Energy &
Environmental
Science

ROYAL SOCIETY
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REVIEW

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Cite this: *Energy Environ. Sci.*, 2021, **14**, 106

Photovoltatronics: intelligent PV-based devices for energy and information applications

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Received 4th August 2020,
Accepted 9th November 2020

DOI: 10.1039/d0ee02491k

rsc.li/ees

At present, electrification and digitalization are two significant trends in the energy sector. Large-scale introduction of variable renewable energy sources, energy storage and power-electronics components, all based on direct current (DC), is fundamentally changing the electrical energy system of today that is based on alternating current (AC). This trend leads to a complex hybrid AC/DC power system with the extensive deployment of information and communication technologies (ICT) to keep the system stable and reliable. Photovoltaics (PV) is a technology that will play an essential role in local generation of clean electricity in expanding urban areas. To take full advantage of PV in the urban environment, PV technology must become intelligent. In this article, we identify, describe, and label a new research field that deals with intelligent PV and its application in components with multiple functionalities. We denote this field photovoltatronics. We review photovoltatronics research areas and introduce new directions for each area. Photovoltatronics brings together disciplines of energy and informatics. Since photons and electrons are carriers of both energy and information, photovoltatronics is the field that designs and delivers autonomous devices for electricity generation and information communication. It introduces a pathway from harvesting energy of photons ($h\nu$) to creating bits of information (01) through the energy of photo-generated electrons (eV). We show that ~10 keV energy is at least needed for transceiving one bit of information in the energy-information chain of the photovoltatronics, while the ultimate efficiency of the chain can reach up to 33.4%. We show that the number of publications related to photovoltatronics is exponentially increasing and the publication rate of combined research areas has been doubled in the present decade and reached 3.4% as a clear sign of its emergence.

I. Introduction to photovoltatronics

Photovoltaic (PV) technology directly converts the energy of electromagnetic radiation, such as solar energy, into electricity. The conversion takes place in a solar cell or in a PV module that consists of several solar cells connected together.[1] These devices are also referred to as PV electricity generators. The mainstream PV industry produces cells and modules that are standard in size and shape. They are aimed for the large-scale or local roof-top generation of electricity from direct and ideally unshaded sunlight. In contrast, these modules do not deliver maximal potential electricity when shaded,[2,3] a common situation in urban areas and indoor spaces.[4] To fully harvest available solar energy and to extend the variety of PV applications in the urban environment, the next generation of intelligent PV-based devices has to be developed. In addition to electricity, generation these devices will include many additional functionalities. We denote these devices as PV-based intelligent energy agents† (PV-IEA). In this article, we introduce a new research field of photovoltatronics that study, design and deliver the multi-functional PV-IEAs.

Photovoltatronics is a research field that combines intelligent PV and digital technologies‡ aimed at maximizing the generation of electricity and its utilization, especially in the urban environment. Since photons and electrons are carriers of both energy and information, photovoltatronics offers to design and deliver autonomous devices for concurrent electricity generation and information communication. In this way, it introduces a pathway for generating bits of information (01) by utilizing the energy of photons ($h\nu$) through the energy of photo-generated electrons (eV). Photovoltatronics will deliver solutions for electricity generation and information communication in applications such as building environment, e-mobility, sensing, and domotics.

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† Agent: a component that takes an active role or produces a specified effect.
‡ Digital technologies are electronic tools, systems, devices and resources that generate, store or process data.

This aim is realized by combining different research areas, among others, (1) modelling and multi-layer mapping§ for maximizing energy harvesting from ambient energy sources at a particular location;[5,6] (2) design of PV-IEAs for delivering optimum electrical energy including reconfigurable electrical topologies of PV generators,[7] (passive) cooling elements,[8] electronics,[9,10] sensor systems,[11,12] and control;[13] (3) security and flexibility of electrical energy supply by integrated storage;[14,15] (4) wireless transmission of electricity through a novel design of PV module electrodes,[16–18] and (5) light-based communication (LiFi)[19] by integrating and controlling embedded light-generating elements such as light-emitting diodes (LEDs).[20]

To introduce, define and present the emerging field of photovoltatronics, the rest of this article is organized as follows. Section II introduces building blocks of photovoltatronics by reviewing accomplishments in the five selected areas of photovoltatronics and addressing their future challenges and developments. The mutual interconnections between the selected research areas that contribute to the multi-functionality of photovoltatronics devices are also discussed in Section II. Then, the limit for energy-to-information chain efficiency of photovoltatronics is calculated in Section III. We investigate the photovoltatronics stage-of-life in Section IV by statistically analyzing publication records in related research areas and knowledge-domain visualization. Finally, in Section V, the future prospect of photovoltatronics is summarized.

II. Research areas of photovoltatronics

Photovoltatronics contributes to both the energy transition by utilizing solar energy and the digitalization of the energy system. Novel PV-IEAs will be developed combing PV technology with photonics, micro- and power-electronics, sensors technology, energy storage, wireless communication, and computer science. Like all intelligent agents, PV-IEAs also need three main elements: sensors, "brain" and actuators. Sensors are necessary to measure and observe both environmental conditions and PV-IEA's internal state; given the current state and operating conditions of the PV-IEA, decisions on the next PV-IEA actions have to be taken. Such decisions must ensure optimal¶ overall operation of the PV-IEA rather than focus only on delivering maximum instantaneous electrical power. Therefore, control algorithms are needed to operate PV-IEAs together with a "brain" that is responsible for their execution. Such a "brain" can be embedded in the PV-IEA using devices such as microcontrollers or field-programmable gate arrays (FPGA). A central "brain" can be used *e.g.* a group of independent PV-IEAs or a group of coupled PV-IEAs extended with an external management and data storage unit. This latter approach requires an additional important element of PV-IEAs: communication. Finally, actuators are needed to execute and operate the decision. At present, PV generators fulfil only one function, namely electricity generation, therefore they usually have only electrical actuators such as power optimizers. PV-IEAs instead can be multi-functional, hence they can contain also non-electrical actuators, for instance, optical ones. These devices can have micrometer up to module-level scale. Thus, any research area that contributes to extend multi-functionality of PV-IEAs can be brought under the umbrella of photovoltatronics. Based on the recent research trends, we introduce and discuss the following five research areas that contribute to the field of photovoltatronics.

Research area 1. Modeling and multi-layer mapping for optimum energy harvesting from ambient energy sources

The general trend in the PV industry is to increase the conversion efficiency of solar cells, the peak power and lifetime of modules, and to reduce their production costs. All these improvements are aimed to lower the cost of solar electricity. More than 90% of commercial solar cells is based on crystalline silicon (c-Si) which has theoretical and practical conversion-efficiency limits of 33.16% and 29.43% (considering standard test condition), respectively.[21,22] The best fabricated c-Si solar cells have a conversion efficiency of almost 27%, so their performance is approaching the practical efficiency limit.[23] In addition to high performance, the cost of peak power (Wattpeak or Wp) of c-Si modules has significantly decreased in recent years.[24] Therefore, the PV community has started to pay more attention to the electrical energy yield of PV modules in real operating conditions rather than concentrating on increasing their efficiency. Modelling of the energy yield has become an important tool to evaluate different PV cell technologies[25,26] for delivering maximum electrical energy in a particular local urban environment. The PV-cell technologies are distinguished by a semiconductor material that is used as an absorber layer in a solar cell. In addition to c-Si, amorphous silicon, cadmium–telluride (CdTe), copper–indium–gallium–selenide (CIGS), and perovskite are examples of materials that are used as absorbers in solar cells. It is the knowledge of the energy yield of a particular PV-cell technology from available solar radiation that determines the design of PV-IEAs for a particular application. Nevertheless, the conversion efficiency of solar cells remains an important subject and challenge since it significantly contributes to lowering the cost of electricity. The trend in overcoming the limit of the conversion efficiency of single junction solar cells is to study and develop tandem solar cells where different absorber materials are used in component cells. The use of different absorber materials allows a better energy utilization of solar radiation. The theoretical limit of tandem solar cells comprised of two component cells is 45.71% and it increases when the number of component cells gets larger.[27,28] To come close to the theoretical limit of tandem cells, continuation of research on new absorber materials, tandem solar cell structures, and concepts for improved utilization of solar spectrum is of great importance.

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§ Multi-layer mapping refers to combining the output of parallel analyses from different science disciplines on a particular study case to eventually obtain visual 2D or 3D map(s) for decision making processes (see Fig. 1g, the example of traffic included solar road potential map).

¶ As extracting the maximum ambient energy might not always be cost-effective or safe (*e.g.* due to electrical grid stability and performance requirements, as well as aiming at increasing lifetime and reliability of the PV generator and the connected power electronics), the word optimal is preferred instead of maximal.

The spectral distribution of solar irradiance incident on a PV cell or module in a certain location is an important parameter that affects the energy-yield potential, both outdoor and indoor.[29,30] An accurate evaluation of the spectral distribution of solar irradiance is not trivial as it depends on daily and seasonal fluctuations,[31–35] haze and humidity,[36,37] and effect of shading.[38–40] However, the knowledge of the behaviour of these parameters and a possibility to predict it is crucial for evaluating the optimal energy yield of PV generators. Different maps, which present data related or translated from global irradiation based on a huge amount of measured statistical data, help PV designers to make a quick selection of suitable PV-cell technology for a particular location.[41,42] Recently introduced PV-cell technology selection map and PV-module sensitivity map[43] facilitate a choice of a PV generator.[44] Especially the PV-cell technology selection map, which includes a correlation between shading tolerability[45] and the temperature coefficient of different PV-cell technologies, is of particular value. It has been demonstrated *via* a location-based analysis that a single-junction solar cell absorber with a bandgap of 1.35 eV ensures optimal exploitation of the ambient energy, thus maximum energy yield in most regions of the world (see Fig. 1(b)).[46] Research activities on creating maps that present

