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Advanced modelling of E/UIPV systems from location to load

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***Abstract* — We report on an advanced modelling approach to accurately predict the energy yield of custom environment / urban integrated photovoltaic systems (E/UIPV). Several sub-models are here presented, and their mutual interaction discussed. The flexibility of our software platform allows to exhaustively simulate custom horizons in combination with rigid/flexible PV modules and in presence of albedo component. In this respect, a modelling example predicts AC-side yield with < 1% error on annual basis with respect to actual data. In addition, our platform can also deal with colored/bifacial modules and soiling losses for PV energy yield potential or performance prediction.**

***Index Terms* — Environment integrated PV systems, urban integrated PV systems, modelling, custom horizons, DC-to-AC side yield, soiling.**

I. Introduction

Environment / Urban Integrated Photovoltaic (E/UIPV) systems are progressively used for decentralized electricity generation. The notion of E/UIPV systems includes not only classical low environmental-impact built-added PV (BAPV) and modern building integrated PV (BIPV) systems but also those PV systems that are incorporated both aesthetically and functionally in the place of installation (a building, a road, a neighborhood, etc.) [1][2]. These can be flexibly-expandable modular systems, designed to address specific aesthetical or functional requirements and to exhibit both very high yearly self-consumption of energy and/or very high yearly energy yield. To obtain the maximum energy yield from such systems, the optimal combination of all components is essential as well as their accurate and integrated modelling. In this contribution, we present a comprehensive software platform to remotely model arbitrary E/UIPV systems. We first report on the key components of our platform and later we provide with an example of energy yield prediction of a BAPV system which deviates less than 1% from the measured accrued energy yield. Finally, we discuss special features that will be embedded in a toolbox endowed with a unifying graphic user interface as well as in the Dutch PV Portal 2.0 [3].

II. Modelling approach

Our software platform allows the design of E/UIPV systems to be installed in any location, since it considers shading conditions as function of the height of the installation site and of its horizon. Also, it accounts for the whole chain from the PV panels to the load(s) passing through the related power electronics. In other words, our modelling approach goes *from the DC side to the AC side* [4]. The only inputs needed are the specifications of the chosen PV module, the GPS coordinates of the installation site, its horizon, its geometry, its meteorological conditions, and the eventual load profile (see Fig. 1). We base our modelling efforts on six key components:

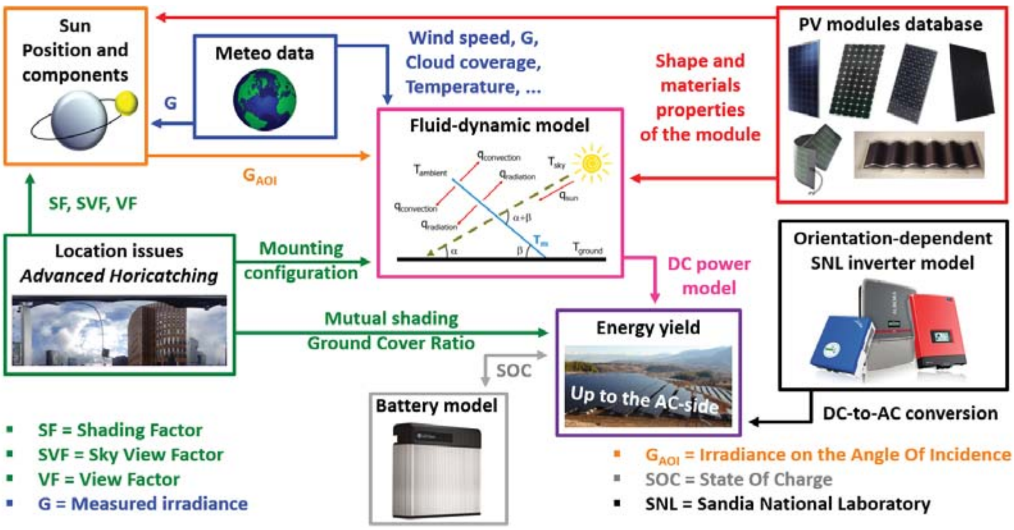

Fig. 1 Schematic of our modelling platform, which rotates around the fluid-dynamic model. From the estimation of the PV modules temperature, which depends on the charactistic of the location, of the meteorological conditions and of the PV module technology and model; and from the choice of the proper inverter, the time-dependent power model furnishes the instantaneous power produced by the E/UIPV system at the AC side.

