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Review

A Review of Smartphone Applications for Solar Photovoltaic Use: Current Status, Limitations, and Future Perspectives

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Abstract: Smartphones and tablets can be effectively used in the solar photovoltaic (PV) energy field for different purposes because of their versatile capabilities incorporating hardware and software functionalities. These multifarious capabilities enable new approaches for measuring and visualizing data that are seldom available in conventional computing platforms. In this study, 100 accessible smartphone applications (apps) developed in the solar PV energy sector were investigated. The apps were categorized based on their main function as follows: computation of sun position, PV system optimal settings, PV site investigation, potential assessment of PV systems, environmental and economic assessment of PV systems, monitoring and control of PV systems, and education and learning for PV system. Each of these categories was further divided based on principal features or functions. Exemplary apps were chosen for each category and their characteristics and usefulness were investigated. Moreover, the apps for roof or rooftops and those that require built-in or external sensors were organized and analyzed according to their topic and functionality. Limitations regarding app implementation in solar PV and implications for future improvement as an alternative solar design tools were discussed. This study has significance in that it has first presented the current applicability and future perspectives of solar PV smartphone apps. Furthermore, they can be effectively used by the energy prosumers as an analysis tool for energy design due to evolving smartphone sensor technologies current opportunity factors.

Keywords: photovoltaic (PV); solar energy; smartphone; application (apps); PV design; sensor

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1. Introduction

The worldwide interest in the market and technologies related to solar photovoltaic (PV) energy is increasing mostly due the increasing demand for sustainable energy production and energy security, which are aggravated by issues like climate change and environmental problems associated with the development of conventional energy resources [1]. Many countries are making efforts to transform current fossil-oriented energy policies into renewable and sustainable low-carbon policies, which have been promoted by several national and international agreements, such as the 21st Conference of the Parties (COP21) in Paris and the Green New Deal policy [2]. The forms of solar power applications are becoming more diverse and now include agrivoltaics [3–5], floating PV [6], minevoltaics [7], generation in remote islands [8], building-integrated PV (BIPV) [9], and rooftop PV [10] systems. Accordingly, solar power projects can be implemented in both national or household and personal scale. Therefore, feasibility studies for solar PV energy projects have also expanded beyond the domain of experts (e.g., scientists, engineers, and policy makers) to the public and personal domains (e.g., energy prosumers and young students).

Various solar PV tools used in PV projects have been developed, including desktop software, web-based programs, and smart-device (i.e., smartphones and tablets) mobile applications (apps). Most desktop software have been developed for professionals and their price range of varies greatly, but they are generally not cheap. Conversely, apps for smartphones and tablets (hereafter mentioned simply as smartphones) can be free or have low costs, and they can be used for various purposes in a PV project, including system optimal settings. Their versatility includes rapid processing, mobility, and connectivity between wireless networks and sensors, enabling physical properties of the smartphone and the surrounding environment to be measured. Recently, people have attempted to use portability and sensing technology of smartphones to overcome what was unfeasible with previous single-platform system [11]. Over 4 billion people are using smartphones by 2020 and the number of users is expected to continue to grow [12]. These smartphone apps related to PV energy have been used not only for scientific purposes but also for educational use, such as in new teaching strategies or to introduce cutting edge technology associated with scientific concepts for future energy prosumers. Since more solar PV apps are anticipated to be developed, an overview of solar PV smartphone apps in the perspective of present limitations, and future prospects is required.

Several researchers have reviewed solar PV design tools and methods [13–17]. One of the first comprehensive recent reviews on solar design tools and methods was reported by Jakica [13], in which various state-of-the-art software and features were investigated and summarized, focusing on solar potential assessment for BIPV or urban areas. Axaopoulos et al. [14] validated and compared the accuracy of the most common PV modeling tools (e.g., SAM, PVWatts, PVsyst, PV*SOL, TRNSYS, Archelios, Polysun, and PVGIS). Freitas et al. [15] examined a wide range of methods from simple two-dimensional (2D) analytical models to more sophisticated three-dimensional (3D) representation and numerical analysis coupled with geographic information system (GIS) tools, for modeling solar potential in urban environments. Pabasara et al. [16] investigated 23 solar PV design and management software and 4 smartphone/tablet applications in terms of catering all geophysical, technical, economic, and environmental factors. Choi et al. [17] reviewed numerous studies on GIS-based tools and approaches for solar radiation mapping, site evaluation, and generation potential. All these reviews tended to focus on desktop- or web-based software and tools (or cover desktop solution only), rather than smartphone apps. To the best of our knowledge, however, no research has been conducted to investigate and analyze the numerous smartphone apps currently available for solar PV applications. Therefore, it is necessary to investigate the current status and characteristics of solar energy apps (tools) based on mobile platforms rather than desktop- or web-based software.

The objective of this study is to review the status and characteristics of smartphone apps developed for solar PV energy applications from various perspectives and to consider future directions for improvement. This paper is organized into six sections, and the remaining sections are as follows. Section 2 presents background knowledge of smartphone technology and built-in sensors. Section 3 presents methods to retrieve, classify, and analyze the apps associated with solar PV. Section 4 reviews the apps dealing with solar PV energy from various perspectives. Section 5 provides a discussion of limitations and future perspectives on solar PV apps. Finally, the conclusions are summarized in Section 6.

2. Smartphone Technology and Built-in Sensors

Before reviewing the apps, the main features and functions of smartphones should be understood. A smartphone is a device that combines communication and sensing functions in a mobile computer. Therefore, it can be used to create, analyze, visualize, and manage various data using built-in software. It is continuously connected to a communication network, and it can perform field measurements when combined with internal or external sensors. With recent developments, smartphones can perform desktop computer-level computations, and the range of smartphone apps has significantly expanded, including those that desktop applications cannot perform due to the use of smart sensor technologies. Moreover, smartphones are an intuitive and easy-to-use device, thereby having cost-effective advantages when designing apps to substitute for existing approaches or software [11].

Numerous state-of-the-art smartphones have a variety of built-in sensors that can detect physical properties associated with three axes (x, y, and z) and are capable of measuring local electromagnetic fields and acceleration [18]. Table 1 summarizes various sensors that can be built into smartphones and their functionalities and expected roles in solar PV apps. These sensors can enable users to acquire physical property information and environmental factors for solar PV systems. The multifaceted sensor applications enable the measurement and visualization of data, which is seldom found in conventional desktop/web-based software.

Table 1. Typical sensors embedded in the smartphones and their roles in solar photovoltaic (PV) apps (added from [18]).

Sensor	Functionalities	Units of Measure	Possible Role in Solar PV Apps
GPS (global positioning system)	Measures x, y, z-coordinate (position)	Degree, minute, second	Location awareness (to obtain information of solar PV sites)
Optical image sensor	Acquires optical images or videos	-	Photo viewer, video playing, and augmented reality (AR) visualization
Accelerometer	Measures acceleration force	m/s^2	Estimate tilt of PV module or roof
Magnetometer	Measures the ambient magnetic field	μT	Estimate orientation (aspect) of PV module or roof
Proximity sensor	Measures the distance of any object	cm or m	Estimate distance between PV module or other components
Gyroscope	Measures a device's rate of rotation	rad/s	Rotates map-screen orientation (PV design on roof or rooftop *)
Barometer	Measures the ambient air pressure	hPa or mbar	Estimate weather conditions (in situ ambient air pressure)
Ambient temperature sensor	Measures the ambient temperature	°C	Estimate weather conditions (in situ ambient temperature)
Humidity sensor	Measures the ambient relative humidity	%	Estimate weather conditions (in situ ambient relative humidity)
Ambient light sensor	Measures the ambient light level	Lx	Estimates solar radiation
Microphone	Converts sound wave into electric signal	-	Records status of the site by voice

* Roof PV refers to a PV system mounted on the (mostly inclined) building roof while rooftop PV indicates a PV system installed (or mounted) on the upper flat place of a building that a person can stand up.

The global positioning system (GPS) is a fundamental built-in sensor that can be used to measure and visualize on-site data associated with solar PV within a smartphone because most information is closely related to geographical location. This sensor calculates the geographical coordinate (latitude and longitude) of the device necessary to obtain additional on-site information for solar design purposes. For instance, latitude and address can be used as input data to assess PV potential. The optical image sensor can be used to acquire optical images as photos or videos. Furthermore, this sensor can visualize the position and trajectory of the sun over time. A particular advantage is that the image sensor can be used to easily check the position of the sun not only outdoors but also indoors when combined with accelerometer and magnetometer that measure the tilt and direction of the smartphone, respectively. The accelerometer and magnetometer can be used to measure the tilt or orientation, respectively, of the PV module or roof. The detailed principle of measuring tile and orientation can be found in Lee et al. [18]. Moreover, environmental sensors (i.e., barometer, ambient temperature, and humidity sensor) are capable of measuring on-site weather conditions with the aid of GPS data. These measured data can be used as input parameters to predict PV power generation.

External sensors that can be connected or attached to smartphones are being actively developed. Examples include solar radiation sensors (pyranometer), thermal infrared sensors, and radioactive detectors [19]. In the past, these external sensors were used for specific equipment or devices, not smartphones. However, with the development of the Internet of Things, opportunistic factors in which various smart sensors are developed have led to this change. Nevertheless, most of these external sensors are still developed for a specific purpose in each field, rather than a smartphone manufacturer. To secure commercialization as an external sensor for smartphones, problems in terms of sensing accuracy and price must be overcome.

3. Methods to Investigate Smartphone Apps for Solar PV Energy

This study employed two mobile app search engines (Android and iOS platforms) to review the features and applicability of solar PV smartphone apps. This choice was made because 99.9% of smartphones apps are developed for these platforms [20]. The selection of smartphone apps was conducted via two official app markets (each website of Google Play and App Store). In the case of the apple store, we reviewed both international and Korean apps.

The scope of this review was confined to commercial apps available to public users concerning solar PV energy. Search keywords (i.e., solar, photovoltaic, PV, PV calculator, panel, irradiance, irradiation, or shading) were input into the search engine to retrieve smartphone apps, and more than 100 apps were obtained. However, various apps were excluded from this study because they were out of scope (e.g., solar thermal energy or other renewable energy), simply introduced a specific company or product, were not intuitive (without English description), or presented low user satisfaction (≤2 out of 5) or few downloads (≤10). After analyzing their scope and characteristics, 100 solar PV apps were selected for further review.