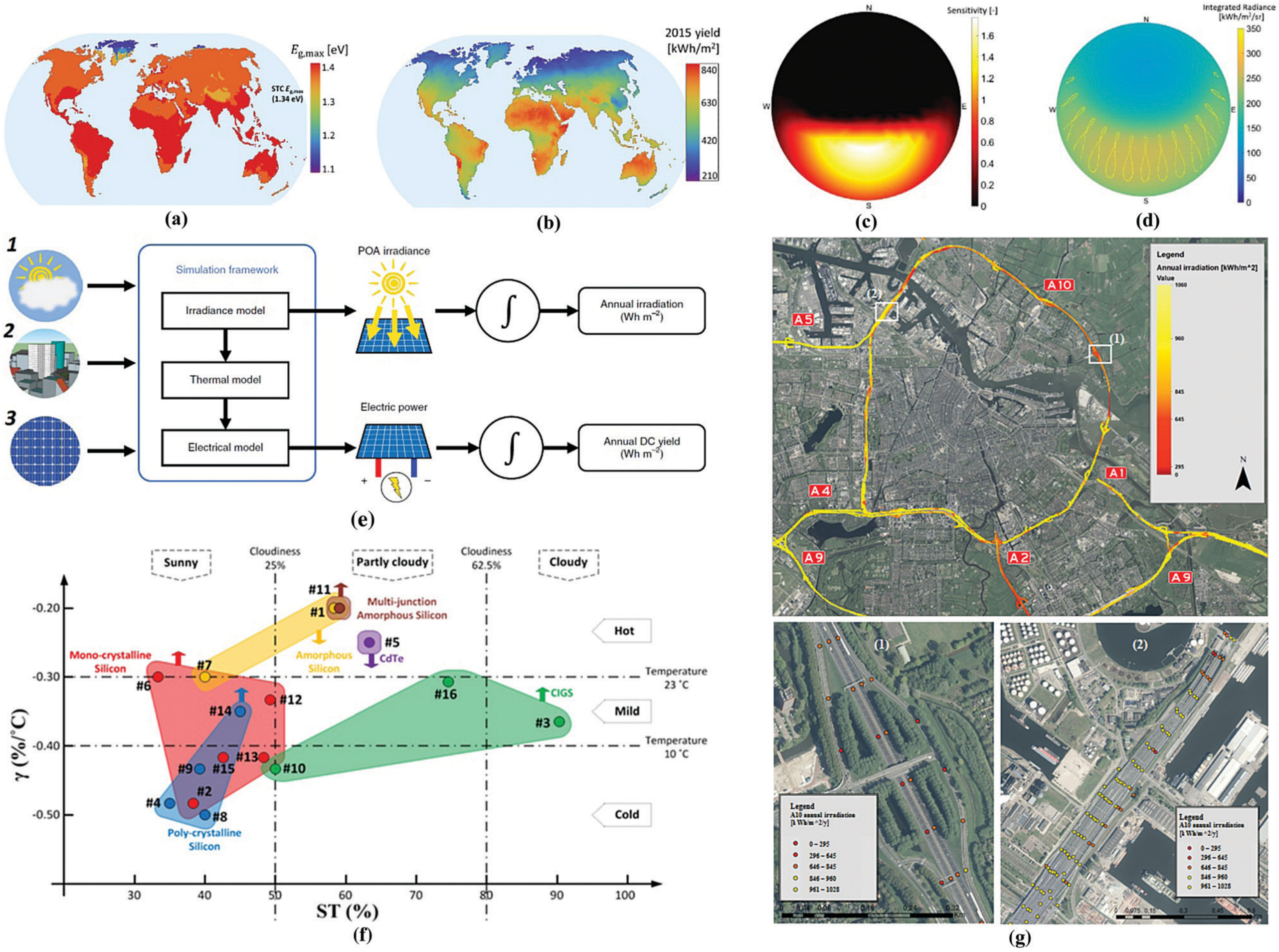

Fig. 1 Research concepts and examples for the research area 1. (a) The ideal absorber-bandgap map to achieve the maximum solar-cell efficiency on Earth.[46] (b) Map of energy yield for 2015 using PV-cell with the ideal band-gap absorber.[46] (c) Concepts of sensitivity map and (d) sky map introduced in ref. 43 for detailed and accurate energy yield calculations using ray-tracing simulations in complex and/or custom geometrical situations. In general, the integral $\int_{\text{sky}} \text{sensitivity map} \times \text{sky map} d\Omega$, where $d\Omega$ is the infinitesimal solid angle, results in the total irradiation on a surface. The maps were obtained from ref. 43 showing a case study performed for ZigZagSolar™ BIPV under the sky of Eindhoven, the Netherlands. (e) Sky-line based modelling approach proposed in ref. 60. This approach uses five fixed parameters for a climatological region and then calculates the PV annual energy yield using spatial 3D information. This approach is fast and well suited for quick or regional level PV energy yield modelling even in complex outdoor geometries. (f) Selection map for PV-module installation proposed in ref. 44 and 71. Inspired by the Ragone plot of energy storage devices,[72] the map uses the probability-based concept of shading tolerability (ST) and a PV module temperature coefficient (γ) of maximum power point (P_{mpp}) for a quick selection of the optimal PV-cell technology in a climatological region to achieve enhanced PV-system performance and energy yield. The numbers in the figure correspond to the serial number of the PV modules tested in ref. 44. (g) Example of multi-layer mapping mentioned in research area 1. The map shows the annual irradiation (layer 1) for highways around Amsterdam, the Netherlands, including the effect of traffic (layer 2). Sub-figure (1) and (2) show the zoomed areas to see more details of the map. Such multi-layer mapping can be quickly generated to cover the entire national roads network. Besides quantifying the PV-delivered energy potential of roads network surfaces, this map serves also as a guide for PV installation on sweet spots. The map was obtained from ref. 50.

solar-energy potential of roofs[47,48] and roads[49,50] demonstrate that PV community needs tools that assess the potential of surfaces to deliver electricity from incident solar energy. This is another way to accelerate a large-scale integration of PV in the urban areas for delivering clean energy.

In addition to the characteristics of incident light and the type of PV-cell technology, the geometrical morphology of the surroundings, in which a PV generator is (going to be) installed, is also important. To study the effect of surroundings on the light distribution on the PV module surface, several simulation tools were developed based-on either a view factor concept[51] or ray-tracing,[52] such as *MoBiDiG* from ISC Konstanz[53] and *bifacial_radiance* from National Renewable Energy Laboratory.[54] The surroundings further influence the spectral distribution of the time- and location-dependent solar irradiance. Researches demonstrated for bifacial and indoor PV that the impact of surroundings is even more pronounced on solar spectral distribution then daily, seasonal and/or weather impact.[55] Recently, it has been shown that the efficiency of bifacial PV cells[56] is bound to spectral albedo[57] and albedo itself is not only spectrally dependent but also dependent on the morphology of surrounding environment.[55] This means, even the geometry of the measurement equipment and, for indoor application, of the room might affect the bifacial cell efficiency. Therefore, a more detailed definition of bifacial PV-cell efficiency and the global map for bifacial PV-cell efficiency are needed. We expect that shortly, accurate and fast modelling of electricity yield from solar energy will play an increasingly important role to extract the theoretical and practical limits of the location-dependent energy yield for PV generators based on different cell technologies.[57–59] For this purpose, researchers have already started to explore simplified models,[60] software-based approaches,[61–65] artificial intelligence,[66] and big data monitoring.[67]

To assess a real neighborhood for the utilization potential of solar energy multi-layer mapping technique can be applied.[68–70] Maps with additional information such as a low-voltage distribution grid that must accommodate the locally generated PV electricity and/or the real-time power profiles of the loads are necessary. This multi-layer mapping technique can result in creating a digital twin of an energy system of neighborhood which can predict the output and utilization of real distributed PV generators, their impact on the grid, required maintenance of system components and serving as an input for electrical grid control strategy. Fig. 1 gives examples of research topics within the research area 1.

Research area 2. PV-based intelligent energy agents

To continuously deliver optimal useful energy for specific applications, PV generators have to be equipped with intelligence to adapt to changing operational conditions. The intelligence is added by integrating electronics and sensors with a PV generator.

There are two main approaches to increase the overall electrical energy yield of PV modules: (1) extending the operational lifetime of a PV module, and (2) increasing the yearly electricity production (W h per year Wp). To extend the operational lifetime of PV modules, the performance of the modules in real operational conditions must be fully understood, which requires collecting and analyzing field-performance data. The reported performance degradation and failures of modules are used to obtain a better understanding of degradation mechanisms and eventually develop aging models that can help the PV manufactures to boost the PV-module lifetime. The development of reliable aging models and understanding of degradation and failure mechanisms is not trivial since degradation and aging are dynamic and can be affected by internal (*e.g.* local defects and production tolerances) and external (*e.g.* partial shading and soiling) factors. However, different mechanisms have different fingerprints. It must be noted that, although all these mechanisms affect the electrical performance of the PV modules, it is often impossible to tell the type of degradation or failure solely based on electrical measurements, since different mechanisms can lead to similar electrical output. However, if electrical measurements are accompanied by thermal, optical and mechanical (*e.g.* strain and deformation) information, the degradation and failure mechanisms can be well understood and distinguished. For instance, encapsulant discoloration affecting a PV cell and a slightly broken cell have similar power losses, while the former is accompanied by a non-uniform irradiance distribution over the cells within the PV module and could be measured with optical sensors distributed over the PV module area.[73]

Setting up dedicated PV monitoring platforms and collection and analysis of field-performance data of PV modules can also accelerate the development of PV-IEA with extended lifetimes.[74] On the other hand, going beyond (and in parallel with) dedicated PV monitoring platforms, PV-IEAs with embedded sensors can start collecting data from real installations from the very first day. Thus, PV-IEAs themselves can accelerate the development of novel PV-IEAs with extended lifetimes. On this aspect, to enable large-scale manufacturing of PV-IEAs with embedded sensors, we expect that future research will focus on seamless integration of sensors onboard of PV modules, *e.g.* (i) through integration within the module laminate of thin-film transistors (TFTs) to be used as thermal sensors[75,76] and thin-film photodetectors (TFPs) to be used as optical sensors;[77] or (ii) integration within the module laminate of glass fibers (or other waveguides) with distributed Bragg reflectors, *e.g.* Fiber Bragg Grating (FBG) arrays, to be used as temperature and strain sensors;[78,79] or (iii) sensors can be integrated directly on the solar cell, *e.g.* the stress and temperature sensors presented in ref. 80. Both TFT and glass fiber technologies are relatively mature and widely used. Circuits for the control of TFT arrays and the interrogation of glass fibers are already available and could be directly used in PV-IEAs. However, whereas sensing through TFTs only relies on electrical signals and the needed control circuits can be straightforwardly integrated into the PV module's junction box, sensing through glass fibers requires an optical interrogator installed on the PV module. Optical interrogators are usually bulky and expensive; however, interrogators with smaller form factors start to appear on the market,[81] driven by the growing interest and wide range of application of fiber-optic sensing. Both solutions are promising for distributed sensing over the large area of a PV module: many sensing points can be integrated (by increasing the size of the TFT array or by having many FBGs in the same optic fiber under a single interrogator) and both TFT foil and glass fibers can be laminated behind the solar cells, therefore they will not affect the energy production. On the other hand, cell-level integration is an extremely novel approach. It has the clear advantage of precision, since the sensors are not separated from the cells by an encapsulation layer, and of full integration, since the sensor and the solar cell are realized on the same bulk material. However, it might affect the performance of the PV device if the area utilized for sensing cannot participate in the production of usable power. Also, additional wiring is necessary to connect the sensors to the PV-IEA's junction box, where the additional measurement circuit is installed. In the short-term, cell-level integration of sensors is a promising solution for research, *e.g.* for *in situ* measurements of temperature and strain during reliability tests of PV modules. Field application of this sensing approach will likely happen in the long-term. It is worth to highlight that, compared to the current approaches, in which thermal sensors are attached to PV modules and pyranometers or reference cells are used to evaluate irradiance at a given location, research in this sub-area of photovoltatronics is evolving towards lamination of sensors as a part of PV modules and integration of sensors on the solar cell itself, giving rise to more reliable and properly distributed data.