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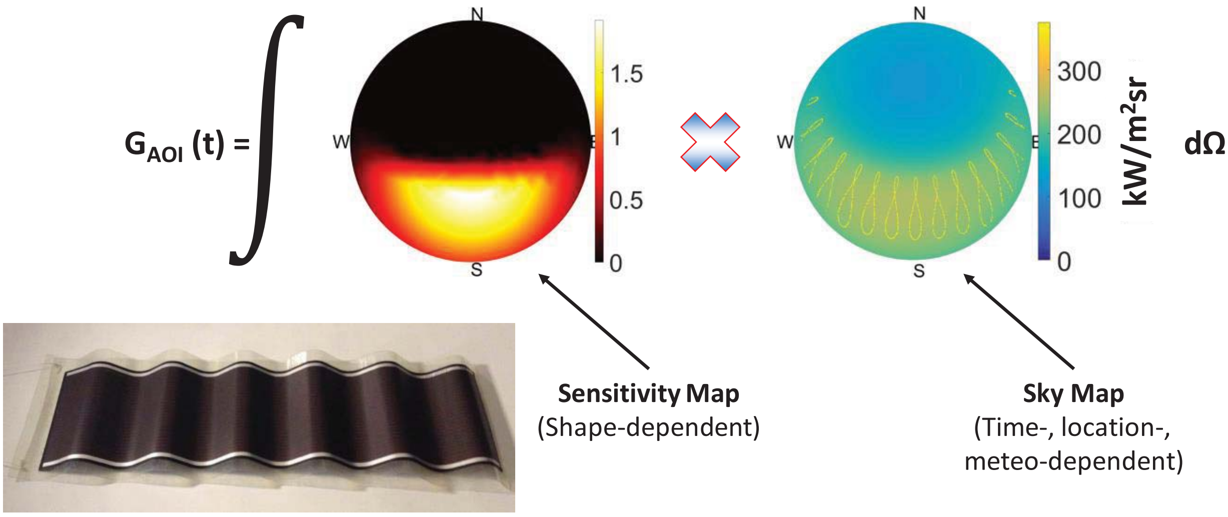

Fig. 2 Time-resolved irradiance on custom modules in horizon-free conditions obtained by convoluting the sensitivity map with the sky map [19].