The 100 apps were then classified into several groups according to their main topic. For this, we reviewed the information posted on their website and downloaded and tested all apps. Various information, such as app name, developer/company, price, main function, website address, as well as the main topic were collected and organized. Several apps have features that are similar to those of the desktop software because the smartphone allows for a similar overall computing. In contrast, other apps utilize wireless connection and built-in sensors, thereby having unique functionalities which are hard or impossible to get via desktops software. Therefore, the apps categorized for each group were classified again with regard to smartphone functionalities. This sub-classification gives an opportunity to identify promise of solar PV apps not only to replace desktops but also regarding their specific features. After classifying the topic and main functions of the apps, their common features and characteristics were carefully analyzed. Based on these results, this paper introduced some apps with a high degree of completeness by topic.

4. Classification and Features of Smartphone Apps for Solar PV Energy

In this study, 100 apps for solar PV applications were evaluated, and their current status, limitations, and future perspectives were reviewed. Table 2 summarizes the topics, functions, and platforms of those apps; 60% of them were Android (Google) apps, 20% were iOS (Apple) apps, and 20% were found in both platforms. The influence of the market share by smartphone OS (Android 85% vs. iOS 15%) was clear [20]. However, the apps investigated in this study did not include all of apps in the solar PV field.

Table 2. Summary of smart-device applications for solar PV energy field.

Topic of Apps	%	Function of Apps	%	Platform	%
Computation of sun position	10	Database (DB) & Visualization	9	Android	60
PV system optimal settings	17	Measurement	18	iOS	20
PV site evaluation	11	Calculation (simple)	17	Both	20
Potential assessment of PV system	16	Analysis & Simulation	26		
Environmental & economic assessment of PV system	16	Monitoring & Control	21		
Monitoring & Control of PV system	21	References	9		
Education & Learning for PV system	9				
∑	100	∑	100	∑	100

The reviewed 100 solar PV apps were classified into seven groups according to their topic or main theme: computation of sun position, PV system optimal settings, site investigation or evaluation for PV system, potential assessment for PV system, environmental or economic assessment for PV system, monitoring and control of PV system, education and learning for PV system. This classification was established by considering the general procedures in solar power planning and management.

The main function of the apps was categorized into six groups, such as visualization from database (DB), measurement using smartphone built-in sensors, simple calculation, analysis and simulation, monitoring and control, and references. In most cases, the apps included only one functional classification, but when two functional categories were observed, (e.g., measurement and calculation), only one main functional classification was selected according to the authors' judgment. The classification ratio is listed in Table 2. Within one topic, two or three functional classification were usually included. Mobile apps perform their functions via basic memory-based computing. However, communication functions and sensors (internal or external) might also be essential. This can be interpreted as their main distinction from desktop software.

4.1. Computation of Sun Position

In this study, the first topic of solar PV apps is the sun's position. Table 3 lists the smartphone apps that address the location and trajectory of sun, and their developer/company, platform, price, and main functions. The apps in this category provide visualization of the location and trajectory of the sun based on the day and time in a specific location, or they calculate the sun's position from a couple of parameters, or calculate shaded areas through intuitive visualization in the smartphone. Although they do not provide specific solar power information, this can be used to effectively survey non-shaded areas to evaluate solar power generation sites. Their prices ranged within 0–9.99 USD.

Most apps in this topic can be used to visualize the sun's location and travel paths at a specific location throughout the day via maps (e.g., Google Maps, Sky Map) or augmented reality (AR) videos [21–29]. They provide supplementary information such as sunrise and sunset times. Several apps also provide the visualization of location and trajectory of the moon [23–29]. These functions use built-in sensors and DBs in the smartphone, and their working principles are as follows. The locations of the sun and moon according to date and time are fixed. In addition, when it is possible to obtain the user's coordinate from the GPS sensor embedded in the smartphone, a relative relationship between the locations of the sun and the user can be defined. When the user launches the app, the direction that the smartphone is facing can be recognized by the built-in accelerometer and magnetometer sensors. Subsequently, the position and trajectory of the sun can be visualized in the video using AR technology and a solar DB. Thus, the smartphone performs a visualization function based on the DB.

In addition to the aforementioned functions, the Sun Locator Pro (Sun and Moon) and Lumos: Sun and Moon Tracker apps can analyze the length or area of shadow (or lightning) of a 3D terrain or building based on the location of the sun at a specific date and time [28,29]. These two apps include simple calculation functions, as well as visualization based on DB. Figure 1 shows screenshots of a representative smartphone app that provides geospatial information of the sun and 3D shadows.

Unlike the apps that visualize the location of sun above, the SunTrack app [30] only calculates the sun track by providing two sets of parameters, for Equatorial (Polar) or Altazimuth mounted apparatus such as solar panels. In other words, the main function of this app is to perform simple calculation.

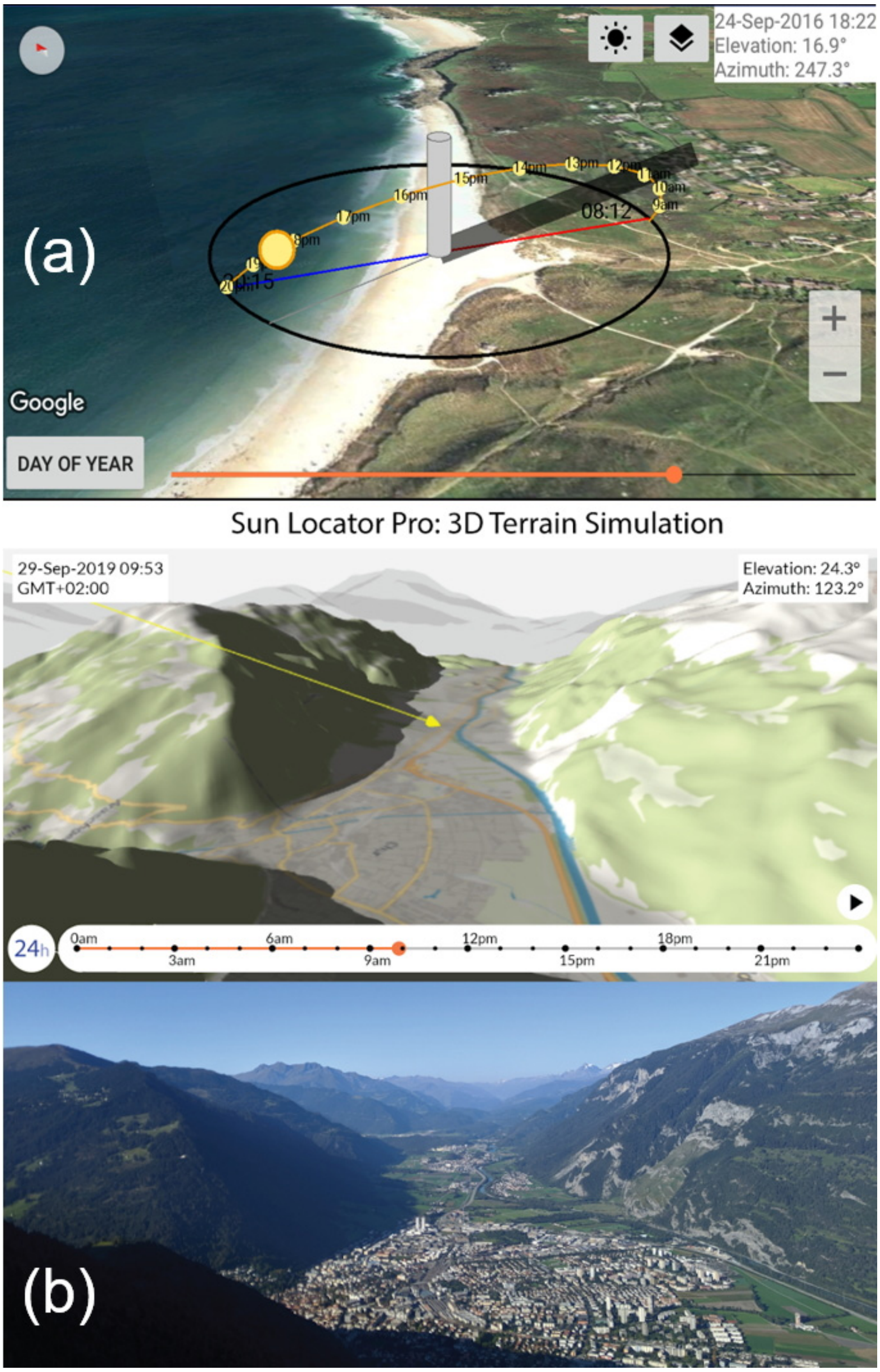

Figure 1. Representative smartphone application, Sun Locator Pro (Sun and Moon), for the sun's location: (**a**) augmented reality (AR)-based visualization of the sun trajectory, (**b**) shade calculation [28].

Table 3. Summary of smartphone applications that compute the sun's position.

Name of App	Developer/Company	Platform	Price *	Function	AR Visualization	Shade Analysis	Reference
SunIZup—Golden Hour Photos	Orca Web Strategies	iOS	$2.99	DB & Visualization	•		[21]
Sun Position and Trajectory	Siranet	Android	Free		•		[22]
Sun Surveyor Lite	Adam Ratana	Both	Free		•		[23]
Solunar Calculator	Xueping Wang	iOS	$0.99		•		[24]
Sun Seeker—Sunrise Sunset Times Tracker, Compass	ozPDA	Both	$9.99		•		[25]
Sun Surveyor (Sun & Moon)	Adam Ratana	Both	$9.99		•		[26]
Sun Locator Lite (Sun and Moon)	GeneWarrior	Android	Free				[27]
Sun Locator Pro (Sun and Moon)	GeneWarrior	Android	$8.99	DB & Visualization + Calculation	•	•	[28]
Lumos: Sun and Moon Tracker	Luminous Labs	iOS	Free		•	•	[29]
SunTrack	ColuzziWeb	iOS	Free	Calculation			[30]

* Price in USD. AR: augmented reality. It should be noted that contents presented in (all) table are compared in the main functional aspects of the app, while detailed information of each app is presented in the text.

