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Hybrid successive discretisation algorithm used to calculate parameters of the photovoltaic cells and panels for existing datasets

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Abstract

This paper presents a new hybrid successive discretisation algorithm, used to calculate the parameters of the photovoltaic cells and panels, by the one diode model and the two diode model. Nine known datasets from the specialised literature were used to validate the new algorithm and then it was firstly applied for two new datasets. For the first time only one algorithm is applied to extract the parameters, in both cases—one and two diode models. The new datasets are for commercial monocrystalline silicon and amorphous silicon photovoltaic cells. The main test used to prove the performance of HDSA is the root mean square error. Other four tests were used for comparison: the mean absolute error, the mean bias error, t-statistic, and the coefficient of determination. The hybrid successive discretisation algorithm proved its accuracy and reliability for parameter extraction of different types of photovoltaic cells and panels for all datasets used. Comparing the hybrid successive discretisation algorithm with the best algorithms from the specialised literature shows an improvement of the root mean square error by up to10.4% for the one diode model and by up to 7.5% for the two diode model, respectively.

1 | INTRODUCTION

The methods to determine the parameters of the photovoltaic cells and panels have been developed since 1963 when Wolf et al. proposed a method to determine the series resistance of the photovoltaic cell [1]. Then, the researchers developed several methods to calculate one, more than one and all parameters of the photovoltaic cells and panels, under different conditions, such as laboratory or natural sunlight conditions, under light or in the dark, in normal light up to 1 sun, 1000W/m^2 or in concentrated light, above 1 sun. Bashahu et al. made a review of the methods developed to calculate the series resistance of the photovoltaic cells [2]. Twenty-two methods to determine the ideality factor of diode, n, are analysed in [3]. Cotfas et al. reviewed pro and cons of 35 methods to calculate the photovoltaic cells parameters in static regime [4] and 10 methods to determine the photovoltaic cells parameters in dynamic regime [5]. Hamada et al. described and discussed comprehensively the methods according to the number of extracted parameters of the photovoltaic cells and panels [6]. The metaheuristic algorithms, applied to extract the photovoltaic cells parameters, begun with the genetic algorithm (GA) proposed by Jervase et al. [7]. Hachana et al. wrote one of the first review papers for metaheurstic algorithms where the performance of nine algorithms is presented, such as simulated annealing (SA), harmony search-based algorithms (HS), differential evolution (DE), modified particle swarm optimisation (MPSO), artificial bee colony-differential evolution (ABC-DE), bird mating optimiser (BMO), artificial bee swarm optimisation (ABSO), innovative global harmony search (IGHS). Grouping-based global harmony search (GGHS) is compared. Two datasets are used: one for RTC monocrystalline silicon photovoltaic cell and the second for Photowatt PWP 201 panel with 36 polycrystalline silicon photovoltaic cells connected in series. The performance is studied for both models: one diode and two diodes.

The metaheuristic algorithms very quickly became the most commonly used tools to extract the parameters of the photovoltaic cells and panels with very good accuracy. The number of these algorithms surpassed the other methods developed to calculate the photovoltaic cells parameters. Pillai et al. reviewed the existing metaheuristic algorithms. They analysed the performance of the algorithms according to the convergence speed, accuracy, compatibility and range of parameters set [8]. Oliva et al. classify the reviewed metaheuristic algorithms in four groups: evolutionary algorithms. physics-based algorithms, swarm-based algorithms and human-based algorithms [9]. The main advantages and disadvantages of the metaheuristic algorithms are presented by Yang. et al. [10]. The algorithms are also classified in four groups: mathematics-based algorithms, physics-based algorithms, biology-based algorithms and sociology-based algorithms. The classification achieved is a comprehensive one considering no less than 28 algorithms. All methauristic algorithms extract all parameters of the photovoltaic cells and panels, five for one diode model (1D), seven for two diodes model (2D) and nine for three diodes model (3D). For the last model there are very few papers [11]. The performance of the metaheuristic algorithms can be improved by using hybrid approach.

The methods and algorithms taken into account for comparison are briefly described. Firstly, the methods and algorithms with the best results are considered. Secondly, the most used methods and algorithms are considered, even if their results are not the best.