In addition to the extended lifetime of PV modules, there is a growing interest in increasing the electrical energy yield of modules in real operating conditions. The electricity yield depends on many external parameters that are beyond our influence, such as weather conditions at the location where the module is in operation. However, there are influences on the module level such as non-uniformities of temperature or illumination that can be tackled to increase the energy yield.[82]

An example is a dynamic shading of a PV module installed in an urban environment. Since several PV systems to be installed in cities will grow rapidly, the effect of dynamic shading from surrounding buildings and other objects on a maximum electricity delivery of a module has become a challenging issue. To solve this issue, researchers have started to introduce elements of intelligence in PV modules. Examples of innovations that make PV modules more shade-tolerant than standard use of bypass diodes are I-module,[83] TESSERA module,[84,85] reconfigurable PV module[86–88] or non-conventional geometrical design of PV modules.[89] The I-module is a concept developed by IMEC that utilize the integration of miniaturized chips at a solar cell level. The TESSERA concept developed by ECN is based on small solar cells (typical 1/16 of a standard 6″ cell), interconnected by a back-contacting foil that shows almost a linear power loss concerning the shaded area. Reconfigurable PV modules are mostly designed in two different ways. In the first case, a central control-circuit unit is integrated into the PV module junction box. In the second case, the power electronics circuit units (reconfiguration switches and local power converters) are distributed among the PV module surface, all controlled by a central control unit.[90]

The control unit adaptively changes the interconnections of solar cells in a PV module according to the partial shading. Switching of the interconnection of cells is controlled using an *ad hoc* routing scheme taking into account the least number of interconnections.[91] It is also worth mentioning that researchers have recently introduced a shadow-effect energy generator (SEG) that works based-on optical manipulation of the work function in metallic thin-film semiconductor structures. It is claimed that this technology can perform 200% better than a conventional PV cell during shading.[92] Such an intelligent PV module can be further equipped with other functionalities to transform it into a PV-IEA, which can eventually enable a higher electricity yield with less chance of failure and higher reliability.[93] These additional functionalities can be, for example, cell-level health monitoring[94] and fault resiliency[95] or anti-theft protection.[96] To suppress degradation, detect unwanted operating conditions, and avoid failures, multi-aspect sensing (optical, thermal, electrical) can be integrated into a PV module. This helps to closely observe the actual internal and external states of the PV module, further distinguish fault figure prints, and take proper counteractions.[97,98] Compared to the current state of the art solutions in which complex models and/or computational demanding algorithms are used to overcome the lack of information, PV-IEAs with integrated sensors will inform about the current status instead of predicting it. Therefore, local control and diagnosis will be much more reliable. This information is shared with other modules or a system management unit, also novel system-level control algorithms are expected to be designed in the future leveraging on the newly available information, distributed and real-time.

Another means to increase both the lifetime and energy yield of PV modules is to keep the operating temperature low and uniform over the module area. This goal can be achieved by using passive or active cooling elements.[82,99,100] Active cooling approaches and combining PV with thermal systems (PV/T) bring in additional complexity and energy consumption[101,102] whereas passive cooling approaches such as adding heatsink to the rear side of the PV module,[100,103] the use of phase-change materials (PCM), and optical filters are found to be promising.[93,104,105] In 1977, a PCM was suggested as potential thermal storage when integrated with a PV module[106] and patented in 1983.[107] However, it was not investigated as a means of cooling of PV modules until the 1990s. PCMs absorb thermal energy as latent heat at a phase-change temperature. A choice of a suitable phase-change temperature can be used to regulate the temperature of a PV module.[108] Depending on an average temperature at a location of a PV module operation, the benefit of using the PCM to control the temperature of a standalone PV module can vary significantly around the globe. To optimize the use of the PCM for cooling PV modules in various applications, *e.g.* building-integrated PV systems (BIPV), all additional parameters influencing the operating temperature should be taken into account, such as the thickness of the PCM and light spectrum variations. One bottleneck for PCMs is that they cannot be applied to bifacial PV modules, unlike the optical filter. Optical filters are multilayer stacks of thin optical layers, which can prevent a PV module from heating up by rejecting wavelengths in a specific range of the incident irradiance. Such optical filters can also be engineered to reflect wavelengths in the visible part of the spectrum to produce colored PV cells.[105,109,110] Solar cells can also be engineered for radiative self-cooling. In the case of silicon absorber, the temperature can ideally be reduced by up to 18.3 K passively through radiative cooling (at the ambient temperature of 300 K and the irradiation of 800 W m^{-2}).[111] However, for terrestrial commercial solar cells, researchers have opposed this high-temperature reduction (by radiative cooling techniques) and limit the reduction to only 1.75 K. They consider that bare silicon absorber has relatively low emissivity in mid-infrared (>4 μm). Their results deviate from reality when one considers a complete silicon solar cell.[112] These studies show that PV researchers can shift their focus to other options of cooling, *e.g.* towards passive cooling techniques relying more on convection rather than radiative cooling.

In summary, we expect that with increasing implementation of PV technology in the urban environment, PV modules and systems will become intelligent to utilize the energy of incident irradiance for delivering maximal electrical energy. The design of PV cells, modules and systems will include sensors, electronics, and cooling elements for shade-resilient and durable PV modules. The intelligent PV cells and modules will enable faster integration of PV on different levels of electricity distribution network, such as households and neighborhood microgrids.[113] We consider all approaches that transform a PV module from a power-delivering component into a PV-based intelligent energy agent (PV-IEA) to be part of the photovoltatronics research area. A PV-IEA can diagnose its working condition such as partial shading and temperature variations, adapt and improve its own working current–voltage characteristic. It should be noted that optimizers and inverters are not categorized in this research area, as they are sheer power electronic-based approaches.[114,115] As stated in ref. 71, pure power electronic approaches can only extract the best out of a *J–V* curve of a module without having any chance to change it. However, it does not mean that research on power electronics' components which enables novel functionalities for the PV modules, such as the wireless transmission of energy (see Section II.4), does not contribute to photovoltatronics. Fig. 2 represents examples of research topics within the research area 2.

Research area 3. Stabilizing energy output by integrating storage within a PV module

In an AC-based electrical grid, the classical swing equation[117] dictates that at every moment the produced- and consumed apparent power must be equal to maintain the desired level of rotor angle, frequency, and voltage in synchronous machines constituting the power system. In nowadays electrical grids, which are rather rigid and sustained by large thermal power plans burning fossil fuels, this can happen through adequate Watt and Var control techniques.[118–121] However, when the grid will be dominated by renewable energy generators, such as PV plants instead of synchronous generators and rotating machinery, a lack of inertia will become an issue.[122] Besides, when instead of controllable valves in power plants and switches in distribution lines, the Sun and the local weather take over, their intermittency becomes another issue.

The large-scale utilization of renewable energy sources for electricity generation has a significant impact on the existing electrical grid. The main issues that have an impact on the stability of a grid with high PV penetration are (1) lack of inertia and (2) fluctuations in electricity generation. Despite the robustness of existing conventional grids, inertia will change from one section of the grid to another in a PV-dominated grid and it will also change by time (on hourly or daily bases).[123] This lack of inertia can be handled with synchronous condensers[124] and techniques such as droop control and virtual/synthetic inertia algorithms applied to storage-inverters units.[125] However, fluctuations in electricity supply would remain still a problem until very fast and highly reliable solar irradiation forecast methods are developed. Due to the inherently complex nature of local weather, it will probably remain difficult and uncertain to have very accurate and fast weather prediction methods. In such a situation, storage is a solution to support the grid by filling the gap (or the shift) between solar-power delivery and power consumption. Therefore, solar energy forecast and energy storage have to be considered concurrently (research areas 1 and 3 are logically linked) and development of affordable storage technologies are crucial for the energy transition in the electricity sector.‖[126,127]

As mentioned above, the inclusion of storage in the electricity grid facilitates the large-scale integration of grid-connected PV generators and PV-IEAs. However, in islanded and autonomous applications, storage becomes a necessity. For instance, medical and rescue equipment, which uses power from PV-installation, can operate safely if it is backed with storage that guarantees a secure energy supply. There are many approaches for storage that is not an internal part of a PV module, such as lead-acid batteries, pumped hydro storage, and Sun in the box among others.[128–130] It has recently been shown that the thermodynamic limit of a solar to fuel energy conversion for a generalized photovoltaic–electrochemical system (under 1 sun illumination** and albedo = 0) is 52.09%.[131] However, any cheap, efficient, and environmentally friendly storage that could be integrated into a PV module will have several advantages: (1) higher volumetric and gravimetric energy density devices because of less wiring and sharing of common encapsulation or electrodes, (2) quicker and cheaper manufacturing as a result of fewer materials and energy consumption in comparison to fabricating individual components separately, (3) possibility of having self-sustaining