4.2. PV System Optimal Settings

The second function of solar PV apps is information and design of PV module (optimal setting). Table 4 lists the corresponding smartphone apps, including their developer/company, platform, price, and main functions. Many of these apps calculate the optimal tilt (inclination or slope) and/or orientation (azimuth or aspect) of PV modules, and analyze the separation distance between PV modules according to their geographic location. Moreover, many of them propose (or provide information on) a combination of solar modules, inverters, batteries, and other elements of PV systems according to the electric power consumption (load). Their prices ranged within 0–9.99 USD.

The tilt angle of the PV module is the angle in degrees from the horizontal line, and the orientation refers to azimuth setting. The PV module collects solar radiation directly from the sun and the sky, and sunlight reflected off the ground or areas surrounding the PV module. PV modules should be positioned in a direction and tilt angle that maximize their exposure to direct sunlight to optimize their collection efficiency. Therefore, tilt and orientation factors (TOF) are crucial in PV system optimal settings because the output of the PV system can be increased by optimizing them based on geographic location. The module collects solar radiation most efficiently when the sun's rays are perpendicular to its surface. However, the angle of the sun varies throughout the year. Therefore, the optimal tilt angle for a PV panel in the winter will differ from that in the summer. This angle will also vary according to latitude.

Many apps can calculate the optimal tilt and/or orientation of PV module based on time and place. A few apps only calculate optimal tilt for annual [31], winter [32], seasonal [33], monthly [34], and daily [35], whereas one app suggests calibration value to both optimal tilt and orientation of PV modules by placing a smartphone on the solar panel bracket [33]. These apps provide the optimum tilt angle or orientation of PV modules based on the geographical coordinate using GPS data or when the user inputs latitude and longitude manually.

Numerous apps also recommend the type, size, and number of PV modules, inverters, batteries, and chargers according to a given power consumption (load) [36–43]. The overall features and principles of the apps are as follows. They first allow the input of individual data for each power appliance or total energy consumption, and the PV module specifications in a simple design. Second, the user sets options associated with PV power output such as weather conditions, area of installation, separation distance, and power losses. In this process, a few apps allow the user to manually input the amount of sunlight (e.g., average daily sunshine hour or average daily global horizontal irradiance (GHI)) [37–39,41–43]. Then, a link to the National Renewable Energy Laboratory (NREL) website are provided to retrieve and apply local solar radiation via a map with legend in a specific app [40], as seen in Figure 2. Thus, most of these apps have limitations that cannot accurately reflect weather information based on exact location. Third, this app calculates the number of required PV modules and batteries based on user's power consumption loads and PV module specifications.

The Solar Calculator app [44] is a tool for homeowners to define the required size of a roof PV system. This app provides information and compares various PV modules from different manufacturers, and it calculates the required number of modules according to the size and by considering the power consumption and degree of exposure in the roof. Another app simultaneously calculates the number of PV modules and batteries [45]. The PV Module Calculator app [46] provides a simple design, and it calculates various characteristics related with PV systems, such as installation area, degradation separation, number, price, weight of PV module, daily power generation time, and distance between PV modules.

Table 4. Summary of smartphone applications on PV system optimal settings.

Name of App	Developer/Company	Platform	Price [a]	Function	Optimal Tilt of Module	PV System Setting [b]	Reference
Optimum Tilt Angle For Solar PV Panel	Green Engineering Tips	Android	Free		• (annual)		[31]
Optimum Solar Panel Angle in Winter	Green Engineering Tips	Android	Free		• (winter)		[32]
SenserAlign	Sensera Systems, Inc.	Both	Free		• (seasonal)		[33]
Seasonal PV Tilt Angles	Green Engineering Tips	Android	Free		• (monthly)		[34]
Solar Tilt	Karl Clark	Android	Free		• (daily)		[35]
Electricity/Solar Calculator	Vivid Techno	Android	Free			•	[36]
Solar Energy Calculation	Green Engineering Tips	Android	Free			•	[37]
4WD Solar Calculator Plus	Tony Parker	Android	$0.99			•	[38]
Solar Calculator	All In One Online Shopping Apps India	Android	Free	Calculation		•	[39]
Solar PV System Estimator Pro	Off-Grid Online	Android	$2.00			•	[40]
Off-Grid Battery Bank Calculation	Green Engineering Tips	Android	Free			•	[41]
Indian Solar Calculator	Prosper India	Android	Free			•	[42]
PV Calculator—off grid	Cristinel Bontas	iOS	$0.99			•	[43]
Solar Calculator	Compare All Solar	Android	Free			•	[44]
PV Master—Professional photovoltaic solar panels	Giacomo Balli	iOS	$9.99			•	[45]
PV Module Calculator	Mal-eum	Both	$4.00			•	[46]
PV Module Photovoltaic Solar Energy	Ángel Martínez	Both	$0.99	Analysis & Simulation	I-V curve of module		[47]

[a] Price in USD. [b] Recommends types and number of PV components (e.g., PV module, inverters, or batteries) suitable for a specific power consumption.

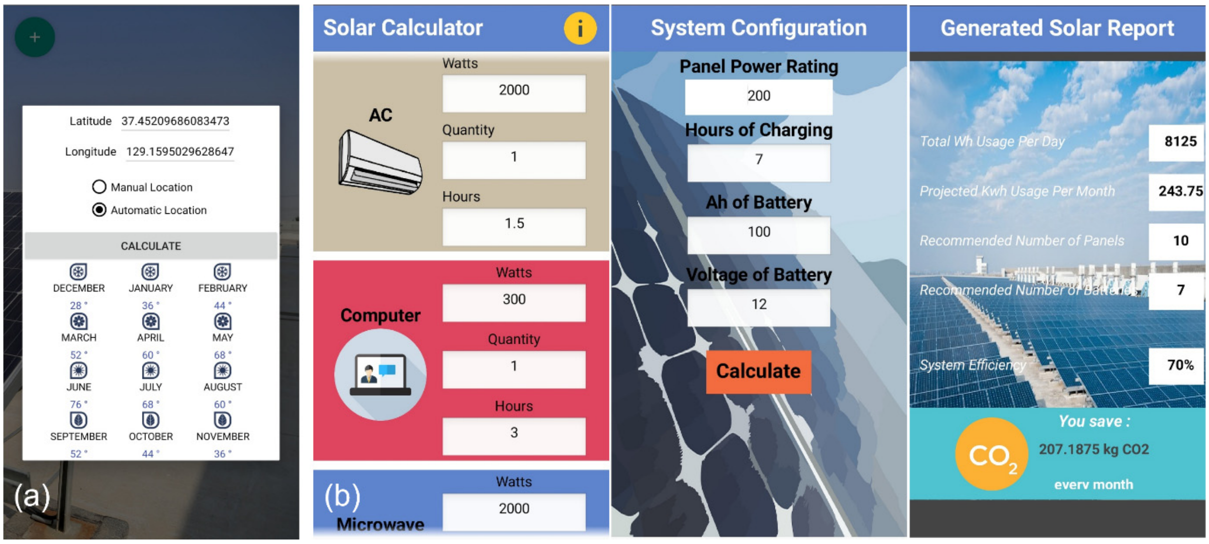

Figure 2. Representative smartphone applications for the module optimization. (**a**) Calculation of optimal module tilt (Seasonal PV Tilt Angles app), (**b**) PV system configuration and report by electrical load (Solar Calculator app).

The PV Module-Solar Photovoltaic app [47] can be used to analyze the electrical characteristics of PV modules. This app can solve simplified equations with a single exponential and five parameters of PV module from test data (Open-Circuit Volt (Voc), Maximum Power Volt (Vmp), Short-Circuit Current (Isc), and Maximum Power Current (Imp)) under standard test conditions (STC: 1000 W/m^2 of irradiation, cell temperature = 25 °C, and 1.5 g spectrum air mass) provided by the manufacturer. This app can be used to determine the parameters of a module by simulating its behavior under different conditions.

4.3. PV Site Evaluation

The third topic of the solar PV apps is site investigation and evaluation of PV system. Table 5 lists those apps and their developer/company, platform, price, and main functions. The apps in this category measure or calculate the tilt and orientation of a building roof or PV module by using built-in sensors, or they measure solar irradiation by attaching an external sensor to the smartphone. In addition, some apps are mainly used to evaluate PV sites based on Google satellite images, extract roof characteristics (e.g., area, tilt, and orientation), or combine insolation and shadow analysis. Despite providing various features, all the investigated apps were free.

Some apps can also be utilized as a solar compass or pyranometer. Solar Compass [48] is an Android app that can be used to find directions in the field using the position of the sun in the sky. When the user rotates it toward the sun, the app automatically rotates to point to the desired direction based on the value obtained from the built-in magnetometer sensor. Solar Measurement—Pyranometer app [49] is a gadget that enables the measurement of on-site solar radiation by attaching external solar radiation sensors to the smartphone. As the field of view of smartphone cameras only have ±30°, they cannot easily perform the pyranometer function. With this app, the user can download the diffusor which is printable and attachable to the smartphone camera lens. The diffusor enables the lens to achieve 180° field of view to fully encompass the sky, thus enabling the measurement of solar radiation. The app is calibrated and measures the solar radiation (in W/m^2) when the user pushes a button with the camera facing the sun. The measurement deviation of the app is approximately ±30%; thus, its accuracy is not high. Professional measurement of solar radiation should be performed by highly accurate thermopile pyranometers. Nevertheless, this app can be used for educational purposes of irradiance measurements in weather, climate, solar energy, agriculture, and other related fields.

Table 5. Summary of smartphone applications for site evaluation of PV systems.