Cotfas et al. proposed the successive discretisation algorithm (SDA) which uses the discretisation technique and is able to find the global optimum for multimodal problem as the current voltage characteristic of the photovoltaic cell is [12]. The results obtained for the three datasets considered were very good using the one diode model. Oliva et al. applied chaotic whale optimisation algorithm (CWOA) which is a metaheuristic optimisation algorithm to enhance the global convergence speed and to obtain high performance in the determination of the parameters of the photovoltaic cells using the one diode and two diode model. It is based on the hunting mechanism of humpback whales. The chaos theory is introduced into whale optimisation process by using the chaotic maps to compute and automatically calculate the internal parameters. This situation is beneficial in complex problems, because along the iterative process, the proposed algorithm improves their capabilities to search for the best solution. The modified method is able to optimise complex and multimodal objective functions [13]. Guo et al. proposed the cat swarm optimisation algorithm (CSO) which is based on observing the behaviours of cats. It consists of two sub-models: tracing mode and seeking mode [14]. Experimental results demonstrate that CSO has much better performance than particle swarm optimisation (PSO). Hamid et al. used a hybrid algorithm (NM-MPSO), which consists of the Nelder–Mead method and modified particle swarm optimisation (MPSO) algorithm, with very good results for the photovoltaic cells and panels. The Nelder–Mead method is a numerical one used to calculate the extremes of the objective function in a multidimensional space [15]. Simplified teaching-learning-based optimisation (STLBO) is an improved TLBO algorithm successfully used by Niu et al. to characterise the photovoltaic cells and PEM fuel cells. The elite strategy is introduced to obtain a better quality of the population and to increase chances to find the global optimum using the local search [16]. Alam et al. proposed using of the flower pollination algorithm (FPA) to find the optimum solution for the one and two diode models being inspired by the flower pollination process of flowering plants. This algorithm has an exponential convergence rate [17]. Other methods and algorithms with higher RMSE are: chaotic particle swarm optimisation algorithm (CPSO) which has the advantage that the strict search range is not required [18]; mutative-scale parallel chaos optimisation algorithm (MPCOA), introduced by Yuan et al. to improve the conventional parallel chaos optimisation algorithm through expanding the search space [19]; the analytical five point method (5P) developed by Chan et al. for one diode model [20] using as input parameters the short circuit current I_{sc}, the open circuit voltage V_{oc}. the current which corresponds to maximum power I_{max}, the voltage which corresponds to maximum power V_{max} and the I–V characteristic slope around V_{oc} and the I–V characteristic slope around I_{sc} [21]; the pattern search optimisation technique (PS) is developed for both models: one and two diode, being used to solve a transcendental function current–voltage [22]; the genetic algorithm is based on the bio-inspired principle of evolution and selection and for parameters calculation it uses the genetic algorithms library implemented in the R programming language [23]; the Harmony Search algorithm based on the technique to obtain the perfect state of harmony for a musical orchestra [24]. The improved shuffled complex evolution (ISCE) is a new version of the shuffled complex evolution algorithm which has some advantages: it is simple to implement and has a powerful ability to find the global optimum, but it has a slow convergence rate. To improve the shuffled complex evolution algorithm, Gao et al. propose a new competitive complex evolution strategy which increases the convergence rate [25]. Gnetchejo et al. used general algebraic modelling system (GAMS) to extract the photovoltaic cell parameters. It can be used to optimise different problems from linear to mixed integer and is based on the language compiler used to formulate the problem and many solvers which must find the best parameters [26]. Chen et al. propose a hybrid algorithm EHA-NMS based on Nelder–Mead simplex method and the artificial bee colony algorithm. This algorithm used an eagle strategy with three steps which combine the strong points of the global artificial bee colony—strong global exploration and the NMS method—powerful local exploitation to improve the performance in the extraction of the optimum parameters [27]. Guaranteed convergence particle swarm optimisation (GCPSO) [17] has the ability to calculate the parameters quickly and accurately and it is an improved version of the PSO algorithm [28]. WDOWOAPSO is a hybrid algorithm which uses the abilities of the PSO and wind driven optimisation (WDO) technique [29]. Jordehi proposed a new approach of the particle swarm optimisation algorithm modifying the values of the personal acceleration coefficient and social acceleration coefficient to avoid the premature convergence. The new algorithm is called time varying acceleration coefficients particle swarm optimisation algorithm (TVACPSO) [30]. Gong et al. present an improved version of the adaptive differential evolution algorithm (JADE) called Rcr-IJADE algorithm, which reduces the computational efforts and is applicable for both models [31]. The ELPSO algorithm enhanced the performance of the PSO algorithm by adding five-staged successive mutation strategy for the leader [32]. Oliva et al. proposed a chaotic artificial bee colony (ABC) algorithm which is an improved variant of the ABC algorithm. In this variant a chaos-generated number is used and from the chaotic maps the Tent map is chosen [33]. Xiong et al. improved the performance of the whale optimisation algorithm (WOA) through the implementation of two modified search strategies, the introduction of the crossover operator and a selection operator and obtained the modified search strategies assisted crossover whale optimisation algorithm (MCSWOA) [34]. Chen et al. proposed a new hybrid algorithm named biogeography-based heterogeneous cuckoo search (BHCS), based on the cuckoo search algorithm (CS), which has abilities for global exploration and biogeography-based optimisation (BBO) which has abilities for local exploration [35]. The biogeography-based learning particle swarm optimisation (BLPSO) is an improved algorithm of the PSO using the migration technique of biogeography-based optimisation [36]. The supply demand-based optimisation algorithm (SDO) is inspired by the economical process and it included the following modes: exploration, exploitation and demarcation between them [37]. Ma et al. used the cuckoo search algorithm (CS) which is a bio-inspired algorithm based on the behaviour of different cuckoo species [38, 39]. Muhammad et al. proposed the approximation and correction technique (ACT) used for the one diode model [40]. Jiao et al. proposed a hybrid algorithm Harris Hawks optimisation (EHHO) based on orthogonal learning and general opposition-based learning [41]. Zhang et al. propose a new comprehensive learning Jaya algorithm CLJAYA with an improved global search ability [42]. Artificial ecosystem-based optimiser algorithm (AEO) uses the following mechanisms: producer-to balance between exploration and exploitation phases, consumer-to reinforce the exploration phase, and decomposer-to promote exploitation phase. [43]. Parallelised successive discretisation algorithm (PSDA) is an improved version of the SDA algorithm to reduce the time needed to extract the parameters of the photovoltaic cell and panel [44].

The novelty and contributions of this paper are:

- Developing and implementing a new hybrid algorithm, namely hybrid successive discretisation algorithm (HSDA), which has proven its performance for extracting parameters, obtaining better results than the best ones from the specialised literature and reducing the extraction time, more than six time comparing with SDA algorithm
- Bringing together most of the reliable datasets for photovoltaic cells and panels from specialised literature, offering researchers the possibility to use them for future works
- Two new datasets are presented for the first time and used to extract their parameters using the one and two diode models
- Using five statistical error tests to ensure a competitive comparison between the algorithms performance.

The rest of the paper is structured in three sections, as follows: the second section is dedicated to the hybrid successive discretisation algorithm which is described in detail and the statistical error tests used. The results and the discussions for the eleven datasets are presented in the third section. The conclusions and further research are presented in the last section.

2 | MODELS AND METHODS

2.1 | Mathematical model of photovoltaic cell and panel

The mathematical models and equivalent circuits of the photovoltaic cell and panel are well known and explained in many papers and books [12, 43, 44]. The mathematical model for two diode model of the photovoltaic panel is following:

$$I = N_p I_{ph} - N_p I_{01}\left(e^{\frac{N_p V + N_s I R_s}{n_1 N_p N_s V_T}} - 1\right) - N_p I_{02}\left(e^{\frac{N_p V + N_s I R_s}{n_2 N_p N_s V_T}} - 1\right) - \frac{N_p V + N_s I R_s}{N_s R_{sh}} \quad (1)$$

where I_{ph} is the photogenerated current, I_0 is the reverse saturation current, R_s is the series resistance, R_{sh} is the shunt resistance, n is the ideality factor of diode and V_T is the thermal voltage, $VT = kT/q$, k is the Boltzmann constant, the index 1 relates the diffusion mechanism and 2 the generation-recombination mechanism, N_s represents the number of the photovoltaic cells connected in series and N_p represents the number of the photovoltaic cells connected in parallel. In the case of the one diode model, one exponential term is eliminated from Equation (1). The mathematical model for the photovoltaic cell is obtained from Equation (1) if N_s and N_p are both equal to 1.