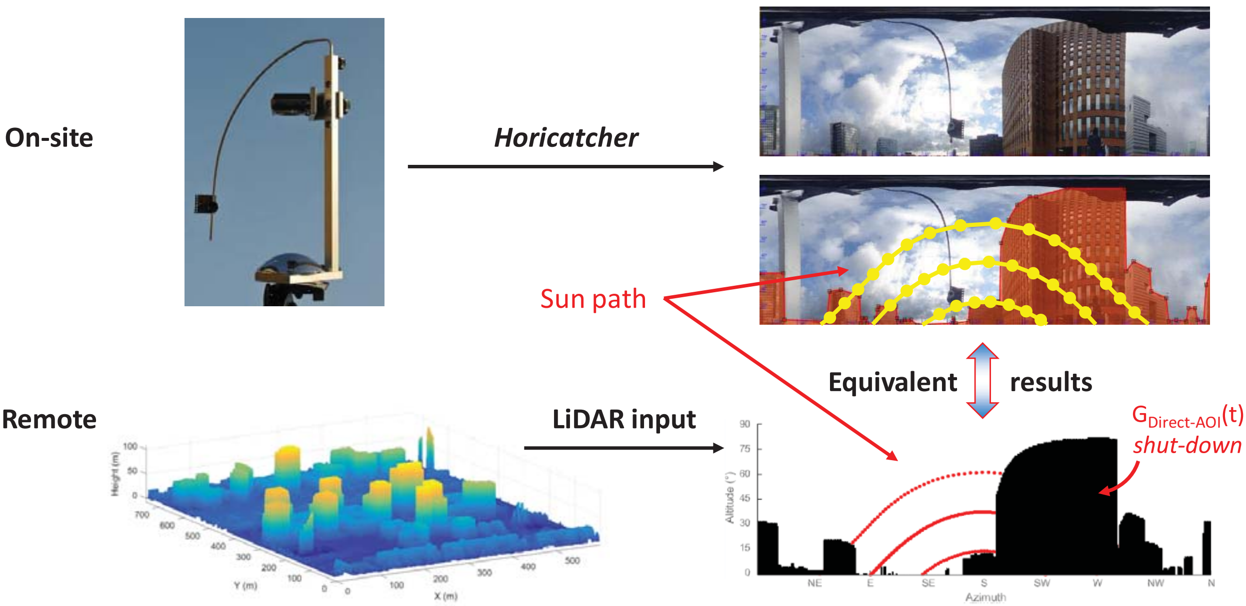

Fig. 3 Comparison between on-site and remote horicatching. If LiDAR data input is avaialable [7], results are equivalent. When the Sun, in different moments during the year, is behind surrounding shading ojbects or constructions, the $G_{Direct\text{-}AOI}$ has to be de-rated to 0 W/m^2.

(i) arbitrarily (curved) custom-shaped PV modules optically modelled via ray tracing sub-routines [5][6]; (ii) location-aware and meteo-aware sunlight components (direct, diffuse and albedo) based on LiDAR data [7], CAD software [6][8], and meteorological (real-time) data [3][9][10] with the eventual support of decomposition [11] and transposition [12][13][14] models; (iii) fluid-dynamic effects [15]; (iv) Sandia National Laboratory (SNL) inverters model [16] for tilt/azimuth-dependent sizing [3][4]; (v) state-of-charge battery management for off-grid [17] and hybrid grid-connected PV systems [4]; (vi) real-time irradiation-dependent and temperature-dependent power model [18]. Using all these sub-models, it is possible to remotely carry out the design of arbitrary E/UIPV systems and accurately estimate the energy yield prediction.

III. Results and Discussion

In any E/UIPV system design, the assessment of the PV potential comes first. Then, the design, the validation, and the eventual data mining follow. For a starter, the components of sunlight must be found to compute the time-dependent irradiance on the module, G_{AOI} (angle-of-incidence, AOI). In case of free horizon and custom-shaped PV module, time-resolved irradiance can be computed convoluting the *sensitivity* map from ray-tracing with the *sky* map, which is time-, location- and meteo-dependent (see Fig. 2) [19].