Name of App	Developer/Company	Platform	Price	Function	Remarks	Reference
Solar Compass	Agnibho Mondal	Android	Free	Measurement	Azimuth measurement of sun position	[48]
Solar Measurement/PyranometerApp	Hukseflux Thermal Sensors	iOS	Free		Irradiance measurement	[49]
Solar Calculation Tips	Green Engineering Tips	Android	Free	Measurement + Calculation		[50]
Optimal Tilt Angle for PV System	NRG Labs	Android	Free			[51]
SimplySolar	Matt Privman	iOS	Free			[52]
SOLARPE Pro ☀ PV Photovoltaic Solar Energy	SOLARPE SOFT	Android	Free			[53]
SOLARPE ☀ PV Photovoltaic Solar Energy	SOLARPE SOFT	Android	Free			[54]
Solar Consult	Sander Haanappel	iOS	Free	Measurement + Analysis & Simulation	For roof and rooftop	[55]
RoofSnoop	iRenewables Limited	iOS	Free	Analysis & Simulation	For roof	[56]
Solar Survey	Joe Ranalli	Android	Free		Augmented reality (AR) visualization	[57]
SolarEdge Site Mapper	SolarEdge Technologies	Both	Free		PV module layout design	[58]

Several apps have been proposed not only to measure tilt angle and orientation of PV modules, but also to calculate their optimal values to maximize power generation [50–54]. The apps in this category are different from the apps in the category of PV system optimal settings [42–46] because they can provide functions of on-site measurement as well as calculations. This is a feature available only on smartphone apps, not on desktop software. The measurement of tilt angle and orientation of PV module is possible because of the built-in magnetometer and accelerometer sensors in smartphones, respectively. The on-site measurement of tilt angle of PV modules enables users to obtain the input value for energy simulation or to optimally adjust the tilt angle of the PV module. Some apps [50] can calculate solar factors, such as local time meridian, equation of time, declination angle, zenith angle, and elevation angle. A couple of apps [53,54] can calculate the distance between PV modules to avoid shadows. The SOLARPE Pro app [53] includes all the above-mentioned features, and it connects with the National Aeronautics and Space Administration (NASA) DB to check parameters for the installation place, as shown in Figure 3a.

For roof or rooftop PV power generation, some apps can measure or analyze the characteristics of the roof or rooftop. The Solar Consult app [55] not only measures the tilt and orientation of the roof, but also analyzes the number and size of PV modules considering roof characteristics, such as shape (i.e., flat or pitched), area, tilt angle, and orientation. Figure 3b shows screenshots of PV designs according to the roof type in the Solar Consult app, which can measure the tilt angle of the roof and has an orientation meter that works like a compass to display the deviation from the South. The app can identify if the roof is suitable for a PV module system, according to the amount of sunlight, obtained through an address or by displaying the location. The app calculates multiple types of PV modules for maximum output according to the type of roof (i.e., flat or pitched). In case of a flat roof, the length of the shadow behind a row of PV module can be calculated. On the contrary, the RoofSnoop app [56] can extract characteristic information of the roof (e.g., location, area, slope, orientation, and shape) via satellite images and street view of Google Maps (Figure 3c). This function enables remote-roof surveys before visiting the site to confirm roof dimensions and angles. The user can easily identify the roof to be measured, determine the outlines of the roof, and obtain the roof width, ridge-to-gutter distance, azimuth, and surface area in the map. The main advantage of this app is that it analyzes the roof characteristics via satellite images from anywhere, rather than by using the smartphone's built-in sensors in the field.

The Solar Survey app [57] is a PV site evaluation tool based on AR technology. It can estimate the solar resources in a location based on Typical Meteorological Year 3 (TMY3) data from the internet and measure the potential shading obstacles using an AR display via the camera. Therefore, it can provide more accurate weather information than other apps. Moreover, shading information can be given in a format available for input into other PV simulation software. The SolarEdge Site Mapper app [58] allows to streamline the registration of PV array by mapping its physical layout intuitively.

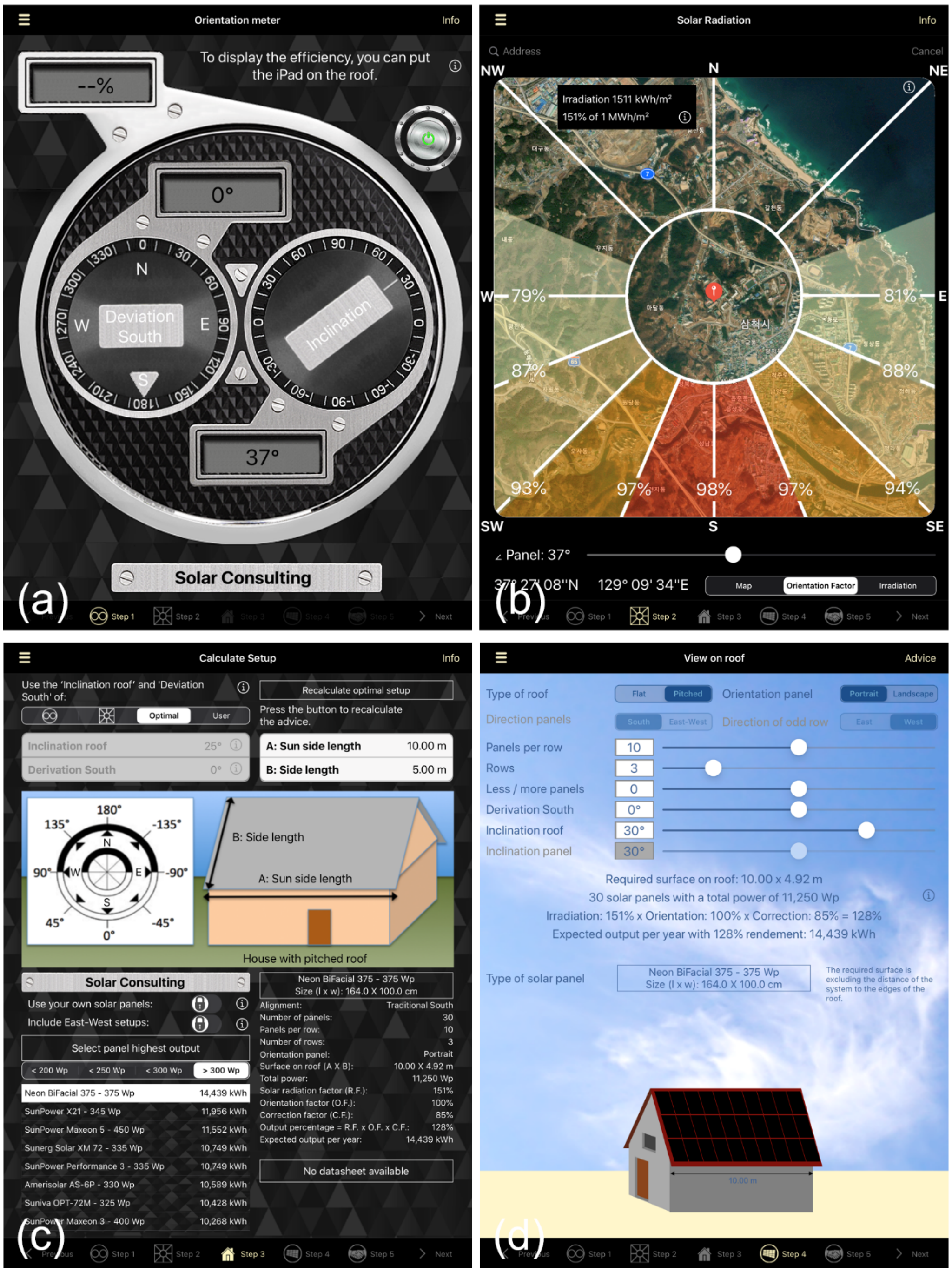

Figure 3. Representative smartphone applications for site evaluation. (**a**) Measurement of tilt and orientation of module, (**b**) Efficiency of solar irradiation according to the module orientation, (**c**) Roof characteristics, and (**d**) Roof PV design using Solar Consult app.

4.4. Potential Assessment of PV Systems

The fourth topic of solar PV apps is the potential assessment (power output estimation) of PV systems. Table 6 lists the corresponding apps and their developer/company, platform, price, and main functions. The fundamental feature of these apps is the analysis or simulation of PV potential energy yield under various conditions and environments [59–73]. The respective high-level calculations consider variables and options for various scenarios compared to the aforementioned simple calculations. In addition to the potential assessment, apps that also assess environmental benefits or economic profitability are summarized in the next section. The prices for apps in this category ranged within 0–14.99 USD.

In general, local weather data, site characteristics, and performance of PV modules and inverters are essential to predict PV power generation. Local weather data include GHI, direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), ambient temperature, wind speed, wind direction, pressure, albedo, and other parameters. Site characteristics include area, shading, inclination, separation distance, and other conditions. Performance of PV system includes capacity, efficiency, miscellaneous loss, and other electrical characteristics of module and inverters. The more data is considered, the higher the accuracy of potential power generation. The factors considered vary depending on the purpose for which the app was developed and their accuracy also vary.

As summarized in Table 6, apps in this category can be divided into hourly [65,66,72,73], daily [61,62], monthly [63,64,68–71], and yearly [60,67] estimations. Originally, this distinction is associated with the temporal resolution of weather data that can be provided or entered into the app. The app that predicts hourly power generation can obtain hourly weather data (i.e., irradiance value) by connecting to a worldwide irradiance DB link via wireless communication and/or measuring solar irradiance via external sensor. Similarly, the apps that estimate monthly power generation utilize a DB with average monthly irradiance data. However, instead of considering actual irradiance data, several apps allow the users to simply determine the options and values to analyze or simulate PV power output.

In addition to PV energy yield, many apps in this category also include additional features mentioned in earlier sections such as visualization of sun path [65,73], calculation of power consumption (electric load) for comparison with potential power generation [61,62,64,66], determination of optimal tilt and orientation of PV module based on geographic coordinates [60,67,70–72], or on-site measurement of solar irradiance, tilt, and orientation of module or roof [67–73]. These functions can help maximize power generation and enhance the understanding of the power output calculation process.

SolarTester Pro [73] is a representative app that includes various of the aforementioned features. This app makes hourly performance predictions for grid-connected PV projects based on system design parameters specified by the user. The user can simulate the sun path, perform shading modeling, and obtain the optimal TOF as well as measure tilt and orientation of module and roof. The app recognizes the user's location and automatically loads the irradiance data of the region using an internal worldwide irradiance DB by NASA. In addition, the users can attach external pyranometers for accurate real-time measurements of solar irradiance components (i.e., GHI, DNI, and DHI) and current ultraviolet (UV) index, as shown in Figure 4. Conversely, the SolarMore app [71] provides five types of PV array setups frequently used in PV systems (i.e., fixed-angle setup, fixed-angle tracker, horizontal tracker, full-time tracker, and horizontal setup) to establish the maximum solar power for each season. This app includes a solar irradiance meter that detects the amount of solar power that can be generated at sunny conditions at any time. A raw picture is captured by a wide-angle camera with real light conditions to be analyzed by the unique color differential technology. The tolerance is maintained within ±5.5%, and the test range of irradiance power within 0–1000 W/m^2. Therefore, this app has the advantage of being able to measure a certain level of solar radiation without an external sensor.