2.2 | Hybrid successive discretisation algorithm

The hybrid successive discretisation algorithm (HSDA) is designed to work as a hybrid between any known algorithm for determining the parameters of the cell or panel and SDA. The first algorithm constructs a solution which is called seed for SDA. A vicinity is constructed around this seed. SDA is applied on this vicinity and a new solution is obtained. If the new solution lies inside the vicinity, then it is considered final. This final solution is called settled. If the new solution is located on the border of the previous seed's vicinity, then it is considered a new seed and SDA is applied again on its vicinity and so on, a new iteration of the algorithm begins and that is because it is very likely that a better solution is located outside the former vicinity. The solution found by SDA at the end of each iteration is better or (rarely) the same compared with the seed (a solution is considered better than another if RMSE of the first is lower than RMSE of the second). So, HSDA can also be used as a tool to test the optimality of a solution given by an algorithm. If it is not optimum, then SDA improves it.

SDA is designed to work on an n-dimensional interval, where $n = 5$ or $n = 7$, depending on the considered model, 1-diode and, respectively, 2-diode. The construction of the vicinity of the seed is illustrated below.

Let $X = (x_1, x_2, \ldots, x_n)$ $(x_i > 0)$ be a seed. An n-dimension interval vicinity of X is:

$$\mathrm{J} = [a_1, b_1] \times [a_2, b_2] \times \ldots \times [a_n, b_n] \tag{2}$$

where $x_i \in (a_i. b_i)$. $i = 1. 2. \ldots. n$. The interval J is constructed starting from X and from a vector of given percentages $P = (p_1, p_2, \ldots. p_n)$, where $p_i \in (0, 100)$, $i = 1, 2, \ldots, n$:

$$a_i = x_i \times (1 - p/100) \tag{3}$$

$$b_i = x_i \times (1 + p/100) \tag{4}$$

It is easy to see that the vicinity conditions $x_i \in (a_i, b_i)$ are all fulfilled and $a_i > 0$, $i = 1,2, \ldots, n$. The last n conditions are important since all parameters of the cell/panel are positive. In practice, when SDA is applied on J, the percentages p_i are commonly considered in the interval [1, 5], so that the corresponding vicinity is tied to X.

We recall from paper [11] that for SDA n positive integers $d_1, d_2, \ldots, d_n \in \boldsymbol{N}^*$ are considered. For each interval (a_i, b_i) $(i = 1, \ldots, n)$ d_i values are taken v_j^i $(j = 1, \ldots, d_i)$, respecting the inequalities:

$$a_i < v_1^i < v_2^i < \ldots < v_{d_i}^i < b_i \tag{5}$$

The candidates for the new solution built by SDA are taken from $(v_{m_1}^1, v_{m_2}^2, \ldots, v_{m_n}^n)$, $j_i = 1, \ldots, d_i$, i = 1, 2, …, n. The seed X must be among these values (X must be one of the candidates of the new solution). This can be assured by considering d_i $(i = 1, 2, \ldots, n)$ as odd numbers. Moreover, it easy to see that:

$$X = \left(v_{(m_1)}^1, v_{(m_2)}^2, \mathrm{n}, v_{(m_n)}^n\right), \text{where } m_j = \frac{d_i + 1}{2} \tag{6}$$

The flowchart of HSDA is presented in Figure 1:

Usually the algorithm has one iteration or a few. There are cases when it runs multiple iterations (especially when initial seed is far from the optimum and the values of P are considered very small). So, a maximum number of iterations was introduced. This prematurely stops the algorithm but even so, the improvement of the initial seed is achieved.

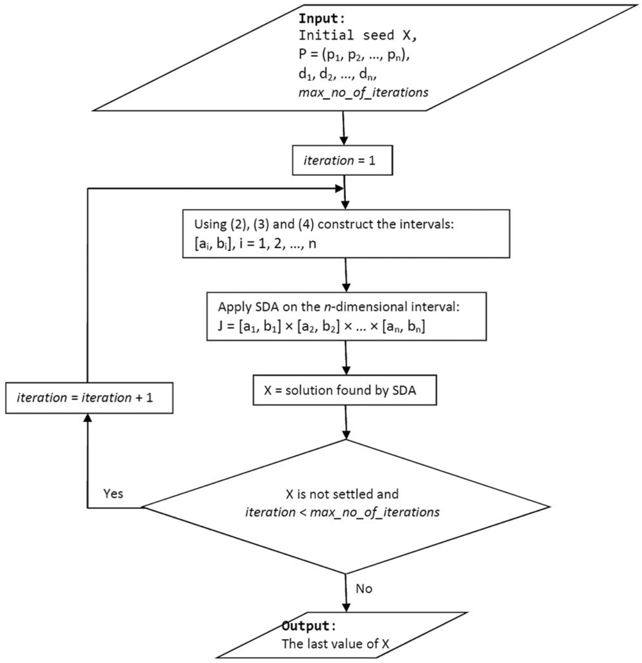

FIGURE 1 The flow chart of the HSDA algorithm

2.3 | Erorrs

The performance of the HDSA algorithm is proved using different statistical error tests, such as: absolute error (AE) Equation (7), the root mean square error Equation (8), the mean absolute error (MAE) Equation (9), the mean bias error MBE Equation (10), t-statistic (t) Equation (11) and the coefficient of determination R^2 Equation (12):

$$\mathrm{AE} = \sum_{i=1}^{n} |I_{ic} - I_{im}| \tag{7}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (I_{ic} - I_{im})^2}{n}} \tag{8}$$

$$\mathrm{MAE} = \frac{\sum_{i=1}^{n} |I_{ic} - I_{im}|}{n} \tag{9}$$

$$\mathrm{MBE} = \frac{\sum_{i=1}^{n} (I_{ic} - I_{im})}{n} \tag{10}$$

where I_{ic} represents the calculated values of the current of the photovoltaic cell or panel, I_{im} is the measured values and n is the total number of measurements.