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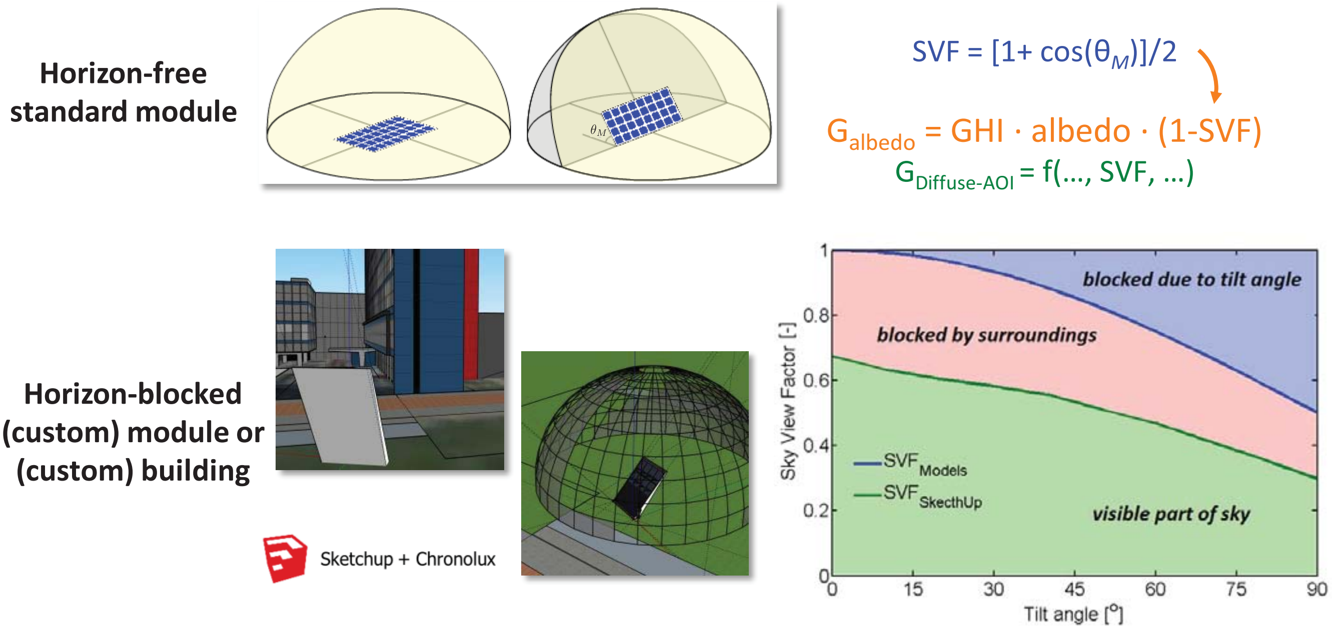

Fig. 4 CAD-enabled Sky View Factor (SVF) computation. A more accurate estimation of SVF gives better grip on the G_{albedo} and the $G_{Diffuse}$ components, which are instrumental in the proper treatment of E/UIPV systems especially if endowed with bi-facial PV modules.

In case of blocked horizon, whatever is the shape of the PV module, the direct component of G_{AOI} ($G_{Direct\text{-}AOI}$) needs to be derated or even *shut-down* for certain moments in time. This is what is called horizon catching (*horicatching*), which is accomplished on-site with a fisheye lensed camera and overlaying on the resulting image the yearly path of the sun at that location [20]. In our remote approach, satellite-based LiDAR data give equivalent results (see Fig. 3). In absence of such an input, the design of the entire neighbourhood in a CAD environment will do as well. In modern cities with tall glassy buildings and/or in case of recent bi-facial PV modules, also the albedo component (G_{albedo}) plays a crucial role. This component is function of both global horizontal irradiance (GHI) and sky view factor (SVF). By using CAD software, it is possible to find out per each specific installation site which part of the SVF is blocked by surroundings (see Fig. 4). A more accurate estimation of SVF allows also for a better modelling of the $G_{Diffuse}$ component.

Referring to Fig. 1, the PV potential of a certain location in terms of G_{AOI} (W/m^2) is - at this point - known. The subsequent design of the E/UIPV system starts by estimating the temperature of the chosen PV module (T_M). The powerful fluid-dynamic model devised by Fuentes [15] is preferred here and in [18] over (i) the NOCT model [21], which does not depend on wind and it is not applicable to any climate; and (ii) its modification by Duffie & Beckman [22], which crudely underestimates T_M. On the other hand, the Fuentes model depends on wind and other meteorological conditions, differentiates between turbulent and laminar flow, is applicable to any climate and can be adapted to both open rear and bolted modules. As all the inputs converging to this sub-module are time-dependent, also T_M is time-dependent.