Several apps in this category can also assess potential of roof or rooftop PV systems [63,64,68,69], as shown in Table 6. Most of them provide intuitive visible roof area measurements on a map for PV panel installation. From the results, the user can determine the type and size of the PV modules. The PV OptiMizer app [63] is useful only for Australian regions, and it provides mounting configuration options such as parallel to roof, rack type, and top of pole mount. However, the information obtained by measuring or extracting the characteristics of the roof from the map within the app is not automatically used to estimate power generation.

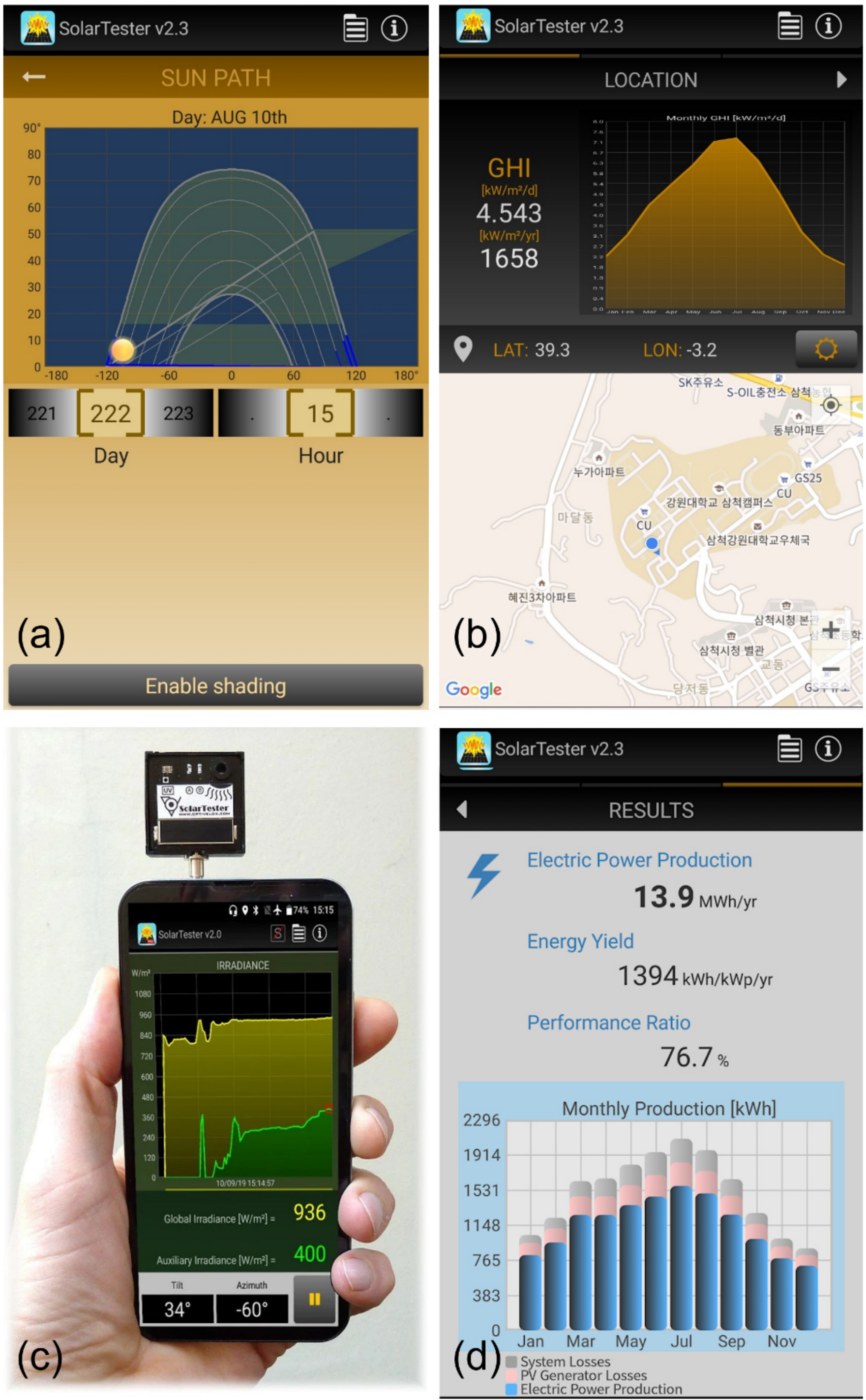

Figure 4. Representative smartphone applications, SolarTester Pro, for (**a**) PV potential assessment, (**b**) analysis of solar irradiation DB, (**c**) solar irradiation measurement [73], and (**d**) final results.

Table 6. Summary of smartphone applications for potential assessment of PV systems.

Name of App	Developer/Company	Platform	Price [a]	Function	PV Power Output			For Roof/Rooftop	Source of Irradiation	Reference
					Hourly	Daily or Monthly	Yearly			
SolarUp—PV Solar Design Tool	Earth Wise LLC	iOS	Free	Analysis & Simulation			•	•	Unknown	[59]
Solar Analyzer	Lewis O'Leary	Android	Free				•		NASA	[60]
Solar PV Optimal Spot	Simone Rizzo	Android	Free			•			PVGIS [b]	[61]
PV Solar Calculator	SRey.net	Android	Free			•			User input	[62]
PV OptiMizer	Exemplary Energy	Android	Free			•		•	NOAA [c]	[63]
SolarPV	Hursh Hazari	iOS	Free			•		•	Unknown	[64]
SolarTester	Optivelox	Android	Free		•				NASA	[65]
Scan The Sun	Scientific Mobile	Android	Free		•			•	NASA	[66]
Solar Engineering Calculator	Green Engineering Tips	Android	Free	Analysis & Simulation + Measurement			•		SolarGIS [d]	[67]
SolarMeter ǀ Sun Energy Planner	VisTech.Projects LLC	iOS	$3.99			•		•	Measurement	[68]
SolarMeter Solar Panel Planner	Vistech.Projects	Both	$3.99			•		•	Measurement	[69]
Solar Panel Simulator for PV System 3D	NRG Labs	Android	$3.81			•			NASA	[70]
SolarMore	Ying Hao Wu	iOS	$14.99			•			Measurement	[71]
SolarCT—Solar PV Systems	M. N. N.	Android	Free		•				NASA and NREL	[72]
SolarTester Pro	Optivelox	Android	$8.45		•				NASA or Measurement	[73]

[a] Price in USD, [b] PVGIS: https://cc.europa.eu/jrc/en/pvgis, [c] NOAA: National Oceanographic & Atmospheric Administration for the Japan Meteorological Agency, [d] SolarGIS: https://solargis.com/maps-and-gis-data/overview (accessed on 27 February 2021).

4.5. Environmental and Economic Assessment of PV Systems

The fifth topic of solar PV apps is environmental or economic assessment of PV systems. The layout design function of the PV system is also included in some apps. Table 7 lists smartphone apps in this category and their developer/company, platform, price, and main functions. Unlike conventional power generation approaches (e.g., thermal steam or nuclear), renewable energy resources, including PV, have environmental advantages but also economic limitations due to their high costs. Therefore, most PV projects often estimate not only the potential power generation, but also the environmental benefits and economic profitability. Some apps in this category can also measure the optimal tilt and orientation of PV modules [74–77], which were already discussed in detail in the previous subsection.

PV power generation is commonly an indispensable input factor to assess environmental benefits (e.g., CO_2 emissions reduction) or economic profitability (e.g., expected profit, payback period, internal rate of return) of a PV system. Therefore, some apps in this category cover not only environmental and economic evaluation, but also estimation of PV power generation. Conversely, a couple of apps simply assess the environmental or economic benefit by inputting the PV power output. Accordingly, the apps were divided into three groups: only economic assessment, potential and economic assessment, and all three aspects assessment (potential, environmental, and economic).

A couple of apps can only assess the economic profit of PV systems by entering several input values [78–80]. These apps estimate revenues for various conditions and situations considering the balance of system (BoS). The Sunny Solar Panel Calculator [79] allows users to input various parameters, such as amount of panels, panel capacity, panel tilt, power price, based on which it estimates the average yearly profit. The PV Profit Calculator [80] estimates the potential profit of a PV system in a spot market more accurately by entering various parameters such as installation type, capacity of power plant with sunshine hour (automatically retrieved by selecting a date and region in the app) or power generation, system marginal price (SMP), price, and weight of renewable energy certificate (REC; subsidy) (recent DB provided).

Several apps can evaluate both PV potential and economic profitability [74,75,81–85]. These apps estimate PV potential by setting of options and parameters, and the economic profit is assessed based on the estimated PV potential. Most of these apps provide a cash flow diagram for the PV plant (the net amount of cash and cash-equivalents transferred in and out of a PV business) to clarify the costs and benefits considering compound interest over time. The expected yearly profit and payback period for different scenarios are then analyzed. However, the accuracy of the financial analysis is not high as the assumptions and parameters provided are not close to actual values in PV businesses.

Numerous apps can assess power generation, environment benefits, and economic profits of PV systems [76,77,86–90]. The environmental and economic assessments are performed after estimating the power generation. The processes and accuracies of the economic and energy production results were similar to those of the above apps. However, many of these apps also express the amount of CO_2 emissions reduced through PV power generation, or the corresponding effect in various kinds of values such as miles not driven, gasoline not used, coal not burned, crude oil not used, mature trees grown, or recycled garbage. The apps provide various additional functions in addition to these three main features. The Photovoltaic Estimation & IR app [85], for example, provides a feasibility study that shows the economic advantages of using PV insulation glass for canopy or walkway of buildings.

Some apps also provide feasibility analysis suitable for roof and/or ground PV systems [58,59,75,88,90]. Furthermore, a couple of apps allows virtually placing PV arrays on the roof through high-resolution satellite images [59,88] or on the ground through a map [58], as summarized in Table 7. The most representative app that includes all features mentioned above (i.e., assessment of all three aspects, applicable to roof PV, and PV array design) is the Mapdwell Solar System app [88], which reveals the PV potential of a building rooftop by intuitively designing the type and layout of PV array on the satellite image considering the rooftop shape, local weather, and shading from nearby structures and vegetation (Figure 5). It also helps decision making via comprehensive cost-benefit analysis.