Both MAE and RMSE have to be as small as possible and they provide information on the long-term performance—MAE and on the short-term performance—RMSE.

The use of the t-statistic allows to find the best solutions for the parameters because the influence of the MBE and RMSE is considered together, Equation (11). The performance of the methods and the algorithms increases with smaller values of the t-statistic [45].

$$t = \sqrt{\frac{(n-1)\,\mathrm{MBE}^2}{\mathrm{RMSE}^2 - \mathrm{MBE}^2}} \tag{11}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \left(I_{ic} - I_{im}\right)^2}{\sum_{i=1}^{n} \left(I_{im} - \overline{I_{im}}\right)^2} \tag{12}$$

The coefficient of determination is a measure of the matching between calculated points and measured points. If it is equal to 1, this indicates that the predictions points perfectly fit the considered data.

3 | RESULTS AND DISCUSSIONS

Most of the datasets from the specialised literature are taken into account to analyse the newly proposed algorithm and to verify its versatility. Another aim for the researchers is to have correctly presented datasets to be used for future works. The parameters of the photovoltaic cells and panels are calculated using the following values: for the Boltzmann constant $k = 1.3806503\mathrm{E}{-23}$ and for the elementary electrical charge $q = 1.60217646\mathrm{E}{-19}$. It is very important that the researchers use the same values when the parameters of the photovoltaic cells and panels are calculated, in order to have a uniformity of the calculus and the comparison between the performance of different parameter extraction approaches to be made fairly easy. The statistical error tests are calculated using the developed software in LabVIEW programme language.

3.1 | RTC photovoltaic cell

The dataset for the RTC photovoltaic cell (diameter—57 mm) is obtained at 33 °C and 1000 W/m^2 [46] and is presented in Table 1. The calculated current for both one—1D and two—2D diode model using the hybrid HSDA algorithm and the absolute errors are also presented in Table 1.

Table 2 presents the best parameters of the RTC photovoltaic cell for both one and two diode using the HSDA algorithm and the lower and upper bound. The performance of the HDSA algorithm provides the least RMSE, MAE and t-statistic comparison with the other algorithm considered for the one diode model, less ISCE algorithm see Table 3. The coefficient of determination is similar with that found for SDA, CSO and NM-MPSO. The parameters of the RTC photovoltaic cell, such as: the shunt resistance, the reverse saturation current and the ideality factor of diode, vary a lot for the 5P, PS and GA algorithms in comparison with the best algorithms. This can be observed by analysing the statistical error tests: RMSE is more than ten times higher and the coefficient of determination decreases to 0.999 and even under this value. The t-statistic also increases over 1.

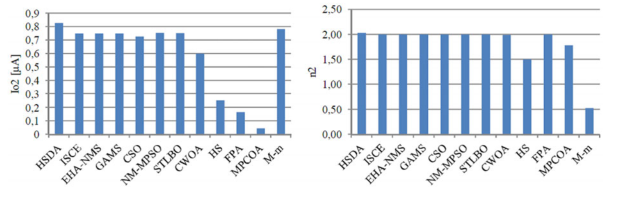

FIGURE 2 The values of two parameters for RTC cell in 2D model: a) I_{02} and b) n_2

The RMSE for the FPA algorithm is higher than that provided in [17], but it is in accordance with the result given in [26], the same result is obtained for [43]. The difference is high and it is very important for the researchers to give the approaches used to calculate it, in order to make a realistic comparison.

The HDSA algorithm also proves its superiority in case of the two diode model for the RTC photovoltaic cell in comparison with the best algorithms from specialised literature. Table 4 presents the results for the statistical error tests obtained for the RTC photovoltaic cell. The values of the RMSE, MAE and R^2 are the best ones. There are high differences for some parameters of the RTC photovoltaic cell obtained with the first three algorithms and with the last three. The highest differences are obtained for comparison between HDSA and HS: 69% for I_{02}, 44% for I_{01}, 26% for n_2 and 15.5% for R_{sh}. The values obtained using HS algorithm for the parameters mentioned before are: 0.2547 μA, 0.12545 μA, 1.49989 and 46.8269 Ω respectively. Also, the reverse current $I_{02,}$ calculated with MPCOA algorithm, is 0.04528 μA, which means a difference of almost 96%.

The distribution of the reverse saturation current, I_{02}, for the considered algorithms in the case of 2D model illustrates a good uniformity for the algorithms with RMSE smaller than 0.001 and high variation for the rest, Figure 2(a). In the case of n_2 the distribution is quasi-uniform and only for two algorithms, both with RMSE higher than 0.001, HS and MPCOA, there are significant differences, Figure 2(b). Additionally, the difference between the considered parameter values obtained with HSDA and the poor values is presented, *M-m*, Figure 2.

The comparison between the (I, V) measured pairs and the (I, V) calculated pairs using HSDA algorithm in both cases, one and two diode models, is presented in Figure 3. Figure 3 also presents the zoom for three important points: around the short circuit current, around maximum power and around the open circuit voltage. The matching between the calculated and measured data is very good. The comparison shows that although the two diode model offers better results in statistical error tests, this did not happen for all points.

3.2 | PWP201 photovoltaic panel

Table 5. presents the dataset for the PWP201 photovoltaic panel [46], the calculated current for both one—1D and two—2D

TABLE 1 (I,V) points of RTC photovoltaic cell and results in current and errors using HSDA algorithm