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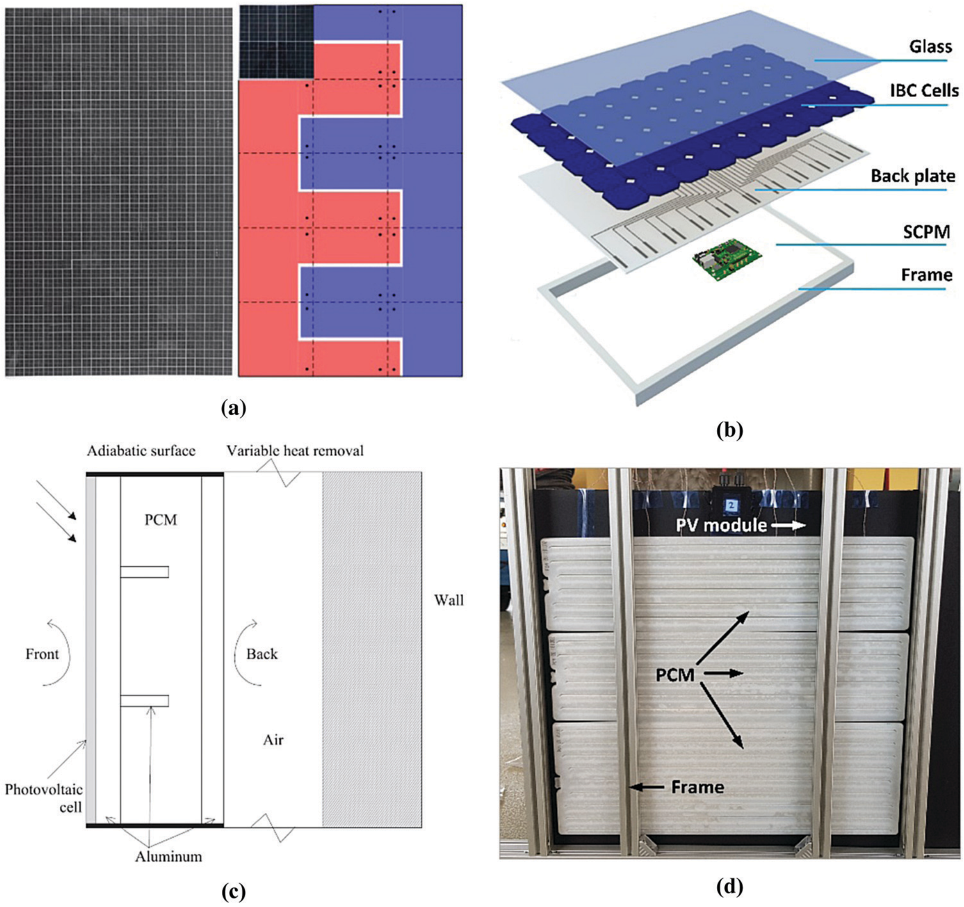
‖ There are also other concerns with high penetration of PV in grid such as power system protection, voltage fluctuations, unintentional islanding, harmonic distortions, reverse power flow, black start, which can be all handled by intelligent control algorithms implemented in inverters.

** Irradiation of 1000 W m^{-2}, cell temperature of 25 °C, air mass ratio of 1.5.



(a) (b) (c) (d)

Fig. 2 Research concepts and examples for the research area 2. (a) In the TESSERA module concept, each Metal Wrap Through (MWT) c-Si cell is cut into 16 smaller pieces to reduce the current and increase the voltage and achieving linear shading response. As the cut space between the small pieces is 1 mm, the TESSERA concept loses 3.84% of the active area for a 16-inch MWT cell. On the other hand, the novelty of TESSERA relies on the fact that shading is an area-based phenomenon but bypassing at shading is a string-based approach. The left and right figures show the front view of the TESSERA PV module and its conductive-back sheet interconnection design (different colors show different polarities), respectively. The figure is obtained from ref. 85. (b) The concept of smart cell-level power-managed (SCPM) PV module. The SCMP concept, inspired by random access memory and matrix converter theory, treats shadow with spatial granularity and electrical dynamics at the cell level. Equipped with sensors and electronic switches, SCPM detects the shading condition and re-arranges PV-cells interconnection to obtain the maximum output power.[91] (c) Schematic of a PV module endowed at the rear side with a phase-changing material (PCM) pad (PV-PCM system) installed on a building façade. The figure with slight modifications was obtained from ref. 93. (d) PV-PCM ready to be tested. The PCM is attached to the rear side of an IBC-based PV module using thermally conductive paste. The aluminum frame ensures mechanical stability. PV panel is passively cooled and solar cell energy conversion efficiency is enhanced.[116]

devices for portable solutions where no external power sources are needed, and (4) user-friendly devices that are easier to be installed.[132] A challenge of having storage as an internal part of a module is the thermal management because physical integration of storage leads to a higher temperature with a non-uniform temperature profile within the module.[133] Also, the power electronics used to optimize the operating point (MPPT) of PV generators and manage the battery system will operate at a higher temperature. The higher operating temperatures affect both the performance and reliability of PV-battery integrated systems: on the one hand, PV cells will produce less energy; on the other hand, power converter lifetime may be reduced, and its performance may degrade. Therefore, the overall effect of higher operating temperatures must be studied in more details, and the optimum placement of all components must be found, to reduce the operating temperature of all system components and increase their performance and lifetime. Also, the combination of storage and cooling techniques (as the ones shown in research area 2) may help in reducing the overall operating temperature, therefore further research is needed that combines energy storage with both active and passive cooling approaches. System sizing also represents a challenge in PV-battery integrated systems. On the one hand, batteries are the most expensive component, therefore it would be preferable to minimize the amount of storage. However, this clashes with the continuous (day and night) need for energy in islanded and autonomous systems. Also, battery sizing has direct consequences on battery cycling (number of cycles, depth and rate of charge/discharge), thus on battery lifetime. Therefore, further research is needed to develop a methodology for proper sizing of integrated PV-storage solutions. Two approaches should be followed: on the one hand, general-purpose solutions must be studied, since this would enable large-scale implementation; on the other hand, methodologies for application-specific sizing are needed, to find optimality related to the application requirements (*e.g.* ensure a certain minimum operating time of medical and rescue equipment independently of the availability of solar source). Finally, safety must be ensured. Nowadays, Li-ion batteries made of liquid electrolytes represent the most used technology. Battery failures leading to explosion or malfunction have been reported, often due to leakage of the liquid electrolytes subject to intensive operation. It is of utmost importance to prevent this from happening. Here, technological development will help, as recent research aims at developing the so-called solid-state batteries, that replace the liquid electrolyte with a solid electrolyte. Their overall performance is still worse than the current Li-ion batteries, but research will improve solid-state batteries performance and durability, as well as their volumetric and gravimetric energy densities.[134]

Approaches combining energy harvesting and storage, which are effective ways to obtain compact and reliable energy systems, are reviewed in ref. 135. Integration of electricity storage at the PV module level has less than two decades of history and the number of researches in this area is rapidly growing (all were reviewed in ref. 132). It has been demonstrated that batteries and supercapacitors can be integrated into PV modules in different configurations such as planar, in-plane, parallel, one-device, fiber, and coaxial for both low-power and high-power applications.[132] Commercial portable solutions that fully integrate photovoltaic, storage, and energy management units in one package has also been developed.[136] Since the utilization of PV technology is spreading from outdoor to doorsteps/indoor applications, we expect that in all applications the PV module-storage integration will play an important role soon. However, to enable large-scale integration of storage in PV modules, the abovementioned challenges must be still overcome. Fig. 3 shows examples of research topics within the research area 3.

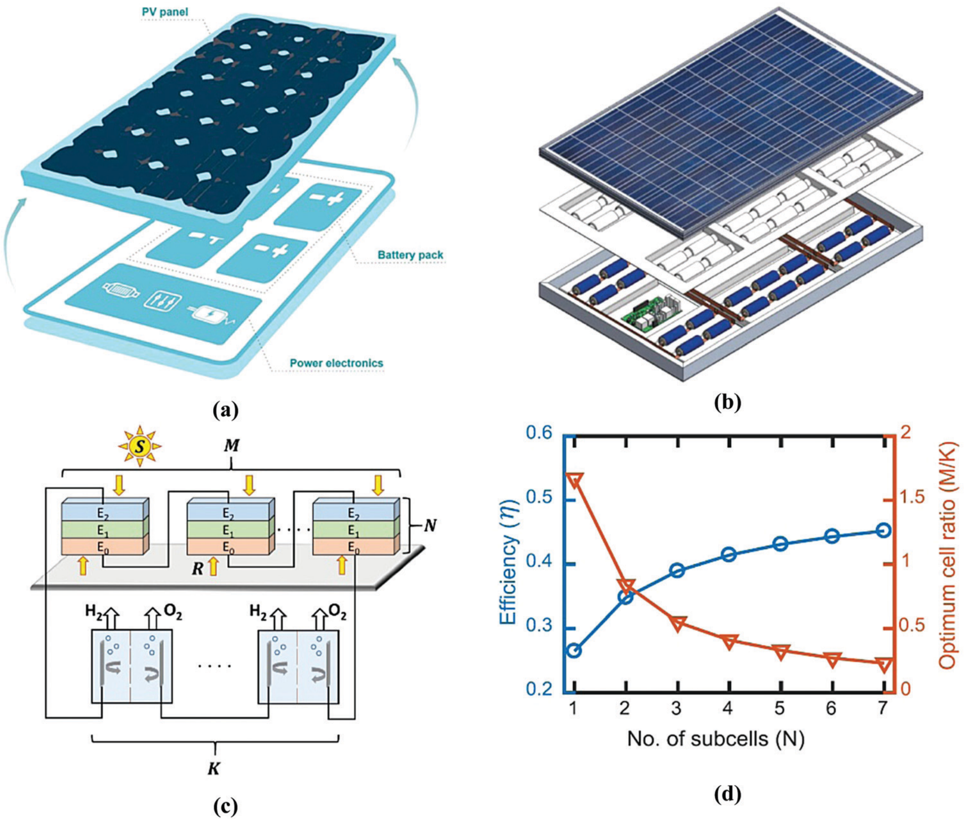


Fig. 3 Research concepts and examples for the research area 3. (a) An abstract representation of the battery-integrated PV module. The figure was obtained from ref. 133. (b) Completely integrated supercapacitor array with a PV module. The supercapacitor array is placed at the back of the PV module as well as the two-stage DC/DC converter (buck-boost + fly-back) to step up the PV module output of 30 V to 400 V. This solution is prototyped for micro-grids application and operates in four states: charge, discharge, standby, and float. Maximum efficiency of 92.5% was reported for a PV module with a nominal power of ~160 W. The figure was obtained from ref. 148. (c) Schematic configuration of the integrated PV module based on tandem solar cells into electrochemical cells. The terms S, R, M, N, and K are the sunlight intensity, ground albedo, series-connected cells in the PV module, number of sub-cells in a multi-junction tandem solar cell, and the number of series-connected electrochemical cells, respectively. These parameters were used in ref. 131 to optimize the best PV-EC cell configuration and finding the efficiency limit for that. The figure was obtained from ref. 131. (d) The thermodynamic efficiency limit of PV-EC system for the configuration shown in Fig. 3(c), concerning M, K, and N while $S = 1$ and $R = 0$ (1 sun condition). For large values of N and optimum M/K ratio, the efficiency limit converges to 52.09%. The graph was adapted from ref. 131.