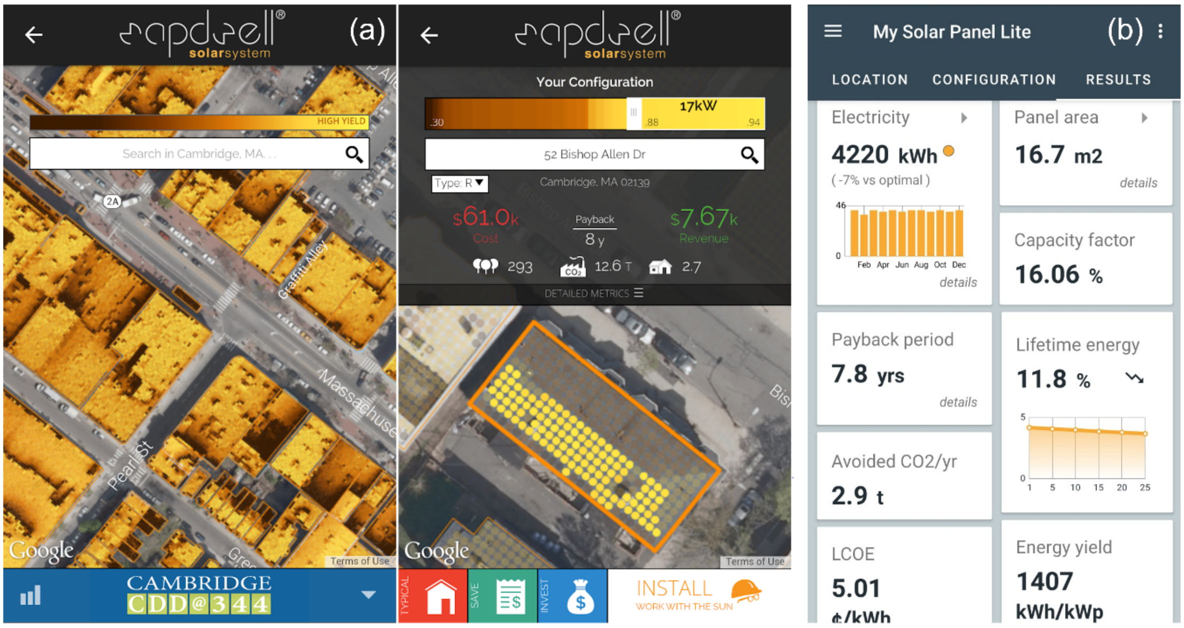

Figure 5. Representative smartphone applications for assessment of environmental benefits and economic profit. (**a**) Mapdwell Solar System app [88], (**b**) My Solar Panel Lite app.

4.6. Monitoring and Control of PV Systems

The sixth topic of solar PV apps is monitoring and control of PV systems. Table 8 lists the corresponding apps and their developer/company, platform, price, and main functions. The main purpose of these apps is to monitor and log various details of a PV power system and the local environment. The CO_2 emission reduction or profitability mentioned in earlier sections were included in the monitoring items of some apps. If only the final value was included in the monitoring item (without principles of calculating process), the app was assigned to the current category, not the previous one. Apps for a certain solar product of a company were included in this category only if they provide various information. The app price ranged within 0–31.00 USD.

Numerous apps can monitor and log the details of a PV system and the local environment [91–102]. They monitor and provide visualization of various PV system information in different time ranges (i.e., hourly, daily, weekly, monthly, and yearly), such as power production, power consumption, power exported, power imported, profit, efficiency, irradiation, ambient temperature, module temperature, voltage, current, inverter, and battery. Many of them provide a function to download historic statistical data for a certain data range than enables the analysis of the PV power generation pattern. The type of information provided in each app is different, but the functional aspects are similar. Only a few apps provide supplementary functions in addition to the basic features. The SunPower Customer Portal app [93] shows various environmental savings and benefits upon electricity generation in the PV system, including CO_2 emissions avoided, miles not driven, gasoline not used, coal not burned, crude oil not used, mature trees grown, and garbage recycled. The Tigo SMART app [96] is a PV management tool with an intuitive interface that allows users to design a PV array layout. SolarAnalyzer Pro for Android™ [97] provides a PV yield prediction function based on weather forecast.

Table 7. Summary of smartphone applications for environmental and economic assessments of PV systems.

Name of App	Developer/Company	Platform	Price *	Function	Assessment			For Roof/Rooftop	Reference
					Power	Environment	Economy		
PV Optimizer & Solar Compass	Joao Caetano	iOS	Free	Measurement + Analysis & Simulation	•		•		[74]
Solar Kumbara	Solar Kumbara	Both	Free		•		•	•	[75]
My Solar Panel	NRG Labs	Android	$6.68		•	•	•		[76]
SolarCalc Pro—Solar PV & Electrical Calculator	SolarElectroCalc	Android	$11.00		•	•	•	•	[77]
Payback Solar	WEG	Both	Free	Analysis & Simulation			•		[78]
Sunny Solar Panel Calculator	Maantje	Android	Free				•		[79]
PV Profit Calculator	Mal-eum	Android	$3.00				•		[80]
PEA Solar Hero	Provincial Electricity Authority	Both	Free		•		•		[81]
iSolergo	ELECTRO GRAPHICS SRL	Android	Free		•		•		[82]
Solar Power Evaluator	Evaluate Solar LLC	iOS	Free		•		•		[83]
AHA Solar	AHA! Rooftop Solar Helper	Android	Free		•		•		[84]
Photovoltaic Estimation & IR	ONYX Solar Energy S.L.	Android	Free		•		•		[85]
Solar Application	Juan Arias	iOS	Free		•	•	•		[86]
My Solar Panel Lite	NRG Labs	Android	Free		•	•	•		[87]
Mapdwell Solar System	Mapdwell LLC	Both	$4.99		•	•	•	•	[88]
PV Forecast: Solar Power Generation Forecasts	NRG Labs	Android	Free		•	•	•		[89]
SolarCalculator	Changzhou Trina Solar Energy Co., Ltd.	iOS	Free		•	•	•	•	[90]

* Price in USD.

Many apps can compare the electricity generated and consumed (load) through monitoring and logging of PV system components, such as modules, inverters, and batteries [103–110]. Although some design functions, such as layout and configuration of PV arrays are also included, this study determined that monitoring and logging are the main functions of those apps. Most of them summarize hourly, daily, weekly, or monthly power generation and consumption over the years for the entire system or each module, and provide visualization of an intuitive dashboard including comparison table, graphs, diagrams, or charts (Figure 6a). Several apps also provide an energy flow diagram including the PV system, battery, grid, and home [105–110]. The intuitive energy flow of the PV system allows users to further understand potential savings, battery storage, and electricity import and export in a micro-grid system (Figure 6b). Users can remotely monitor all the energy flows and the performance of their own solar plants, with and without an energy storage installed. From these results, the user is able to control the components connected with the PV system while away from the PV sites. There was only one paid app that allows users to check the current status and history of PV inverters [111].

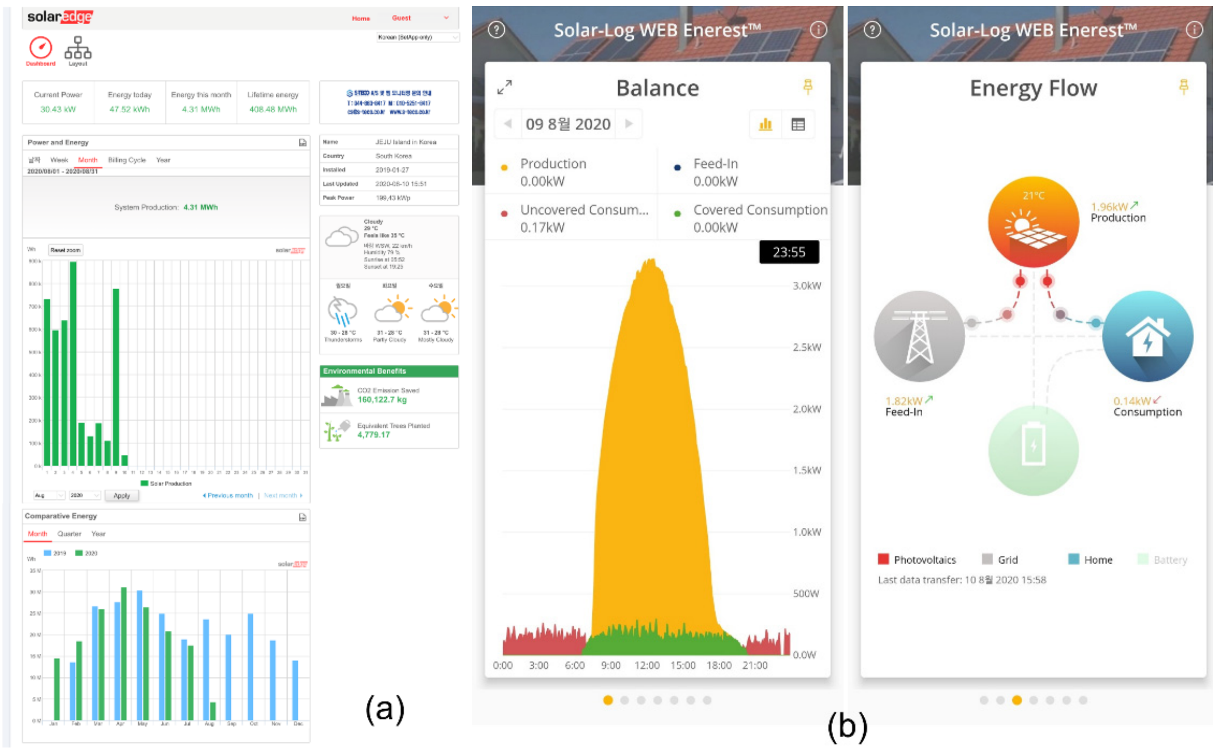

Figure 6. Representative smartphone applications for monitoring and control of PV systems: (**a**) PV system monitoring and logging (SolarEdge Monitoring app), and (**b**) energy flow (Solar-Log WEB Enerest™ app).