Measured data		HSDA-1d	HSDA-2d	Error	Error
V [V]	I [A]	I_c [A]	I_c [A]	HSDA-1d	HSDA-2d
−0.2057	0.7640	0.764088225	0.764001258	8.82E-05	1,26E-06
−0.1291	0.7620	0.762663501	0.762619764	0.000663501	0.000619764
−0.0588	0.7605	0.761355625	0.761351345	0.000855624	0.000851345
0.0057	0.7605	0.760154219	0.760185521	0.000345781	0.000314479
0.0646	0.7600	0.759055355	0.759117546	0.000944645	0.000882454
0.1185	0.7590	0.758042417	0.75812935	0.000957583	0.00087065
0.1678	0.7570	0.757091657	0.757194409	9.17E-05	0.000194409
0.2132	0.7570	0.756141306	0.756246924	0.000858694	0.000753076
0.2545	0.7555	0.755086759	0.755177817	0.000413241	0.000322183
0.2924	0.7540	0.753663716	0.753719914	0.000336284	0.000280086
0.3269	0.7505	0.751390765	0.751394117	0.000890765	0.000894117
0.3585	0.7465	0.747353622	0.747294991	0.000853622	0.000794991
0.3873	0.7385	0.740116978	0.740004809	0.00161698	0.00150481
0.4137	0.7280	0.727381984	0.727244258	0.000618016	0.000755742
0.4373	0.7065	0.706972431	0.706852906	0.000472431	0.000352906
0.4590	0.6755	0.67527997	0.675219223	0.00022003	0.000280778
0.4784	0.6320	0.630758143	0.630773901	0.00124186	0.0012261
0.4960	0.5730	0.571928286	0.57200892	0.00107171	0.00099108
0.5119	0.4990	0.499607	0.499717334	0.000607	0.000717334
0.5265	0.4130	0.413648818	0.413738101	0.000648818	0.000738101
0.5398	0.3165	0.317510163	0.317542415	0.00101016	0.00104242
0.5521	0.2120	0.212155001	0.212111698	0.000155001	0.000111698
0.5633	0.1035	0.102251361	0.102148077	0.00124864	0.00135192
0.5736	−0.0100	−0.008717526	−0.008803301	0.00128247	0.0011967
0.5833	−0.1230	−0.125507451	−0.125546217	0.00250745	0.00254622
0.5900	−0.2100	−0.208472415	−0.208359217	0.00152758	0.00164078
AE				0.0215278	0.0212354

TABLE 2 The parameters of the RTC photovoltaic cell for 1D and 2D

Algorithm	I_{ph} [A]	I_{o1} [μA]	n_1	R_s [Ω]	R_{sh} [Ω]	I_{o2} [μA]	n_2
HSDA 1D	0.7607758	0.323016532	1.48118232	0.03637708	53.714520885		
Range set	0–1	E−6–E+1	1–2	0-0.5	0-100		
HSDA 2D	0.7607941296	0.226703208	1.451	0.036762879	55.3983857677	0.82673085	2.030362764
Range set	0–1	E−6–E+1	1–2	0–0.5	0–100	E-6–E+1	1–2.5

diode model using the hybrid HSDA algorithm and the absolute errors. The (V,I) pairs are measured at 45 °C temperature and 1000 W/m^2 irradiance. The PWP201 photovoltaic panel is achieved using 36 polycrystalline silicon photovoltaic cells connected in series.

The extracted parameters of the PWP201photovoltaic panel using the HSDA algorithm for both models and the lower and upper bound are presented in Table 6.

The parameters of the PWP201 photovoltaic panel calculated with HDSA algorithm for one diode model are practically identical with the ones calculated using ISCE and EHA-NMS algorithms, Table 7. This shows that the solution found is the best and is almost sure that it can no longer be improved. The methods or algorithms which gave less reliable results for RTC photovoltaic cell, also have less reliable results for the PWP201 photovoltaic panel.

TABLE 3 The statistical error tests for RTC photovoltaic cell -1D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HDSA	9.8602E−04	0.000827989	1.42971E-8	7.24988E-5	0.9999893
ICSE [25]	9.8602E−04	0,000827959	-8,61057E-9	4,36632E-5	0,9999893
SDA [12]	9.8602E−04	0.000832881	-1.06942E-6	2.93757E-4	0.9999893
CLJAYA [42]	9.8603E−04	0.000828519	-5,27629E-6	0,0267554	0,9999893
CSO [14]	9.861 E−04	0.000876078	-8.83263E-6	0.0447865	0.9999893
CWOA [13]	9.862 E−04	0.000829524	-6.47353E-6	0.00107726	0.999979
NM-MPSO [15]	9.862 E−04	0.000829863	-1.01854E-5	0.0516434	0.9999893
AEO [43]	9.8911 E−04	0,00082581	6,63123E-8	0,000335212	0,99998924
STLBO [16]	9.978 E−04	0.000810465	8.29533E-5	0.417112	0.999989
FPA [17]	1.212E-03	0.000833775	0.000385109	1.67535	0.9999838
CPSO [18]	1.386E−03	0.00108192	-0.000497143	1.91934	0.999979
MPCOA [19]	2.313E−03	0.00155471	0.00115409	2.87862	0.999941
5P [20]	0.009134	0.00613732	0.00360061	2.1504	0.999086
PS [22]	0.01494	0.00938345	0.00844223	3.42576	0.997546
GA [23]	0.01908	0.010653	0.0100428	3.09566	0.995997

TABLE 4 The statistical error tests for RTC photovoltaic cell -2D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HDSA	9.82174E−04	0.000816746	−3,30237E-6	0.0168116	0.99998939
ISCE [25]	9.82485E−04	0.000818278	−9.32695E-10	4.74661E-6	0.99998938
EHA-NMS [27]	9.82485E−04	0.000818276	4.94405E-9	2.5161E-5	0.99998938
GAMS [26]	9.82557E−04	0.000820111	−6.52966E-6	0.0332286	0.99998938
CSO [14]	9.82531E−04	0.000819209	−1.23358E-**6**	0.00627757	0.99998938
NM-MPSO [15]	9.82716E−04	0.000821084	−1.52035E-5	0.0773951	0.99998937
STLBO [16]	9.99255E-04	0.00080196	9.98608E-5	0.50219	0.999989
AEO [43]	1.0199 E-03	0.000818651	8.74263E-8	0.000428566	0.99998856
CWOA [13]	1.15735E−03	0.0007955	0.000342575	1.54942	0.99998527
HS [24,19]	1.259652E−03	0.00105412	−0.000256262	1.03892	0.9999825
FPA [17]	1.24239E−03	0.000880114	0.000432585	1.85715	0.999983
MPCOA [19]	2.33475E−03	0.00156846	0.00116248	2.87062	0.99994

There are high variations for the parameters of the PWP201 photovoltaic panel, calculated for two diode model with the considered algorithms, see Table 8. The reverse saturation currents I_{01} and I_{02} for HSDA, GPSO and TVACPSO are the same sizes order E-6 A and respectively E-12 A, while for CPSO they have E-12 A and E-6 which means practically an inversion, for WDOWOAPSO, are E-6 A and E-7 A, and for PS both are E-9 A. Also the n_1 and n_2 are the same for HSDA, WDOWOAPS and GPSO around 47 and very different for the rest. In the case of the TVACPSO, n_2 is 100, but it can be more than 100 without significant changes for the error statistical tests and for PS they are around 30. The shunt resistance has high variation from 195.55 Ω for PS to 822.14 Ω for CPSO. It is almost the same for the other three HSDA, WDOWOAPS and GPSO around 744 **Ω**. All these show that the solutions can be optimised. At this time the best solution is given by the HSDA algorithm. In the case of the AEO* algorithm 26 pairs were considered [43].