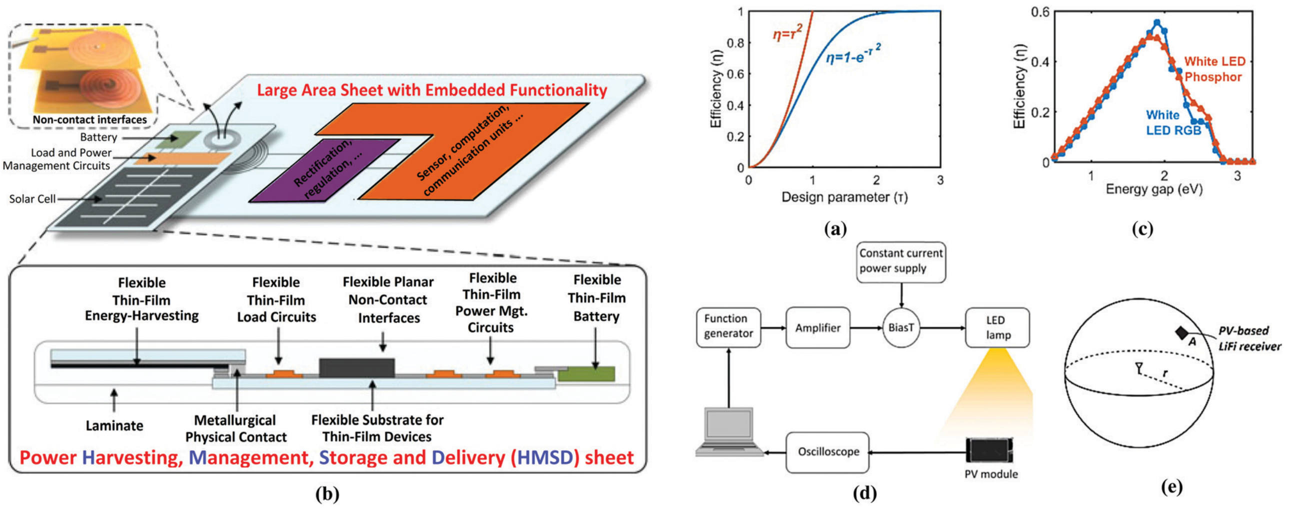


Fig. 4 Research concepts and examples for the research areas 4 and 5. (a) Wireless efficiency in the near field (blue curve) and far-field (red curve) as a function of the design parameter τ. As stated in ref. 141, for $\tau > 2$ energy transfer efficiency can be considered almost 100% for WPT systems. (b) System concept and physical assembly of the HMSD sheet system for wireless power delivery to large-area sheets with embedded functionalities. Interfacing to large-area sheets is achieved by placing the HMSD sheet onto a power-receiving surface without the need for complex metallic connections. The power delivery by the HMSD concept is not constrained by the physical form factor of the large-area sheet. The HMSD sheet also comprises subsystems for the management of flexible thin-film lithium-ion batteries. The figure was obtained from ref. 153. (c) Energy gap E_g and semi-empirical efficiency of an ideal indoor PV detector for the spectral photon flow of an RGB white LED and phosphor white LED. Digitized data from ref. 58 were used to produce the graphs. Indoor PV efficiency gains more importance when considering PV cells as receivers for artificial light energy and information modulated on that (see Section II.5). (d) Diagram of the experimental test setup developed in ref. 163 to assess two commercial PV-based LiFi receivers: CIGS mini-module of DisaSolar and amorphous silicon mini-module of SunPartner Technologies. The figure was obtained from ref. 163 with slight modifications. (e) Spherical distribution of PV-based LiFi receivers as an ideal case for energy efficiency calculation of a wireless communication system. For a PV-based LiFi size of A distributed over a sphere of radius r, the total number of $4\pi r^2/A$ PV-based LiFi detectors are required. The figure was obtained from ref. 164 with slight modifications.

Research area 4. Wireless transmission of electricity through novel electrode design of PV modules

One of the advantages of PV technology is that it can generate electricity at a place of its consumption. Not only the losses related to electricity transmission can be avoided, but huge amounts of materials for transmission cables can be saved. An additional saving on energy could be a wireless power transmission of electricity directly from a PV generator. Wireless power transmission (WPT) was the dream of Nicola Tesla.[137,138] As WPT has the advantages of safety, simplicity and high efficiency at short distances, it has attracted scientists' since the 1960s and is gaining increased attention in recent years.[139–141] WPT has a wide range of applications from near-field (*e.g.* smartphone charging pads[142] and e-bike wireless charging[143]) to far-field (*e.g.* satellite solar power station[144–147]) power transmission. The beam efficiency of a WPT system can theoretically be almost 100%.††[141] WPT can do for energy the same as it did for information: from using wires (telegraphy) to wireless transmission (internet era).

The transmission efficiency of WPT decreases with the distance between the sender and the receiver. Therefore, the closer the sender and the receiver, the highest the transmission efficiency. As explained in the previous sections, PV-IEAs combine different components (*e.g.* PV cells and batteries) in one device. The PV cells and the other components (*e.g.* integrated storage discussed in research area 3), will be placed close to each other so that WPT becomes an interesting option for their electrical connection in comparison to direct ''wired'' electrical connection (logical links between research areas 1 and 4).[149] The main challenges for the conventional interconnection of PV cells within a PV module are series resistance, shadowing losses, and thermomechanical stress in the solar cells.[150] The overall effect of conventional interconnection can be quantified in 2.27–2.76% relative cell-to-module efficiency losses for conventional modules.[151,152] Reduction of cell-to-module efficiency losses can be obtained by implementing novel WPT within the module. However, WPT requires alternating current (AC) while PV units deliver direct current (DC). Thus, DC/AC conversion within the PV module or at cells' level is required to be able to transfer power wirelessly. The need of integrating power conversion at the module or cell level paves the way towards a novel approach that combines the step of maximum power point tracking (MPPT) with WPT: MPPT can be performed at the same level of WPT implementation. For instance, if WPT is implemented per cell, also MPPT can be deployed per cell. Then the feasibility of the WPT at PV module or cells' level might increase. This inherently means that the power conditioning stage must become a part of a PV module, establishing a link between this research area and research area 2. The power harvesting management, storage and delivery

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†† This statement is true if the design parameter of τ (which depends on the transmitter and receiver sizes, distance between them, and the wavelength) is greater than 2, see Fig. 4a.

(HMSD) system introduced in ref. 153 (see Fig. 4(b)) and the wireless power transfer for the lunar rover,[154] are a good example of activities in this research area. Use of WPT in PV-IEAs will likely start by integrating DC/AC conversion and a planar PCB coil into the PV-IEA junction box. Here, a question may arise about the size of this power conversion stage compared to current module-level solutions such as power optimizers and microinverters. The actual peak power of a PV module is in the range 300–500 W. An example of WPT system that can process up to 500 W in shown in ref. 155 where a planar PCB coil with a diameter of 20 cm is used. For comparison, the Enphase IQ 6+ microinverter (peak output power of 290 VA) has 21.9 cm width and 19.1 cm height.[156] Therefore, integration of WPT at module level has the potential to be at most as bulky as nowadays microinverters. When it comes to cell-level integration instead, innovative architectures could be designed for the solar cell (or part of it) to act as primary coil of an inductive WPT system or primary plate of a capacitive WPT system.[157]

Integration of WPT in PV modules is advantageous not only at the module level but also at the system level. The most straightforward example is related to PV systems installed in the urban environment. The complex urban fabric leads to non-uniform PV energy yield maps as discussed in research area 1. In such a condition, standard PV module interconnection suffers from significant mismatch losses due to non-uniform irradiation of the series-connected PV modules' forming a PV string. It is worth to note that mismatch can be responsible for up to 10–12% power loss in conventional string connection.‡‡[158,159] If every PV module can transfer its produced power to a shared energy exchange hub, it will be not necessary to create strings of series-connected PV modules. Therefore, mismatch losses will be removed. Also, WPT could be used at sub-module level, *i.e.* for small groups of cells. The lower power and voltage levels could reduce the size of each WPT converter and leverage the benefits of higher granularity of power processing which brings on a better performance under non-uniform operating conditions (WPT-based shade-tolerant PV module, linked also to research area 2). Furthermore, the energy exchange hub can be designed so that the rather low voltage generated by the PV modules is automatically boosted to reach the voltage level needed into the building, *e.g.* by implementing a high turn ratio between the secondary coil (energy exchange hub) and the primary coil (PV module). Besides that, WPT is more durable for outdoor working conditions as all the coils and components are enclosed, whereas cables are exposed to outdoor circumstances for a long time. Moreover, in another architecture, PV cells can be placed at the energy exchange hub and work as the receiver of the wirelessly transmitted optical energy in form of laser beams.[160,161] Therefore, from module-level upward, we expect that another novel research topic falling under research area 4 is the wireless transmission of electricity from PV modules to an energy exchange hub. The possibilities of the medium-field wireless transmission of electrical energy generated by a PV module can be investigated and facilitated by a novel design of PV-module electrodes. Such electrodes can be engineered to provide high directionality or even to beam the electrical energy omnidirectionally (in a strongly coupled regime of operation[162]). The trade-off between aesthetics, performance, and modularity will need to be considered.

Research area 5. Integration and control of light-generating elements for light communication, lighting, and infotainment

To endow a PV-IEA with intelligence, the agent must be able to handle information, or in other words, receive and process data or to send it. Data can be transferred using different carriers. We expect that soon, the light will not only play a role as a carrier of light energy but also of information. A digital technology called light fidelity (LiFi) is emerging for wireless communication between devices that utilizes light for transmitting data using light-emitting diodes (LEDs).[19] It has been shown experimentally that the wall-plug efficiency (WPE) of LEDs can be higher than unity caused by the combination of electrical work and the Peltier heat originating in the device lattice.[165] Further, a theoretical study showed that for the visible and infrared ultra-low-power LEDs the WPE can reach up to 130% and even 250%.[166] On the other hand, LiFi offers higher speed in comparison to radio wave communication protocols because of wider bandwidth.§§[164,167,168] These two facts (high WPE of LEDs and high speed of LiFi), alongside with continuously increasing flow of information flow,¶¶[169] make shortly LED-based LiFi technology a promising solution for wireless communication.