Table 8. Summary of smartphone applications on monitoring and control of PV systems.

Name of App	Developer/Company	Platform	Price *	Function	Production vs. Consumption	Energy Flow	Reference
Felix Solar PV Log	Felix The Puddy Tat	Android	$8.12	Monitoring & Control			[91]
Solar Watch for SolarEdge	Marko Radakovic	iOS	$2.99				[92]
SunPower Customer Portal	SunPower	iOS	Free				[93]
FusionSolar	Huawei Network Energy	Android	Free				[94]
PV Monitoring & Management Application	Form Elektrik	Both	Free				[95]
Tigo SMART	Tigo Energy	Both	Free				[96]
SolarAnalyzer Pro for Android™	sunics.de	Android	$31.00				[97]
Solar Energy Monitor	Imperial Innovations	Android	Free				[98]
Oxley Solar Pro	Oxley Web Services	Android	$6.00				[99]
Cloud PV	MRT	Android	Free				[100]
ReMACS Solar Monitoring FlexiMC	FlexiMC Solutions Private Limited	Android	Free				[101]
PV Monitoring	D&E Lab	Android	Free				[102]
PVOutput Pro	Corrado Bellini	Android	Free		•		[103]
PV Output	Marlon Buntjer	Android	Free		•		[104]
Photovoltaic Monitor	Conena	Android	Free		•	•	[105]
Sunny Portal	SMA Solar Technology AG	Both	Free		•	•	[106]
SolarEdge Monitoring	SolarEdge Technologies	Both	Free		•	•	[107]
Enphase Enlighten	Enphase Energy, Inc.	Both	Free		•	•	[108]
Solar-Log WEB Enerest™	Solare Datensysteme GmbH	Both	Free		•	•	[109]
Energy Viewer	ABB Information Systems AG	Both	Free		•	•	[110]
DazzleSoft Solar Kostal Piko	DazzleSoft	Android	$3.50				[111]

* Price in USD.

4.7. Education and Learning of PV Systems

The last topic of solar PV apps is education and learning. Table 9 lists the corresponding apps and their developer/company, platform, price, and main functions. The apps in this category show the principles or conceptual diagram of a general PV system rather than a manual only for a specific product. Apps that deliver solar news were excluded. The apps in this category mainly show the structure or operating principles of PV systems, explain the connection method for various types of system, or provide a PV-related DB. Most investigated apps were free, but one was 4.00 USD. As they provide relatively simple functions, the role of built-in sensors was difficult to define.

Table 9. Summary of smartphone applications for education and learning purposes of PV system.

Name of App	Developer/Company	Platform	Price *	Function	Reference
Full Solar Wiring Diagram	Devdroid79	Android	Free	References	[112]
Solar Panel Wiring Diagram	BTStudio	Android	Free		[113]
Solar Panel Diagram Wiring Free	Florentinus WD	Android	Free		[114]
Solar Wiring Diagram Free	Wiring Diagram	Android	Free		[115]
Solar Wiring Diagram Best	Electrical Studio	Android	Free		[116]
Solar Energy Systems	The JAMBRONG	Android	Free		[117]
Solar PV Technology Mobile Course	Ishan Talks Apps	Android	Free		[118]
PV Local Laws and Regulation	Mal-eum	Both	$4.00		[119]
SolarDanawa	Bitmoa	Android	Free		[120]

* Price in USD.

Several apps can show image-based solar PV wiring diagrams for educational purposes [112–117]. They provide a simple visual representation of the physical connections and layout of an electrical system or circuit. They show how the electrical wires are interconnected and where fixtures and components can be connected to the system for grid-connected or off-grid PV systems. Conversely, the Solar PV Technology Mobile Course app [118] provides a flexible learning course with quizzes for practicing electricians who have basic skills in electrical, mechanical, or electronics field (Figure 7). This educational app emphasizes the development of practical and theoretical knowledge in basic solar PV technology, products, and systems. It covers various topics such as electrical concepts, PV modules, battery, charge controller, system sizing, and system maintenance.

A couple of DB-type apps were also observed, and they allow users to retrieve specific data. The PV Local Laws and Regulation app [119] can be used to easily search information on national or regional laws related to solar PV energy in Republic of Korea. It covers legal information such as permission to develop activities (i.e., guidelines for permits, city planning ordinances), permission for power facility development, basic energy ordinance, low-carbon green growth ordinance, PV promotion ordinance, autonomous law, and solar construction bidding. For instance, it clarifies that the separation distance between residential areas or roads and a PV system to be installed is different for each region within a province. The SolarDanawa app [120] provides a DB of manufacturers of PV system equipment such as solar modules, solar inverters, connect boards, and PV system monitoring in Republic of Korea. Through these apps, solar vendors, government officials, and researchers responsible for solar projects can easily and quickly find useful information.

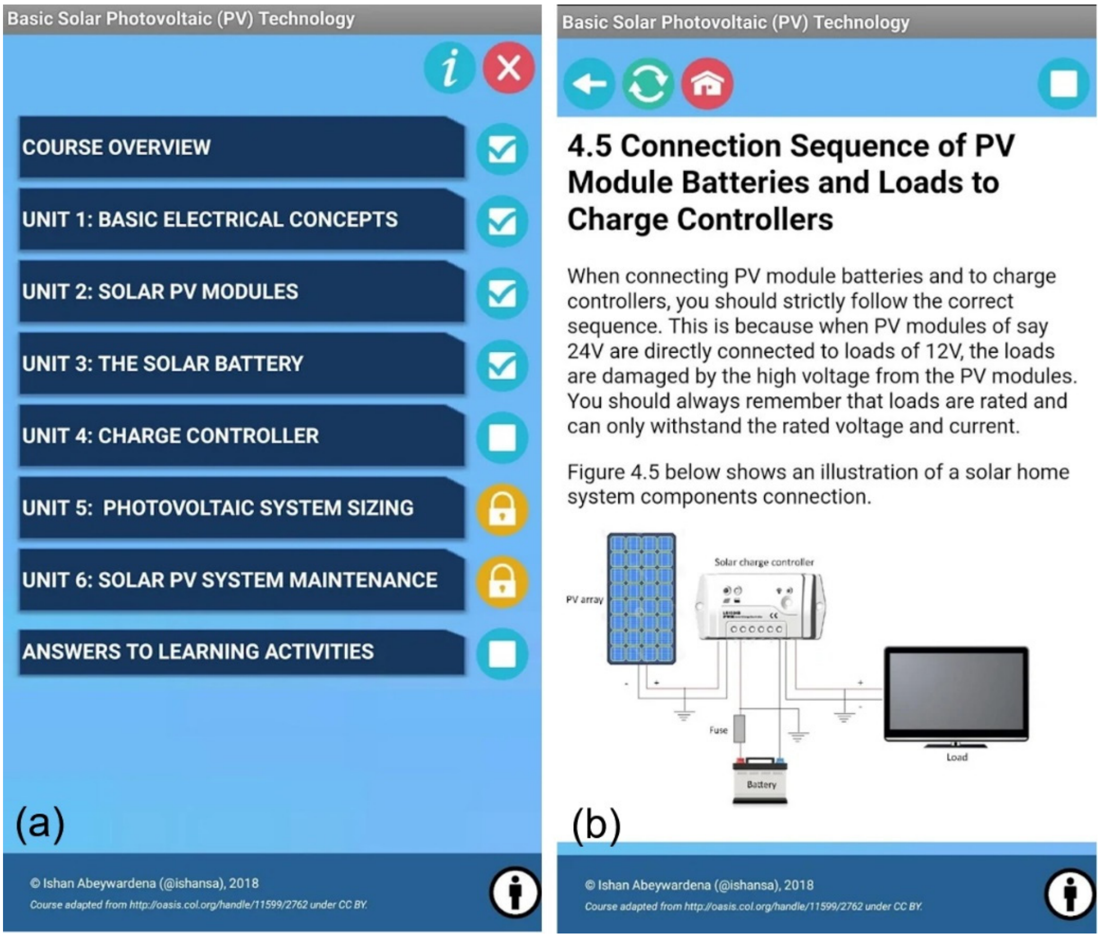

Figure 7. Representative smartphone application (Solar PV Technology Mobile Course) for education and learning purposes related to PV systems: (**a**) outline of educational course, (**b**) educational material.

5. Discussion

5.1. App Cost and Topic

Figure 8 shows the price and ratio of PV apps according to their topic. Free apps accounted for 74%, and paid apps for 26% of the 100 analyzed apps. The price of most paid apps ranged within 0.99–10.00 USD, and the most expensive app was 31.00 USD. The cost to use some apps increases through in-app purchases for additional functions, but this part was excluded from the analysis. The costs of external sensors, such as a pyranometer, was also not considered. Nevertheless, considering that the apps provide functions that can partially substitute measuring equipment or analyzers, their prices were considered reasonable.

As a result of comparing paid apps and free apps, it was found that, in general, paid apps provide various functions or materials more than free apps. In the case of an app that has both the Lite version and the Pro version, there are examples of allowing an external insolation sensor to be used by connecting it to a smartphone instead of inputting statistical value. Some paid app allows reliable NASA weather information to be used instead of entering simple weather information to estimate PV power output. However, considering that the app selected as the representative app in four of the six topics is free, it should be noted that this does not mean that the function or usability of the free app is low-level.

The interest in energy prosumers, community solar, and micro-grid systems has increased rapidly due to the influence of decentralization energy production policies. There are increasing cases of individuals or local communities producing PV power in unused areas of residential buildings. Therefore, apps associated with PV on roofs or rooftops are expected to be increasingly used at the individual or local community level. A rooftop PV app with new functions is also expected to be developed in the near future.