Given a certain PV module, G_{AOI} and T_M finally allow to compute not only the DC-side yield in a period, but also the time-dependent V_{OC} or V_{MPP} of the PV module/array. This is the input that facilitates the choice of a certain inverter. In fact, deploying the SNL model [16] and from the massive SNL database [16], the right inverter(s) can be chosen not only based on the installed peak power but also on the input voltage of the string(s), which is function of the installation orientation [3][4]. In fact, when PV modules are oriented away from the optimal tilt and orientation, the PV system will have power outputs far below the installed capacity for most hours. It is then beneficial to select a smaller inverter capacity as this results in an increase in conversion efficiency compared to an inverter with a nominal conversion capacity equal to the installed PV capacity, as shown in Fig. 5. Convoluting the time-dependent DC-side output power with the time-dependent efficiency of the inverter, the power

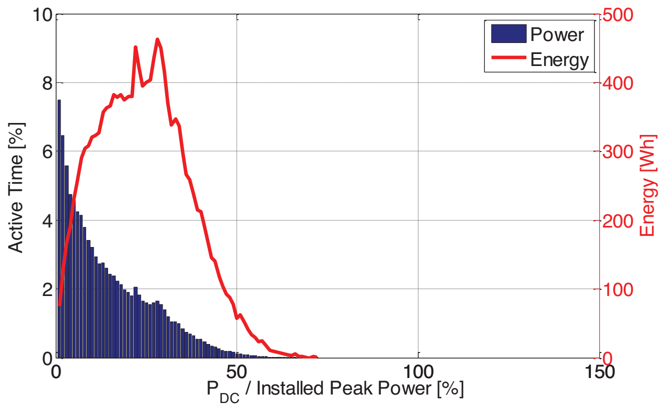

Fig. 5 Effect of inverter capacity choice on the DC-to-AC conversion efficiency. The PV system evaluated has a 1 kWp capacity, a tilt of 45° and an azimuth of 0°

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output at the AC-side is finally obtained.

For off-grid and hybrid grid-connected E/UIPV systems, the knowledge of the load profile is essential not only for the appropriate computation of the installed PV capacity, but also for the correct dimensioning of the battery bank [4][17]. In this respect, a sub-model that describes the state-of-charge of the battery bank [16][17] can be plugged in our software platform as additional input of the energy yield calculation block in Fig. 1 (see an example in Fig. 6).