The role of PV cell or PV module in supporting the LiFi technology is two-fold. These PV components of the PV-IEAs can be not only a power source for the LiFi devices but they can also work as receivers.‖‖[58,170,171] or even transceiver of the bits of information. LiFi can be used both indoor and outdoor.[172] In both cases, but especially outdoor where they outperform photodiode receivers,[173] PV-based receivers could be the solution. Research has shown that conventional PV cell technologies can be used as a receiver in LiFi transmission infrastructures. However, better LiFi performance and higher data rates can be achieved with the adaption of solar cell technology. For instance, it has been possible to achieve a data transfer of 56 Mbps by using a triple-cation perovskite solar cells optimized for visual light communication with a custom active layer thickness.[174] However, design requirements for better

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‡‡ This value is severely case-dependent and increases by PV module aging and geometrical complexity of the surrounding.

§§ Infrared and visible light spectrum together is approximately 2600 times the size of the entire radio frequency spectrum of 300 GHz. A record of 7.91 Gb per s data transmission rate was reported. The ultimate energy efficiency (EE) of a wireless communication multiple antenna system is 0.6 Pbit per Joule including circuit power and Landauer's limit.

¶¶ Compound annual growth rate of wireless traffic has been 60% during the last 10 years. The traffic follows Cooper's law, doubled every two-and-a-half-year.

‖‖ Due to higher resilience to saturation effect compared to classical photodiode-based detectors, maximum semi-empirical indoor efficiencies of a single-junction solar cell (as a light receiver) of phosphorous white and RGB white LEDs are 47.70% and 58.40%, respectively.

performance as a receiver (higher bandwidth) may clash with design requirement for higher efficiency (increased power production). Future research should focus on the design of the solar cell that balances these two aspects. In addition to the very recent photovoltaic LiFi communication solutions introduced in the literature,[163,175] photovoltatronics will investigate the integration of LEDs and their control as a part of PV-IEA. In this way, wireless communication can become an additional functionality of a multi-functional PV-IEA. With the advent of high-efficiency III–V/c-Si tandem devices,[176,177] the III–V-based top cell could be driven by an external circuit to emit light beams at certain frequencies compatible with LiFi communication protocol(s). In parallel to the development of novel emitters and receivers and their integration in PV-IEAs, it is necessary to develop novel electronic circuits able to separate information from power and simultaneously perform MPPT. Examples of circuits able to separate information from power, namely high-frequency signal from DC (or slowly-varying) power can be already found in the literature.[178] However, the major focus nowadays is purely on self-powering the LiFi device. Future research will focus on integrating self-powering with MPPT. On the one hand, the electronic circuits of future LiFi PV-IEAs will be able to separate information from power and power up the LEDs and the connected electronic circuit(s) using the energy harvested from the PV module (namely the DC component discussed above). On the other hand, such circuits will also be able to make the PV-IEA itself work at its maximum power point so that the energy not used to power up the PV-IEA internal electronics can be used by external circuits (as in conventional PV systems) or stored in (integrated) batteries. We expect that a compact PV-based device can be built, realizing electricity generation and LiFi beaconing for several applications such as IoT, automotive and infotainment. In this way, PV-IEA will act as key autonomous components for both energy and information flows in the future.

Researchers have started to look into indoor light recycling options, considering optimum receiver materials[29,179] and light source positioning.[180] If the available surfaces in urban areas are optimally used, the incoming outdoor light can also be recycled using PV cells and LEDs (or other artificial light sources). The sunlight is converted into electricity by PV cells and the electricity is converted to photons by LEDs for both energy and/or information needs. These photons can be then re-captured by other PV cells and converted to electricity for further use. In this scenario, PV cells and LEDs can be combined within one device (as both have similar essence) to capture and emit light. We expect that a new research topic will start in the future focusing on maximum light recycling in urban areas by optimum geometrical placement and technological design of LEDs and PV cells.

Next to light communication, integration of LEDs within PV-IEAs offers additional functionalities. Future urban environment will make effective use of solar energy. Most building facades will be endowed with PV generators. In our vision, most of these generators will be PV-IEAs. It means that facades will be multifunctional: on the one hand, they will provide the building with electrical power; on the other hand, they will serve as media facades to share visual information using the integrated LEDs. Visual information available on the building facades will serve the whole population. Compared to the present situation, where media facades are mostly used by companies for advertising purposes, we foresee that PV-IEAs facades will be used to share information with a high societal value and impact: population can be for instance informed in real-time about among others quality of air, interruption/problems with public transport. The messages can be of different types delivering invaluable impact and benefit. It is worth to note that, thanks to PV-IEAs, there will be no need of choosing if a façade must be used to produce energy or to act as an information medium since it can be both at the same time. Fig. 4(c–e) represent examples of research topics within this research area.

III. Photovoltatronics energy-information efficiency chain

In the future, every surface in urban areas can play an important role in providing useful energy from solar radiation to urban dwellers. Not only use energy but also the flow of information can potentially be powered by solar radiation as illustrated in Fig. 5. It is interesting to determine how much light energy is needed for transferring/receiving one bit of information. One possible design of such energy-information chain is visualized in Fig. 6, which combines and utilizes approaches of the five reported photovoltatronics research areas. In this chain, solar energy is converted into electrical energy in a photovoltaic system, electrical energy is transferred to an energy hub, and then it is used to light up an LED for a transfer of both radiation energy and/or information, which is received by a PV-based detector. Within this chain, it is interesting to know the ultimate energy efficiency. We can consider two chains in Fig. 6: photons-to-electrons and photons-to-bits that are bound respectively to $\eta_{h\nu\to e}$ (efficiency with no unit) and $\mathrm{EE}_{h\nu\to 01}$ (energy efficiency with the unit of bit per Joule). Photons-to-electrons chain consists of four series conversion and transmission links and the overall efficiency can be written as:

$$\eta_{h\nu\to e} = \eta_{\mathrm{PV}}\cdot\eta_{\mathrm{WPT}}\cdot\eta_{\mathrm{WPE}}\cdot\eta_{\mathrm{IPV}}, \tag{1}$$

where $\eta_{h\nu\to e}$ is the photovoltatronics efficiency. η_{PV}, η_{WPT}, η_{WPE}, and η_{IPV}, are photovoltaic system efficiency, wireless power transfer efficiency, LED irreversible thermodynamic wall-plug efficiency, and indoor PV efficiency for white LED lighting (no unit), respectively. $\eta_{h\nu\to e}$ is maximized when the combination of all four links maximizes. The detailed derivation of the η_{PV} and η_{IPV} are done using the detailed balance method described in ref. 21 considering respectively AM1.5 and LED lighting as input light sources. η_{WPT} is obtained using the formulation described in ref. 141. η_{WPE} is obtained based on irreversible thermodynamic analysis of wall-plug efficiency for LEDs described in ref. 166.

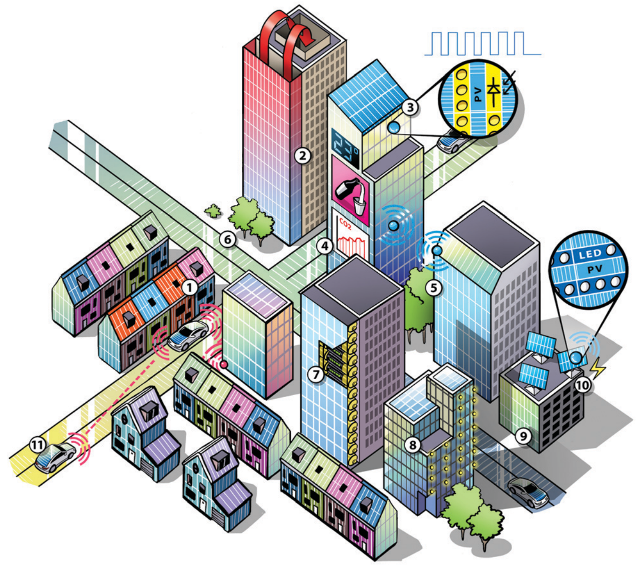


Fig. 5 A possible embodiment of various photovoltatronics-related concepts integrated into an urban area: (1) colored PV cells with a selective optical filter for passive cooling; (2) concept of PV-chimney integrated into a natural ventilated façade, to use the inherent cavity as a ventilation channel to transfer heat;[182] (3) optimally placed PV module as electricity producer and LiFi signal receiver (merely PV cell); (4) LED powered by clean electricity, working for outdoor lighting and data sharing (merely LED unit); (5) a PV device that can produce electricity, wirelessly transform it, and also send/receive data signals (PV-LED cell); (6) solar road;[49] (7) storage-integrated PV modules installed on a façade; (8) semi-transparent PV cells covering a building for energy harvesting and indoor light management; (9) smart PV modules with high shading tolerability incorporated with sensing electronics for urban monitoring; (10) building added PV modules with wireless power transfer and data sharing capabilities. (11) Solar-powered vehicles with embedded PV-IEA communicating *via* LiFi between each other as well as "with the city". As discussed in the article, all mentioned examples within this figure are currently experiencing different technology readiness levels.

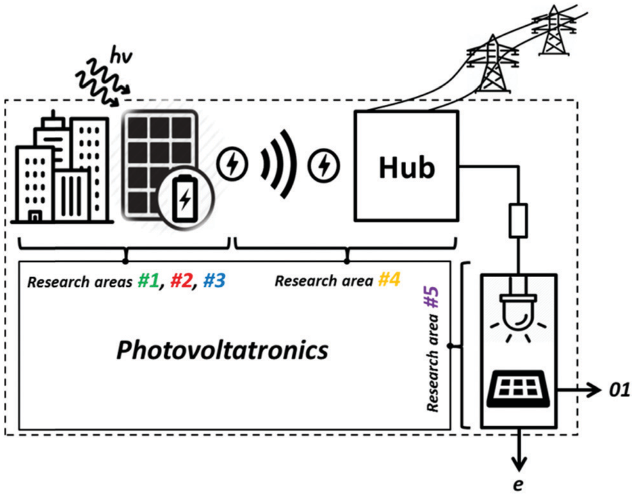


Fig. 6 A typical visual representation of photovoltatronics main energy-information chain, including the five reported research areas. It graphically shows, how PV modules integrated into urban areas and equipped with integrated storage and electronics send energy wirelessly to an energy exchange hub, and how the energy flow continues to provide power for LEDs to send out information-based radiation modulated on visible light to be detected by a PV cell.