The optimum solutions for the two models, one and two diode, have a different behaviour, the statistical error tests for the one diode model are better than those for two diode model, which can be observed by comparison between the data from Table 7 and 8, but also from Figure 4. The zoom for three important points of the *I*–*V* characteristics shows that the (*I*, *V*) points calculated with the one diode model are closer to the points measured in two cases and the points calculated with the two diode model in one case.

TABLE 5 (I,V) points of PWP201 photovoltaic panel and results in current and errors using HSDA algorithm

Measured data		HSDA-1d	HSDA-2d	Error	Error
V [V]	I [A]	I_e [A]	I_e [A]	HSDA-1d	HSDA-2d
0.1248	1.0315	1.029718774	1.030368929	0.00178123	0.00113107
1.8093	1.0300	1.027887236	1.028067186	0.00211276	0.00193281
3.3511	1.0260	1.026162644	1.02592193	0.000162644	7.81E-05
4.7622	1.0220	1.02445005	1.023843902	0.00245005	0.0018439
6.0538	1.0180	1.022563612	1.02166196	0.00456361	0.00366196
7.2364	1.0155	1.020137816	1.019035019	0.00463782	0.00353502
8.3189	1.0140	1.016511929	1.015337129	0.00251193	0.00133713
9.3097	1.0100	1.010593414	1.009513295	0.000593414	0.000486705
10.2163	1.0035	1.000681906	0.99988737	0.00281809	0.00361263
11.0449	0.9880	0.984565331	0.984236802	0.00343467	0.0037632
11.8018	0.9630	0.959511745	0.95976715	0.00348826	0.00323285
12.4929	0.9255	0.922811693	0.923654087	0.00268831	0.00184591
13.1231	0.8725	0.87256485	0.873861145	6.49E-05	0.00136114
13.6983	0.8075	0.807240241	0.808725878	0.000259759	0.00122588
14.2221	0.7265	0.728309462	0.72969183	0.00180946	0.00319183
14.6995	0.6345	0.637121752	0.638125369	0.00262175	0.00362537
15.1346	0.5345	0.536208818	0.536643644	0.00170882	0.00214364
15.5311	0.4275	0.429517689	0.42936162	0.00201769	0.00186162
15.8929	0.3185	0.318788892	0.318092714	0.000288892	0.000407286
16.2229	0.2085	0.207408054	0.206360679	0.00109195	0.00213932
16.5241	0.1010	0.096185996	0.094980293	0.004814	0.00601971
16.7987	−0.0080	−0.008312012	−0.009197669	0.000312012	0.00119767
17.0499	−0.1110	−0.110931794	−0.111308013	6.82E-05	0.000308013
17.2793	−0.2090	−0.209254616	−0.208871574	0.000254616	0.000128426
17.4885	−0.3030	−0.300886328	−0.299434127	0.00211367	0.00356587
AE				0.0486685	0.053637

TABLE 6 The parameters of the PWP201photovoltaic panel for 1D and 2D

Algorithm	I_{ph} [A]	I_{o1} [μA]	n_1	R_s [Ω]	R_{sh} [Ω]	I_{o2} [μA]	n_2
HSDA 1D	1.0305143	0.348226304	48.642835	1.201271	981.98228037		
Range set	0–2	E−6–E+1	1–2*36	0–2	0–1000		
HSDA 2D	1.0322708072	2.5119662904	47.422967	1.2349375032	737.27967961	1.00838351E-6	47.73212158375
Range set	0–2	E−6–E+1	1–2*36	0–2	0–1000	E−6–E+1	1–2*36

3.3 | STM6-40 photovoltaic panel

The STM6-40 photovoltaic panel has 36 monocrystalline silicon photovoltaic cells connected in series. Its I–V characteristic was measured at 1000 W/m^2 irradiance and 51 °C temperature. The (I,V) measured points [32], the values for the calculated ones with HSDA algorithm in both cases, one and two diode models, and the errors are presented in Table 9.

The extracted parameters of the STM6-40 photovoltaic panel using the HSDA algorithm for both models and the lower and upper bound are presented in Table 10.

The statistical error tests for the STM6-40 photovoltaic panel in both cases are presented in Table 11 for one diode model and in Table 12 respectively, for the two diode model. The HSDA algorithm has the best results for the one diode model, but very close to ISCE, EHA-NMS, Rcr-IJADE and SDA. The difference for RMSE calculated with HSDA in

TABLE 7 The statistical error tests for PWP201 photovoltaic panel -1D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HDSA	2.42507E−03	0.00195695	−9.49346E-10	1.91781E-6	0.99997
SDA [12]	2.42507E−03	0.00195695	−8.49475E-10	2.93757E-5	0.99997
ISCE [25]	2.42507E−03	0.00195695	−9.49475E-10	1.91807E-6	0.99997
EHA-NMS [27]	2.42507E−03	0.00195695	−1.32118E-8	2.66896E-5	0.99997
CLJAYA [42]	2.425075E−03	0.00195691	7.49026E-7	0.00151313	0.99997
AEO [43]*	2.606962 E−03	0.00212558	4.41795E-7	0.00084733	0.999965
WDOWOAPSO[29]	2.63132E−03	0.00214891	−3.64647E-5	0.0678961	0.99996
GCPSO [28]	2.63132E−03	0.002149	−3.67245E-5	0.0683801	0.99996
FPA [17]	2.74245E−03	0.00217225	0.000721613	1.33614	0.99996
MPCOA [19]	3.78232E−03	0.003031	0.00176485	2.58449	0.99992
5P [20]	4.1251E−03	0.00333409	−0.00180911	2.39068	0.99991
PS [22]	4.5075E−03	0.00375529	0.00335397	5.45628	0.99989