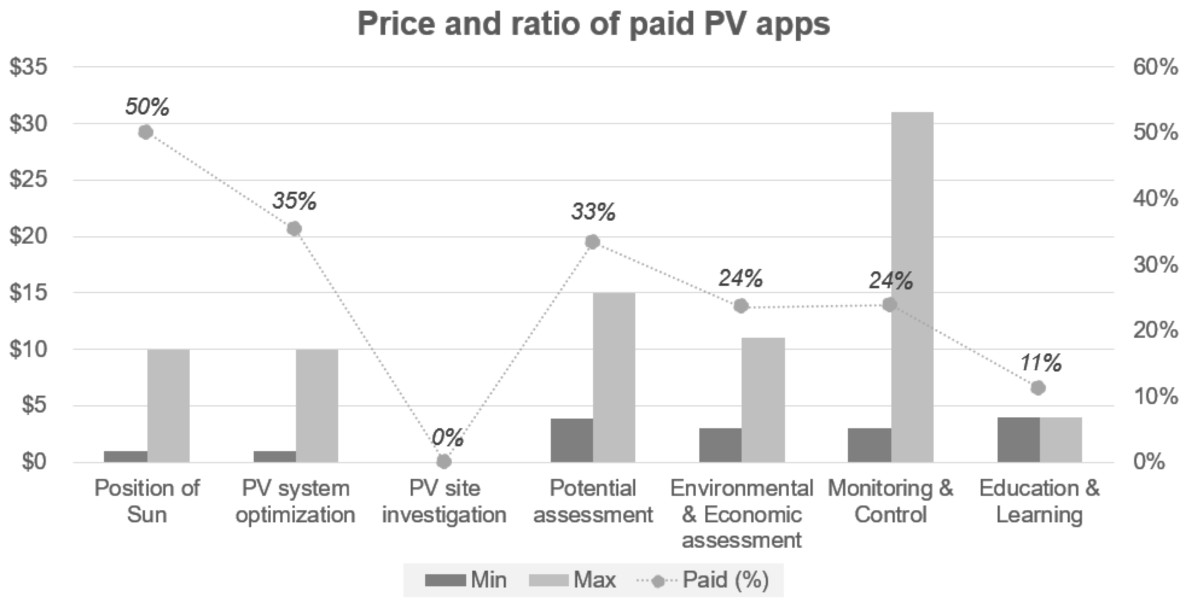

Figure 8. Price and ratio of paid solar PV apps according to their topic.

Table 10 summarizes smartphone apps for roof or rooftop PV systems according to their topic. These apps allow the user to remotely extract various characteristics of roof or rooftop, such as shape (pitched or flat), area, tilt, and orientation, using high-resolution satellite images. They can also suggest the optimal layout of solar arrays or installation methods based on the extracted characteristics. The power generation can also be assessed based on PV system capacity and solar irradiance according to the geographic location. Furthermore, they can be used to assess environmental or economic effects over time. Game apps on solar energy topics could provide interesting learning motivation for this field and help users to become familiar with solar PV technology. Given the growing interest in gamification of learning as a new strategy in the field of education, an app for solar energy games could be developed for such purpose. Apps for different types of PV systems (floating, rural, mine, and BIPV) should also be developed.

Table 10. Summary of smartphone applications for education and learning purposes of PV system.

Topic	No.	Apps Associated with Roof PV or Rooftop PV
PV system optimal settings	1	Solar Calculator [44]
PV site evaluation	3	Solar Consult [55], RoofSnoop [56], SolarUp—PV Solar Design Tool [58]
Potential assessment of PV system	5	PV OptiMizer [63], SolarPV [64], Scan The Sun [66], SolarMeter ∣sun energy planner [68], SolarMeter—GPS Cell Panel Planner [71]
Environmental & economic assessment of PV system	3	Solar Kumbara [75], Mapdwell Solar System [88], SolarCalculator [90]
∑	12	

5.2. Sensor Issues for an Alternative PV Design Tool

Sensor issues include the applicability of sensors within the app and the sensing quality. These issues are closely related with the utilization scope of apps in the solar PV field and the possibility of replacing existing equipment or software for PV projects.

The first issue is the usability of built-in or external sensors within the app. Table 11 summarizes various sensing features of solar PV apps, associated sensors, and corresponding apps. Various types of built-in sensors (GPS, optimal image sensor, gyroscope, accelerometer, magnetometer, and ambient light sensor) can be used to measure physical properties or data in various ways at PV sites. AR-based apps have advantages in educational aspects as they can improve the learning process while increasing the interest in solar energy by providing intuitive visualization of the sun trajectory.

Table 11. Sensing features of solar PV apps and corresponding hardware sensors of smartphones.

Features of Solar PV Apps	Sensor	Reference
Automatic location awareness	GPS	[21–29,31–34,45,50,51,53,54,56,57,59,63,65–76,81,82,84,87–89]
Access to external meteorological data	GPS	[39,53,57,60,61,63,65–67,72,73]
AR visualization	GPS, optical image sensor, gyroscope	[21–26,28,29,57,66]
Measurement of module tilt	Accelerometer	[31–35,50–54,60,65,70–74,76,89]
Measurement of module orientation	Magnetometer	[35,65,67,70–74,76,89]
Measurement of roof tilt	Accelerometer	[55,56,65,68,69,75]
Measurement of roof orientation	Magnetometer	[55,56,65,68,69,75]
Estimation of solar radiation by measuring the ambient light level	Ambient light sensor	[71]
Measurement of solar radiation or UV	Pyranometer (external)	[48,73]

Few apps utilize external sensors, such as a solar radiation sensor. The measurement accuracy of an external solar radiation sensor is lower than that of existing devices. However, these sensors are useful as they allow solar radiation data to be measured using a smartphone, not a pyranometer. This suggests that smartphone apps will likely replace various equipment or devices required at PV sites. From this standpoint, external sensors and corresponding apps should be further developed. Apps that employ built-in sensors such as barometer, ambient temperature sensor, and humidity sensors were not found, which was ascribed to the sensor quality problem. If the accuracy of built-in sensors increases, the utilization of apps in this field will likely expand. For example, improved sensors would provide more accurate estimations of PV power generation through field measurements compared to the use of nearby weather information.

Smartphone apps can also be a substitute for several equipment commonly used in PV sites including writing instruments, voice recorder, compass-clinometer, and digital camera, which are available within a single device. Memos, documents, and cameras enable users to acquire PV project information in field areas. Moreover, the latest version of web-browsers in the smartphone offers various functions to data collection and field applications web-based digital mapping of solar radiation DB.

The second issue on this topic is sensor quality. A collection of data on physical properties at the PV sites rely on sensors. These sensors play a key function in the field property investigation with the help of the mobility of the smartphone and its own data processing and transmission functions. Therefore, it is essential to develop related hardware and software technologies to improve the accuracy and accuracy of measurement and expand the applicability. Nonetheless, only few apps explain the measurement accuracy of the apps.

Smartphone built-in sensors are based on microelectromechanical systems, so the accuracy, precision, and sensitivity of these sensors are low [121]. Therefore, prior calibration is highly required to obtain accurate value. In general, the current OS performs the calibration process itself, thereby offering calibrated property values. Nonetheless, the built-in sensors of latest smartphones are sufficiently improved to be used to measure the physical properties in the PV sites. The accuracy of accelerometer, one of the built-in sensors, is similar or higher to that of a digital compass instrument [18]. Nonetheless, if the level of uncertainty is high, calibration or improvements can be performed through measurements using additional equipment. However, internal interference issues are closely related with the internal construction of device and can therefore not be cleared up by enhancing the sensing capability independently. With the improvement of sensing technology, appropriate calibration techniques should be accompanied [121].

In order to take place of conventional measurement instrument used in solar PV energy by smartphones, the consistent simulation of the output of the equipment and their characteristics (i.e., accuracy, precision, and sensitivity) is necessary. There are different kinds of hardware packages with different specifications although the user employs an identical platform. Thus, a measurement using the same algorithm cannot yield the same level of results, which implies that numerous smartphones with different packages should be tested to ensure accurate measurements. Consequently, appropriate calibration should be carried out for different hardware.

6. Conclusions

In this study, numerous commercially available smartphone apps available in solar PV energy sector was reviewed from various perspectives, including main topic, features, functions, cost, platform, and sensors. The 100 analyzed apps were categorized into several topics associated with solar PV design projects. Although some apps have been designed for data visualization or simple calculations, numerous other apps can be utilized for practical purposes such as sensor-based measurements, high-level simulation, and system design. The current status of the solar PV apps reflects the advances in hardware technology for smartphones, which is increasingly integrated with a variety of built-in and external sensors. At present, most apps with sensor-applied software programs perform only simple measurements or visualizations. However, an integration of advanced software capability and additional analytic functionality can make it possible to develop solar PV apps of wider variety and applicability.

Solar PV smartphone apps can be effectively used by the common public as an analysis tool, or to learn strategies for both solar energy design and energy issues due to their strengths (i.e., smartphone capability and various contents and usefulness of apps) and current opportunity factors (prevalence of smartphone use, popularization of energy issues, and need for education). The overall capabilities of smartphones and their built-in sensors will gradually evolve. As such, if various external sensors are developed, the applicability of apps in PV sites will increase. Nonetheless, there are still limitations for smartphone apps to substitute existing desktop-based solar design tools in the expert domain for PV projects. This shift would require a significant amount of data and option settings, and a high degree of accuracy and reliability of input data and analysis algorithms. Since the investigated apps can be used to analyze or design site characteristics or PV systems at a certain level, it is expected that they can partially substitute existing equipment and can be used in combination with desktop tools in preliminary feasibility studies of PV projects. This research is of great significance in that it is the first to review the current status, implications, and future perspectives of 100 smartphone apps that can be used effectively in the solar PV field. This review paper can be used as a basis to help researchers, developers, and future energy prosumers to propose appropriate apps, and it provides basic data for further app development in the future.

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Abbreviations

The following abbreviations are used in this manuscript:

Apps	Applications
AR	Augmented Reality
BIPV	Building-integrated PV
BoS	Balance of system
COP21	Conference of the Parties 21
CO2	Carbon dioxide
DB	Database
DHI	Diffuse horizontal irradiance
DNI	Direct normal irradiance
GHI	Global horizontal irradiance
GIS	Geographic information system
GPS	Global positioning system
I_{mp}	Maximum Power Current
I_{sc}	Short-Circuit Current
NASA	National Aeronautics and Space Administration
NREL	National Renewable Energy Laboratory
OS	Operating System
PV	Photovoltaic
REC	Renewable energy certificate
SMP	System marginal price
STC	Standard test conditions
TMY3	Typical Meteorological Year 3
TOF	Tilt and orientation factors
UV	Ultraviolet
USD	US Dollars
V_{oc}	Open-Circuit Volt
V_{mp}	Maximum Power Volt

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