The light produced by the LED can also serve as a carrier electromagnetic wave to transfer information, forming a communication system between the LED sender and the PV cell receiver. The energy efficiency of this communication system can be found by:

$$\mathrm{EE}_{h\nu\to 01} = \frac{B\log_2\left(1+\dfrac{P_{\mathrm{Sun}}A_{\mathrm{PV}}\eta_{h\nu\to \mathrm{e}}\beta}{BN_{\mathrm{O}}}\right)}{P_{\mathrm{Sun}}A_{\mathrm{PV}}\eta_{h\nu\to \mathrm{e}} + c_1 B + c_2 B\log_2\left(1+\dfrac{P_{\mathrm{Sun}}A_{\mathrm{PV}}\eta_{h\nu\to \mathrm{e}}\beta}{BN_{\mathrm{O}}}\right)}, \tag{2}$$

where B is the communication bandwidth (Hz), P_{Sun} is the input sunlight intensity to the photovoltatronics chain (W m^{-2}), A_{PV} is the area of the PV device which receives power from the sunlight (m^2), β is the communication channel gain (no unit or dB), N_{O} is the noise density (W Hz^{-1}). As the transmitted power decreases and bandwidth increases, the energy efficiency of the communication system increases. However, a communication system with zero transmitted power is useless. Therefore, c_1 (in Joules) and c_2 (in Joules per bit) were introduced to the equation, which respectively represents the associated energy consumptions for analog-to-digital/digital-to-analog and encoding/decoding processes. Using the approach described in ref. 164, it can be shown that $\mathrm{EE}_{h\nu\to 01}$ is maximized when the following criterion is satisfied:

$$\frac{P_{\mathrm{Sun}}A_{\mathrm{PV}}\eta_{h\nu\to \mathrm{e}}}{B} = N_{\mathrm{O}}\frac{e^x-1}{\beta}, \tag{3}$$

where

$$x = W\left(\frac{\eta_{\mathrm{LED\text{-}PV}}\beta c_1}{N_{\mathrm{O}}e} - \frac{1}{e}\right) + 1. \tag{4}$$

From eqn (1)–(4), it can be concluded that $\eta_{h\nu\to e}$ influences the $\mathrm{EE}_{h\nu\to 01}$ in a photovoltatronics chain. It is interesting to see how $\eta_{h\nu\to e}$ and $\mathrm{EE}_{h\nu\to 01}$ change for main parameters and what are the ultimate values for each. We consider the bandgap of the PV generator absorber (E_{g}) and the LED radiation intensity (I_{LED}) as the main influential parameters on $\eta_{h\nu\to e}$. For a given pair of (E_{g}, I_{LED}) the ultimate $\eta_{h\nu\to e}$ of the photovoltatronics chain are shown in Fig. 7(a and b). According to eqn (3), the value of $A_{\mathrm{PV}} \times P_{\mathrm{Sun}}$ that guarantees the maximum achievable $\mathrm{EE}_{h\nu\to 01}$ for a pair of (E_{g}, I_{LED}) are shown in Fig. 7(c and d) which will result in the $\mathrm{EE}_{h\nu}\to 01$ values shown in Fig. 7(e and f). Results are obtained considering AM 1.5 ASTMG173 standard spectrum as input and two options of RGB and phosphorus-based white LEDs. The calculated values for the efficiency limits of each photovoltatronics energy-information chain are in agreement with the reported values in the literature.[58,141,164,166,181]

The results show that for a photovoltatronics energy-information chain consisting of an ideal single-junction PV generator (working under 1 sun standard condition with no albedo) transferring its power through WPT to a white LED

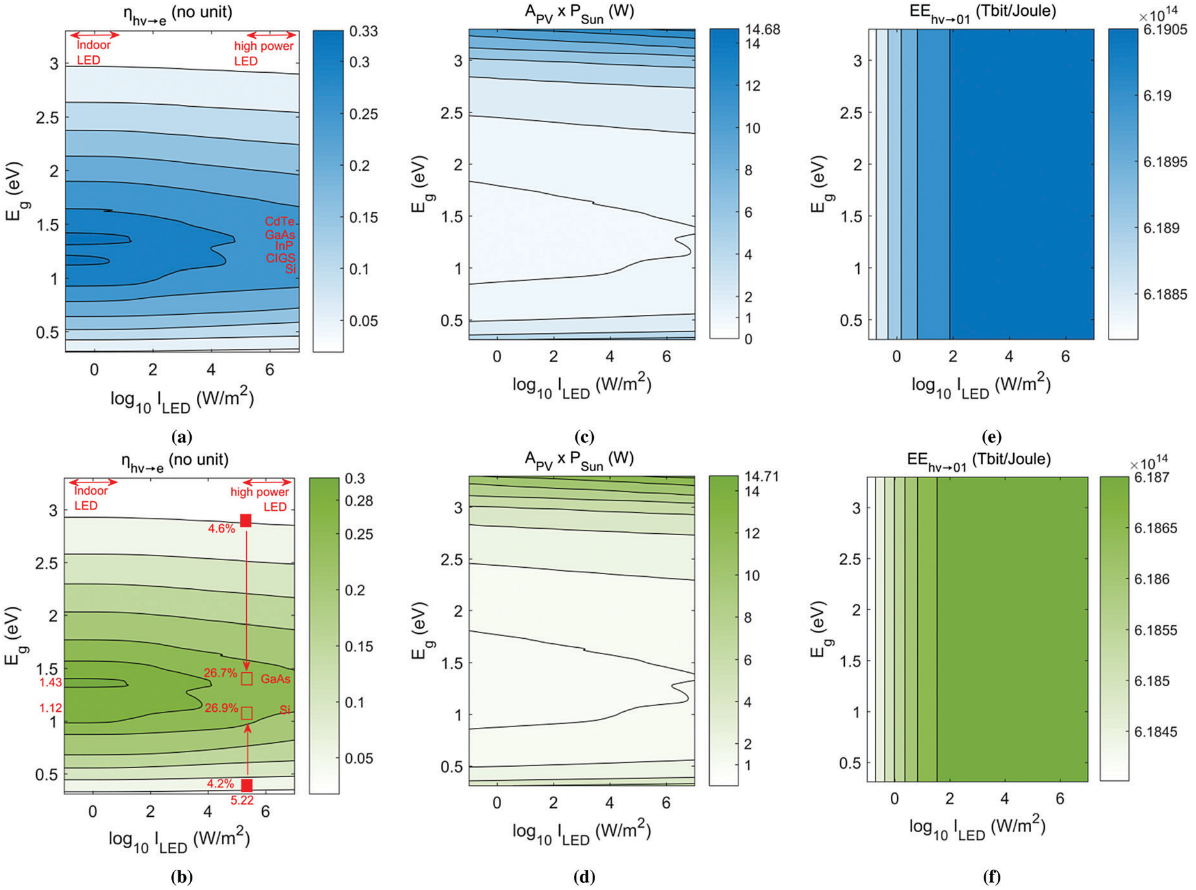


Fig. 7 Ultimate energy-information efficiency of the photovoltatronics chain as a function of PV generator absorber bandgap and LED radiation intensity. (a) Contour plot of ultimate $\eta_{h\nu\rightarrow e}$ considering RGB white LED with peaks at 465 nm, 522 nm, and 626 nm with full-width-at-half-maximums (FWHM) of respectively 30 nm, 34 nm, 20 nm for blue, green, and red spectra. For the shown ranges of $0.31 < E_g$ (eV) < 3.3 and $0.1 < I_{LED}$ (W m^{-2}) $< 10^7$, the maximum $\eta_{h\nu\rightarrow e}$ is 33.4%. For smaller LED intensity $\eta_{h\nu\rightarrow e}$ increases, however, having very low radiation intensity is normally not desired. For wireless power transfer, the design parameter was set as $\tau \gg 2$, which theoretically means no power transfer loss. For RGB white radiation, indoor PV receiver with the E_g = 1.93 eV was considered as this yields the highest indoor efficiency regardless of LED radiation intensity of the same spectrum. Commonly used materials for single-junction PV cell fabrications are also noted according to their bandgap energies. Intensity ranges for high power and indoor LEDs are shown in the plot. (b) Contour plot of ultimate $\eta_{h\nu\rightarrow e}$ considering a phosphor white LED with the intensity peaks at 456 nm and 565 nm with FWHMs of respectively 30 nm and 120 nm for blue and phosphorous part of the LED spectrum. The plot shows by using the phosphor white LED, the maximum $\eta_{h\nu\rightarrow e}$ is reduced to 30.2%. The optimum indoor PV receiver should have the E_g = 2.0 eV. Filled rectangles show the record laboratory efficiencies reported in the literature[23] for silicon (26.7%[183]) and GaAs (29.1%[184]) single junction PV cells multiplied by the highest reported WPE for phosphor white LED (58.5%[185]) and the highest reported PV cell efficiency under indoor phosphor white LED lighting (26.9%[186]). Empty rectangles give a hint about the room for improvement by representing the theoretical upper limits considering the same target PV material and the same LED radiation intensity. (c and d) Contour plots of the amount of power (as a function of E_g and I_{LED}) that should be fed into the photovoltatronics chain to ensures the maximum achievable EE$_{h\nu\rightarrow 01}$, considering respectively RGB and phosphor white LEDs. (e and f) Contour plots showing the maximum achievable EE$_{h\nu\rightarrow 01}$ for the photovoltatronics chain considering respectively RGB and phosphor white LEDs. Results show that using RGB white LEDs leads to higher bit per Joule visible light-based communication system compare to phosphor white LEDs. For the plots of Fig. 7, all the devices body (lattice) temperatures were considered to be at the room temperature of 298.15 K. Spectral data of the RGB and phosphor-based LEDs were obtained from ref. 187. LEDs spectra were assumed to have Gaussian distributions as suggested in ref. 166. Coefficients for energy loss associated with signal processing is estimated considering Landauer limit[188] and the suggestions made in ref. 164. In these calculations, all power electronics-based couplers are assumed to be lossless. The values were obtained by focusing on the thermodynamic of radiation in the photovoltatronics chain while empirical loss mechanisms in semi-conductor devices were neglected. Note that, using multi-junction PV cells or concentrated light will result in a higher ultimate energy efficiency limit.

which is detected by an optimum PV-based light detector arranged in a multiple antennae wireless communication system (arranged spherically around the LED light source), the $\eta_{h\nu\rightarrow e}$ and $EE_{h\nu\rightarrow 01}$ can ultimately reach up to 33.4% and 619.05 Tbit per Joule (equivalent to 10.01 keV per bit), respectively, These values demonstrate how efficient the energy-information chain can be in a PV-powered society and how much energy would at least be consumed to transfer or receive a bit of information. In times when civilization moves towards a sustainable society and there is an increasing need for energy and information flow, these efficiency values will become valuable figures.

