silicon mono		14.3%	143	21	6.74	5.00	[94]
Flexible PV	Nanosolar	UltraLight	On the market		CiGS	11.7%	11.2%	112	43	2.56	4.00	[95]
Flexible PV	Flisom	eFlex 3.1	On the market		CiGS		9.4%	94	36	2.59	2.20	[96]
Flexible PV	Couleenergy		On the market		Si mono shingle	22.4%	17.7%	177	70	2.53		[97]
Flexible PV	Energy Mobile		On the market		Silicon mono IBC		18.3%	183	43	4.31	3.00	[98]
Flexible PV	Go Power	Solar Flex	On the market									[99]
Flexible PV	Ocean Vital		On the market							1.60	0.8-1.5	[100]
Light rigid PV	BenQ Solar		On the market		Silicon mono		16.5%	165	27	6.00		[101]
Light rigid PV	Sunman	eArche 325	On the market	2017	Si mono 4 BB		16.1%	161	42	3.82	5.60	[76]
Light rigid PV	Solarge	Solarge DUO	On the market	2022	Silicon mono		18.9%	189	34	5.48	14	[102]
Light rigid PV	SBM Solar		On the market					160	19	8.30		[103]
Light rigid PV	Fujipream	Nozomi	On the market							6.50		[104]
Light rigid PV	Tulipps Solar		On the market							8.50		[105]

Among the projects listed in Table 2, 50% are flexible PV modules (Figure 6), representing the most active module technology. As flexible modules can be added to existing vehicles (e.g., the roof), in addition to other applications with limited added weight, they represent one of the fastest ways to integrate photovoltaics. On the other hand, curved photovoltaic modules with a 2–3 mm thick glass cover have significant added weight compare to the metal roof. This may explain the lower number of projects listed. Currently, light rigid photovoltaic modules are mainly flat panels, whereas 3D curved ones are in development.

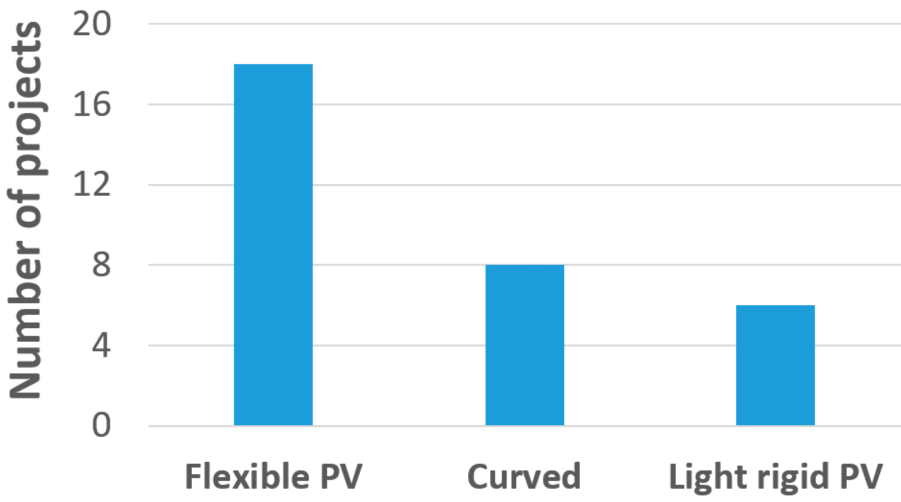

Figure 6. Number of projects for each type module technology.

2.2.3. Curved Photovoltaic Technologies

Glass–backsheet or glass–glass arched photovoltaic modules have a similar structure to standard PV panels with a thick front glass cover of 2.0 to 3.2 mm. This architecture utilizes 3D curved glass and, as listed in Table 2, commercial offers are available [74,77–82].

2.2.4. Bendable Photovoltaic Technologies

Bendable photovoltaic modules employ a variety of different technologies, from crystalline silicon-based cells to thin-film technologies such as CIGS solar cells or organic films (Table 2). These modules are flexible and low-weight (0.7 to 6.7 kg/m^2, see Figure 7) compared with the 11 kg/m^2 of a standard glass–backsheet module. Their power density varies widely due to the diversity of cell technologies used; however, module efficiencies close to standard flat modules exist (Figure 7), and there are commercial offers available.