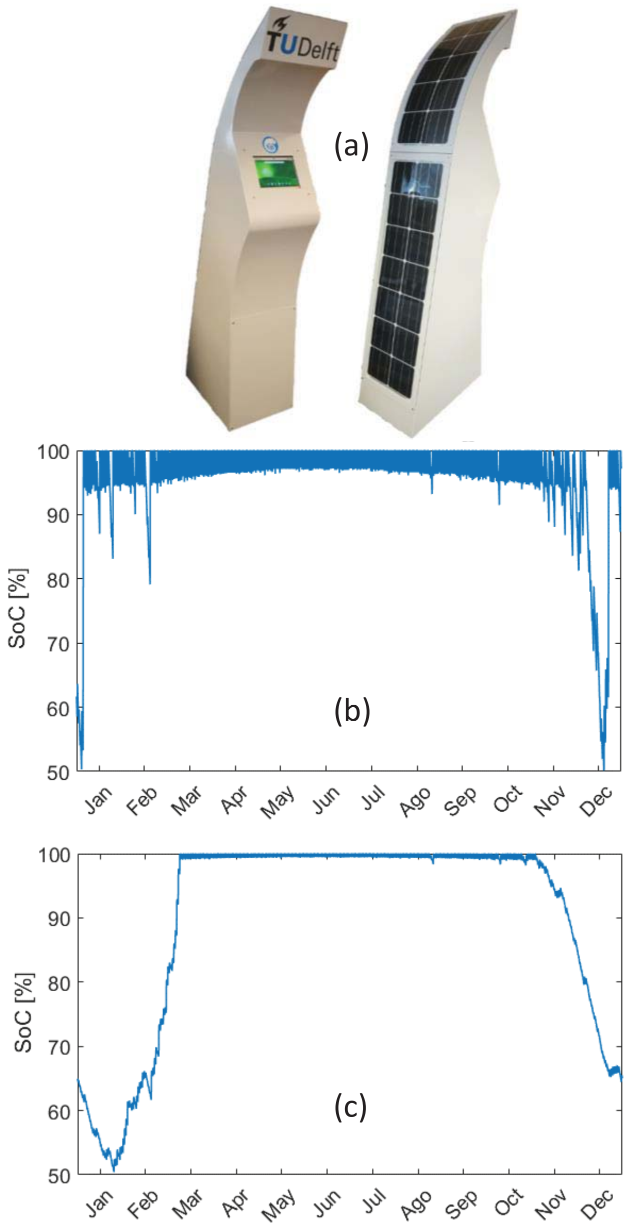

Fig. 6 State of charge of a valve regulated lead-acid (VRLA) gel battery bank serving (a) an off-grid infotainment spot endowed with curved mono-crystalline silicon PV modules during an entire year under two different skyline profiles in Delft, the Netherlands: (b) free horizon, facing South (needed storage capacity: 670 Wh) and (c) TU Mekelpark facing East (needed storage capacity: 3750 Wh).

One example of validation of our software platform is the BAPV system attached on one of the façades of a student house located in Delft (the Netherlands). In this case, all abovementioned sub-modules were run to simulate the choral performance of 216 multi-crystalline silicon modules. The deviation between the actual yearly AC energy yield and its simulated counterpart was less than 1%.

Other aspects affecting the DC power model of PV modules in Fig. 1 are colouring, bi-faciality and soiling. Our platform can deal with the ad-hoc computed lost or gained performance resulting, respectively, from variation of module colour, cell-to-module structure, and climate-dependent rain-free period [3]. For example, Fig. 7 reports the simulated monthly energy production of a BIPV system based on mono-crystalline silicon PV modules, installed on a 35° tilted roof oriented towards South with a total area of 30 m^2 and located either in Amsterdam (the Netherlands) or in Barrancabermeja (Colombia) for three different coloured optical coatings. From cell to module modelling, the presence of green or brown coloured optical coatings versus the standard coloration could be modelled and its impact on the energy yield could be assessed.

IV. Conclusions

In conclusion, we have reported on our comprehensive and flexible software platform, which allows – **remotely** – to design arbitrary E/UIPV systems in any location and with great accuracy.

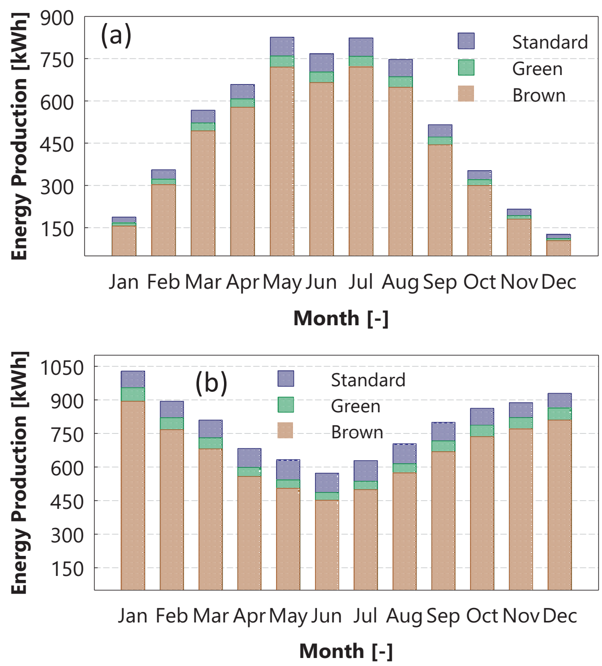

Fig. 7 Simulated monthly energy production of a BIPV system based on mono-crystalline silicon PV modules, installed on a 35° tilted roof oriented towards South with a total area of 30 m^2 and located either (a) in Amsterdam (the Netherlands) or (b) in Barrancabermeja (Colombia) for three different coloured optical coatings: standard (6.2 kWp), green (5.8 kWp) and brown (5.9 kWp).