IV. Scientific life stage of the photovoltatronics

The knowledge of the importance of emerging research fields is essential for making decisions about resource allocation. Any research field experiences three life stages: (1) embryonic, (2) initial and, (3) recognized phases.[189] The embryonic stage is when a topic is not labelled and recognized by a research community, but it is taking shape. In this stage, researchers from different fields are forming new collaborations and working on new concepts. An increase in the number of publications in relevant research topics and growing collaboration rate between these topics are the main statistical indicators to show that there is a possibility for a topic emergence while it is in its embryonic stage.[190] In this article, we use these two indicators to show that the photovoltatronics is in its embryonic stage. First, we worked on a table of keywords (see Table 1) for each photovoltatronics research area introduced in this article. Keywords that are related to a specific topic were sorted together in a group (k_i) as presented in Table 1. Keywords within the same group were combined with logical OR and several groups of keywords that represent a specific research area were combined with logical AND. Then, using all databases of the online web-of-science search system, we showed that the number of publications is increasing for each photovoltatronics research area (see Fig. 8(a)). The considered time was from 1864 to 2018 (all years). Then, by considering keywords co-occurrence (*i.e.* logical AND between research area keywords) we show that the mean collaboration rate index (μ_Δ) between photovoltatronics research areas is positive and increasing over time (see Fig. 8(b)). As proved in ref. 190, this shows a possibility for the emergence of a new research field, which in our case we have labelled as photovoltatronics.

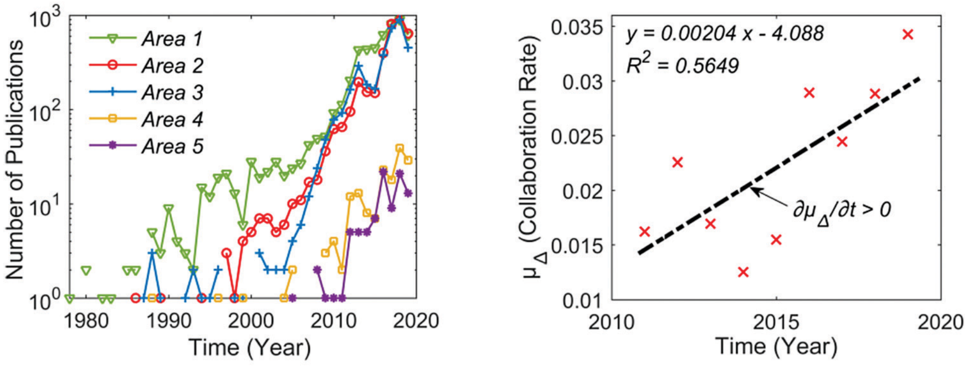
Visualization can help to track the evolution of research topics.[191] For a better understanding of photovoltatronics evolution in its embryonic stage, we visualize the dynamics of photovoltatronics research areas over the current decade in Fig. 9. This figure demonstrates that the research areas publication size and the collaboration between them are both steadily increasing. However, research areas 1, 2, and 3 are growing faster than research areas 4 and 5. This logically makes sense, since the first areas deal merely with the optimization of PV energy yield by applying intelligent PV technology. The latter areas that are related to PV-IEAs are very recent and will grow in the number of publications when the devices will take shape and be integrated into several real-life applications. It is worth noting that the dynamics of any research field is a function of cost and discoveries, and photovoltatronics is no exception. Hence, technology price variation and/or the emergence of new technologies can boost, drag, or shift the activities in the photovoltatronics research areas.

V. Conclusions

In this article, we introduced the emerging research field of photovoltatronics. Photovoltatronics aims at facilitating the

Table 1 Keywords for the literature research. Research area 1: (k1 AND k2 AND k3), research area 2: (k1 AND k4 AND k5), research area 3: (k1 AND k6 AND k7), research area 4: (k1 AND k8), research area 5: (k1 AND k9). Keywords within the same group were combined with logical OR. To avoid any unrelated scientific publications in the dataset, we enclosed the search terms in quotation ("") marks. Right-hand truncation (word*) is used to make sure that different types of a keyword's appearance are included

k1		k2	k3	k4	k5		k6	k7	k8	k9
1. Solar cell	11. Solar battery	1. Modelling	1. Energy yield	1. Smart	1. Phase change material	9. Thin-film technology	1. Batter*	1. Multifunct*	1. Wireless power trans*	1. Light-based-communicat*
2. PV cell	12. Solar capacitor	2. Modeling	2. DC yield	2. Intelligent	2. PCM	10. TFT	2. Energy storage	2. Multi-funct*	2. Wireless energy trans*	2. LiFi
3. Solar PV cell	13. Photo capacitor	3. Estimat*	3. AC yield	3. Reconfigura*	3. Cooling element	11. thin-Film transistor	3. Lithium ion	3. All-in-one	3. WPT	3. Light fidelity
4. Solar module	14. Photo-capacitor	4. Prediction	4. Output energy yield	4. Re-configura*	4. Sensor	12. Photo-diode	4. Lithium-ion	4. One device	4. Contactless power trans*	4. Visible light communicat*
5. Solar panel	15. Solar PV system	5. Mapping	5. Power output	5. Multifunct*	5. Electric chip	13. Photo-detector	5. Electro-chemical cell	5. Physical Integrat*	5. Contactless energy trans*	5. VLC
6. PV module	16. PV system		6. Output power	6. Multi- funct*	6. Integrated circuit	14. Fiber Bragg grating	6. Super-capacitor			6. Light recycl*
7. Photovoltaic panel	17. Photovoltaic system				7. Integrated-circuit	15. Bragg reflector				
8. Photovoltaic module					8. IC					
9. Photo battery										
10. Photo-battery										



(a) (b)

Fig. 8 Results of a statistical study: (a) number of publications per year for the five discussed research areas on a logarithmic scale; (b) mean collaboration rate index between the research areas. Using the defined keywords in Table 1, the first publications for research areas 1 to 5 happened in the 1970s, 1980s, 1990s, and 2000s, respectively. As research areas 4 and 5 are technologically newer to research communities, their dynamics are slower in comparison with the other three research areas. In the current decade, the mean collaboration rate between the five photovoltatronics research areas (μ_Δ) has increased from 1.62% in 2011 to 3.42% in 2018. μ_Δ was obtained using the 5-clique approach described in ref. 192 and further used in several publications related to networks and group structures analyses.[193,194] The dataset was investigated on 28-Feb-2020.

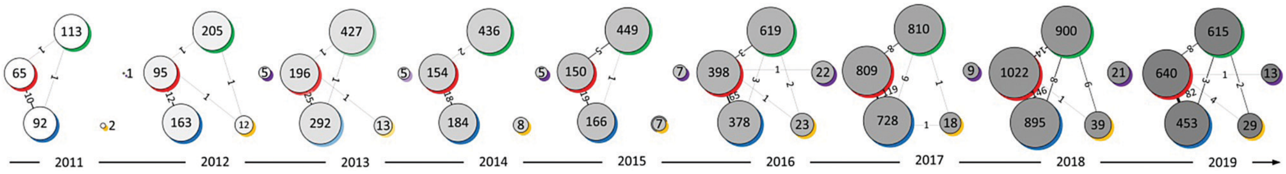


Fig. 9 Dynamics of the photovoltatronics research areas and their collaborations over the current decade. The green, red, blue, yellow, and purple shadows correspond to research areas 1 to 5, respectively. The numbers show the number of publications within a research area (w_i) or between two research area (w_{ij}). Thicker lines mean a higher number of collaborations. For visualization purposes, the size of the circles is logarithmically related to the publication number.

large-scale implementation of photovoltaic technology in expanding urban areas by combining it with electronic and photonic devices as well as digital technologies. As a result, photovoltatronics will deliver intelligent devices that we refer to as multi-functional PV-based intelligent energy agents (PV-IEA). The article describes five photovoltatronics research areas that contribute to design and develop the PV-IEAs and introduces new ideas for research in each research area. Research area 1 describes modelling and multi-layer mapping for maximizing energy harvesting from ambient energy sources and its utilization. The biggest challenge for research area 1 is to develop optimized solutions for interaction between various levels of information to have quick yet accurate and reliable modelling platforms. Research area 2 is related to design of PV-IEAs for delivering optimum electrical energy. This area addresses ideas for designing intelligent PV-based agents by integrating together electronics and/or sensors and/or cooling elements. The biggest challenge in research area 2 is to deliver the PV-IEA that are cost-competitive with decreasing price of conventional PV modules. The cost of PV-IEAs, at least in the short-term, will be higher than the cost of conventional PV modules but, as research trends showed, the efforts in the field of photovoltatronics and future large-scale introduction of PV-IEAs will lower their cost. Research area 3 deals with the security and flexibility of supply of generated solar electricity using storage. The biggest challenge in research area 3 is the thermal management of PV-IEAs with integrated storage unit because a high working temperature of PV modules affects the lifetime of the integrated storage which has an impact on the reliability of the whole systems. Research area 4 discusses the wireless power transmission of PV-generated electricity. The challenge is to find and demonstrate the most technologically optimized approach out of various techniques and solutions for wireless power transmission on a PV module level. Research area 5 is devoted to light-based communication (LiFi) combined with PV-generated electricity. Research area 5 will focus on developing and fabricating optimized PV-based agents that work at the same time as energy and information receivers in outdoor and indoor light conditions.

Soon, these devices can become building blocks for energy and information flows in cities. We have elaborated how the energy and information flows can be governed by PV and LED technologies using photovoltatronics approaches. Using the theoretical platforms provided in the literature, we mapped the ultimate efficiency of energy (photons) to information (bits) conversion chain.

We have presented the increasing number of publications related to photovoltatronics. Statistical analysis of the publications related to photovoltatronics was carried out and demonstrates that photovoltatronics is in the embryonic stage. We expect that in the next decade, the scientific community will witness the growth of the photovoltatronics as a research field. At the same time, to be able to introduce the photovoltatronics devices in real applications, it is necessary to assess the legal issues and obligations that are related to their utilization.

Conflicts of interest

There are no conflicts to declare.

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