TABLE 8 The statistical error tests for PWP201 photovoltaic panel -2D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HDSA	2.587754E−03	0.00214548	−5.3062E-5	0.100475	0.999965
AEO [43]*	2.606962 E−03	0.00212558	4.41713E-7	0.00084718	0.999965
GCPSO [28]	2.6313E−03	0.0021489	−3.64427E-5	0.0678553	0.999965
WDOWOAPSO[29]	2.631325E−03	0.00214891	−3.64546E-5	0.0678773	0.999965
CPSO [18]	7.087581E−03	0.00511339	0.004217	3.62658	0.999745
TVACPSO [30]	7.091795E−03	0.00511577	0.00422007	3.62732	0.999744
PS [22]	2.537344 E−02	0.0191799	0.00614798	1.22348	0.996728

comparison with ISCE is very small, the improvement is observed only at the eleventh digit (RMSE calculated with HSDA is 1.72981370994E-3 and 1.72981370994E-3 ISCE, respectively).

The statistical error tests for ELPSO, CPSO, ABC and BSA—backtracking search algorithm are calculated using q = 1.6E-19 because for this value the RMSE is the same with the one of the papers [32]. There are big differences for the R_{sh} from 606.89 to 938.21 Ω, Figure 5(a), for n_1 from 41.99 to 100, n_2 from 27.79 to 70.73 Figure 5(b), and even the R_s from 0.5 Ω for the majority of the algorithms to 1.23 Ω for the ABC. These variations show there is the possibility to improve the solution for the STM6-40 photovoltaic panel parameters in the case of the two diode model. The HSDA algorithm improves the

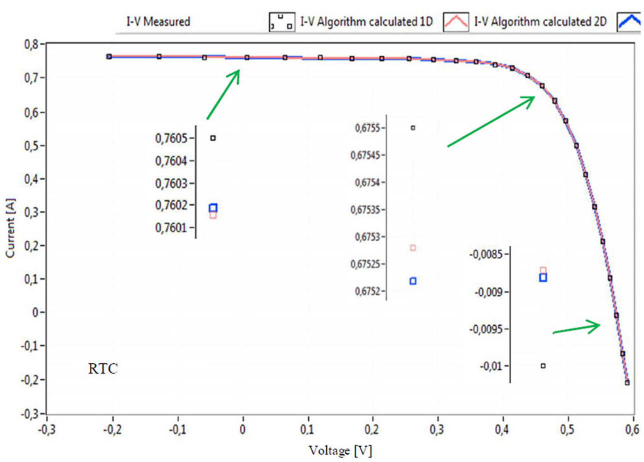

FIGURE 3 The *I–V* characteristics of RTC photovoltaic cell

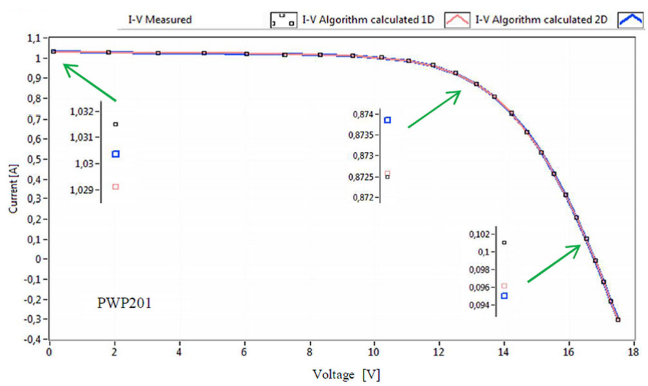

FIGURE 4 The *I–V* characteristics of PWP201 photovoltaic panel

TABLE 9 (I,V) points of STM6-40 photovoltaic panel and results in current and errors using HSDA algorithm

Measured data		HSDA-1d	HSDA-2d	Error	Error
V [V]	I [A]	I_e [A]	I_e [A]	HSDA-1d	HSDA-2d
0	1.663	1.663458258	1.663408649	0.000458258	0.000408649
0.118	1.663	1.663252309	1.663205305	0.000252309	0.000205305
2.237	1.661	1.659550807	1.659549572	0.00144919	0.00145043
5.434	1.653	1.653914695	1.65397358	0.000914695	0.00097358
7.26	1.65	1.650565909	1.650646374	0.000565909	0.000646374
9.68	1.645	1.645430598	1.645506467	0.000430598	0.000506467
11.59	1.64	1.63923353	1.639263263	0.00076647	0.000736737
12.6	1.636	1.63371269	1.633703047	0.00228731	0.00229695
13.37	1.629	1.627285802	1.627244257	0.0017142	0.00175574
14.09	1.619	1.618313571	1.618246915	0.000686429	0.000753085
14.88	1.597	1.603090042	1.603011802	0.00609004	0.0060118
15.59	1.581	1.581588375	1.581519297	0.000588375	0.000519297
16.4	1.542	1.542330591	1.542306008	0.000330591	0.000306008
16.71	1.524	1.521192635	1.521190995	0.00280737	0.002809
16.98	1.5	1.499194745	1.499218256	0.000805255	0.000781744
17.13	1.485	1.485275271	1.485313031	0.000275271	0.000313031
17.32	1.465	1.465654243	1.465708558	0.000654243	0.000708558
17.91	1.388	1.387589369	1.387675357	0.000410631	0.000324643
19.08	1.118	1.118391366	1.118319327	0.000391366	0.000319327
21.02	0	−2.48E-05	−2.00E-05	2.48E-05	2.00E-05
AE				0.0219033	0.0218468

TABLE 10 The parameters of the STM6-40 photovoltaic panel for 1D and 2D

Algorithm	I_{ph} [A]	I_{o1} [μA]	n_1	R_s [Ω]	R_{sh} [Ω]	I_{o2} [μA]	n_2
HSDA 1D	1.6639047799	1.7386543978	54.730899	0.1538559327	543.41834985		
Range set	0-2	E−6–E+1	1–2*36	0–0.5	0-1000		
HSDA 2D	1.6638773307	1.1006110140	53.34089201557	0.1635655746	580.97701828	1.681213674329	65.873264956097
Range set	0–2	E−6–E+1	1-2*36	0-0.5	0-1000	E−6–E+1	1–2*36