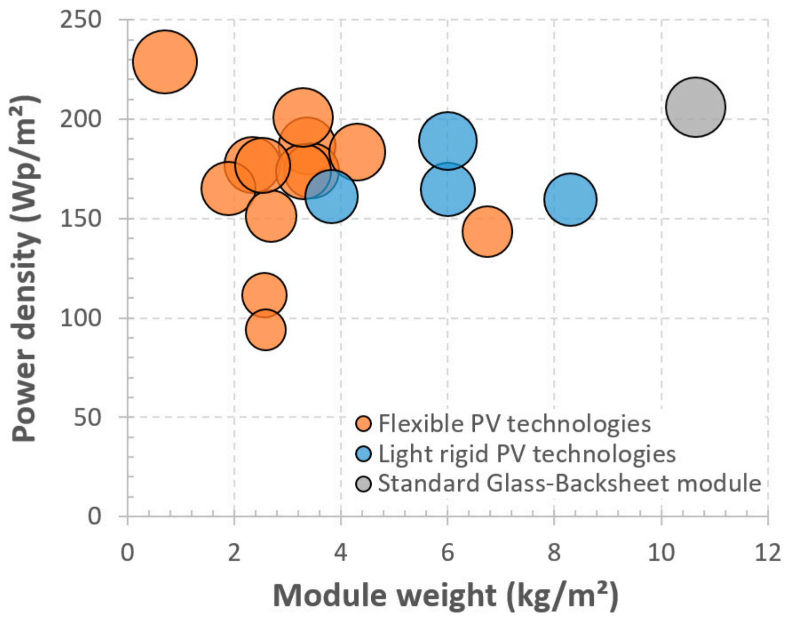

Figure 7. Number of flexible and light (nonflexible) modules in Table 2 (commercial brands) and their weight, where each bubble is a product. The flexible modules do not include the typical 6 kg/m^2 metal sheet of the car body.

2.2.5. Light Rigid PV Technologies

Nonflexible but light and rigid PV module technologies are listed in Table 2. Such modules are not flexible, but they may replace the body parts of a vehicle. They also have the potential to be 3D curved. Commercial offers are available with module weights often between 5.6 and 8.9 kg/m^2 but also down to $\leq$4 kg/m^2 (Figure 7).

Curved PV technologies using composite parts instead of glass for lighter technologies are under development.

3. Conclusions

Our review clearly highlights the rapid development of VIPV for passenger cars, with a large fraction of technologies at the prototype stage. Commercial offers within this product category clearly represent the pioneers of the sector.

Although early prototypes explored the use of high-efficiency cells, silicon-based photovoltaics is currently the dominant technology presenting an optimal tradeoff across performance, price, and reliability. Their drawback is their poor pliability in bidirectional flexion, limiting design options.

Longer-term perovskite-based photovoltaics will have the potential of combining high efficiency, low cost, and flexibility after 2023 according to ITRPV 2021.

Glass–glass and glass–backsheet curved PV modules are currently the most common technology in VIPV despite their higher weight (>11 kg/m^2) and lack of aesthetics. However, its similarity to standard flat PV modules ensures the availability of qualified materials and, hence, higher reliability and durability potential.

Flexible PV module technologies have the advantage of a lower weight (0.7 to 6.7 kg/m^2), with power densities close to standard flat PV modules. Additionally, this technology is suitable for both new and aftersales market by adding PV modules to existing vehicle parts. We anticipate that the rapid development of dedicated module materials for flexible panels and their qualification in both standard PV and VIPV applications will lead to their increasing market share. We anticipate that these technologies will form the second generation of VIPV modules.

Ultimately, light and rigid PV modules represent the most promising technology as they have the potential to replace the body parts of a vehicle. This technology has the potential of a lighter weight balance on the vehicle level thanks to full integration compared to flexible added PV functionality. For example, the development of light and curved PV modules using composite materials is in progress [80].

4. Perspectives

VIPV development will also need to meet other challenges not discussed here, such as energy production forecast, energy management, low environmental impact, and recycling.

The forecasting of PV production for a typical year is possible through tools such as PVGIS [106] of PVSYST [107]. The mean annual energy is, thus, pretty well known and helps the development of photovoltaics. On-board photovoltaics in vehicles usually involve curved PV modules, and the vehicles are, by definition, at different locations, as well as both static and non-static. The mean annual energy production also depends on the use cases, and there is a lack of data available for both irradiance and associated products.

The optimal energy harvesting of photovoltaic requires day-long operation. This situation may imply a significant energy loss from the vehicle system that is required to be partially awake. The optimization of vehicle system energy consumption may, thus, be a significant way to improve on-board photovoltaics. Additionally, cases with more system energy consumption than production must be avoided, for example, via a system shut down.

Other promising applications of EVs, including PHEV, are V2X (vehicle-to-everything) applications, such as vehicle-to-home [108], V2V (vehicle-to-vehicle), V2B (vehicle-to-building), or V2G (vehicle-to-grid). Such functionalities allow using the photovoltaic energy generated in homes and others, which is beneficial for the photovoltaic energy utilization ratio.

A need for new standards has to be highlighted. To the best of the authors' knowledge, the measurement of curved PV modules is not yet addressed by existing standards [4]. It might be more relevant to indicate a calculated power label value from a mixture of measurements at different angles of incidence using direct/diffuse light. Indeed, curved modules can be more sensitive to changes in yield depending on the angle of irradiance and the use of direct or diffuse sunshine.

Standards do exist for photovoltaic modules in automotive applications; however, to the best of the authors' knowledge, they are neither dedicated to on-board PV application nor ensure the compatibility of requirements of both domain standards.

A third point is the need for a standardized calculation of the energy produced. Moreover, in the case of the energy being used for solar kilometers, their calculation requires a standard approach.

Finally, calculation of the impact of CO_2 emissions from on-board vehicle-integrated PV, such as HEV or PHEV, needs to be fully defined and approved as an eco-innovation [2].

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