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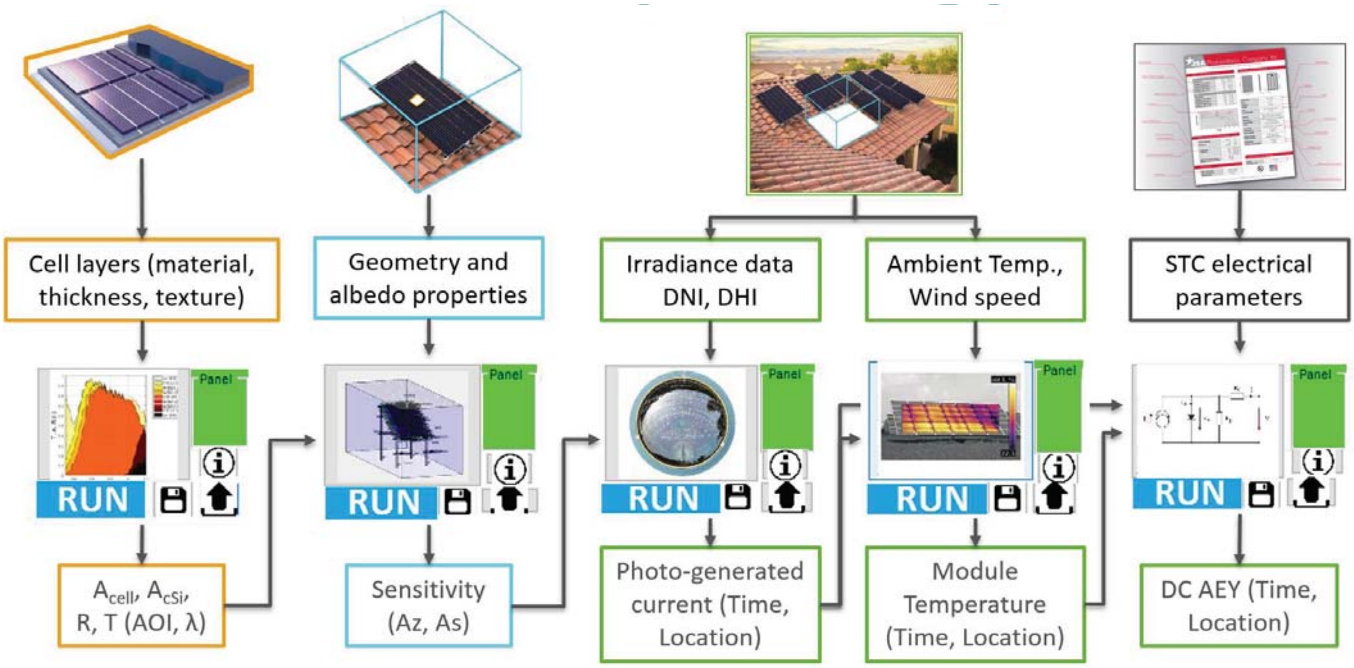

Fig. 8 Toolbox layout, including input and output. Parts corresponding to Cell Technology, System Setup and Location Integration Block are shown in orange, blue and green, respectively.

Our approach (i) covers the full path from cell structure to annual energy yield at the AC-side; (ii) includes a complete shading analysis; and (iii) is ready for colored, bi-facial and soiled PV modules. All the described features are being embedded in the Dutch PV Portal 2.0 [3] and in a user-friendly simulation toolbox, meant for didactical, research and development and designing purposes (see Fig. 8).

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