TABLE 11 The statistical error tests for STM6-40 photovoltaic panel - 1D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	1.72981E−03	0.00109517	1.58385E-10	3.99108E-7	0.999977
ISCE [25]	1.72981E−03	0.00109517	4.93352E-10	1.24318E-6	0.999977
EHA-NMS [27]	1.72981E−03	0.00109517	4.93352E-10	1.24318E-6	0.999977
Rcr-IJADE [31]	1.72981E−03	0.00109517	−2.00588E-8	5.05454E-5	0.999977
SDA [12]	1.72981E−03	0.00109518	4.39395E-7	0.00110722	0.999977
TPM [32]	3.11855E−03	0.00205864	−0.000786852	1.13658	0.999926
5P [20]	7.61636E−02	0.0308501	0.0167717	0.984011	0.956009

TABLE 12 The statistical error tests for STM6-40 photovoltaic panel—2D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HDSA	1.720728E−03	0.00109234	4.98823E-7	0.0012636	0.99998
ELPSO [32]	1.857058E−03	0.0013369	−8.2272E-5	0.182843	0.9998
CPSO [18]	1.861219E−03	0.00135179	0.000115492	0.256339	0.99979
ABC [32]	2.226724E −03	0.00189408	−0.000242145	0.451041	0.99971
BSA [32]	4.131858E −03	0.00344465	−0.000848803	0.865463	0.99901

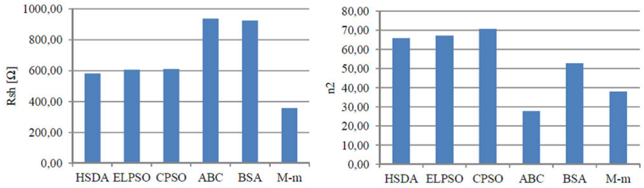

FIGURE 5 The values of two parameters for STM6-40 in 2D model: a) R_{sh} and b) n_2

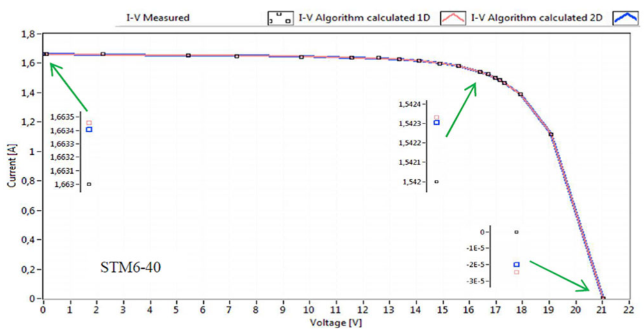

FIGURE 6 The I–V characteristics of STM6-40 photovoltaic panel

solution significantly and has the best results for the statistical error tests, Table 12.

All considered (I, V) points calculated with the two diode model are closer to the measured ones than those calculated with one diode model, Figure 6.

3.4 | Sharp ND-R250A5 photovoltaic panel

The Sharp ND-R250A5 photovoltaic panel has 60 polycrystalline silicon photovoltaic cells connected in series. Its I–V characteristic was measured at 1040 W/m^2 irradiance and 59°C temperature. The (I, V) measured points [28], the values for the calculated ones with HSDA algorithm in both cases, one and two diode models, and the errors are presented in Table 13.

The extracted parameters of the sharp ND-R250A5 photovoltaic panel using the HSDA algorithm for both models and the lower and upper bound are presented in Table 14.

The statistical error tests for the sharp ND-R250A photovoltaic panel in both cases are presented in Table 15 for

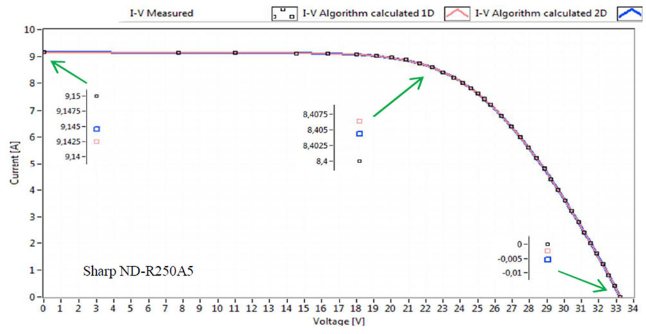

FIGURE 7 The I–V characteristics of Sharp ND-R250A5 photovoltaic panel

one diode model and in Table 16 for the two diode model. The HSDA algorithm has the best results for both diode models.

The values of the statistical error tests, such as: RMSE and MAE, are little smaller and higher for R^2 for the optimum solution found with the two diode model than the one found with the one diode model. The parameters of the sharp ND-R250A5 photovoltaic panel extracted using HSDA and GCPSO differ very little, only for the shunt resistance there is a difference of almost 1%, the R_{sh} for GCPSO being 4999.99 **Ω**. in the 1D model. In turn, for 2D model, there are significant differences between the results obtained with HSDA and GCPSO respectively, especially MCSWOA. The shunt resistance obtained using HSDA is around 8346 and 5000 **Ω** in case of GCPSO and MCSWOA. The difference for the I_{01} is over 500% and I_{02} over 691%. In case of the n_2 the difference is very high. it is 3500%. The values of the parameters calculated using the MCSWOA algorithm are: 1.1142 μA for I_{01}, 5.361 nA for I_{02} and almost 2714 for n_2. In fact, n_2 found with the MCSWOA algorithm can be increased as much as possible without influencing the optimum solution of the Sharp ND-R250A5 photovoltaic panel.

Figure 7 shows the I–V characteristics measured and calculated for the Sharp ND-R250A5 photovoltaic panel. Additionally, it shows the distribution of the current for the three important (I, V) points calculated using the one and two diode model and the measured ones. The difference between the measured current and calculated one using 1D and 2D respectively is variable. It is bigger for points around the maximum power and short circuit current for 1D and is smaller for the point around the open circuit voltage.

TABLE 13 (*I*,*V*) points of sharp ND-R250A5 photovoltaic panel and results in current and errors using HSDA algorithm

Measured data		HSDA-1d	HSDA-2d	Error	Error
V [V]	*I* [A]	I_e [A]	I_e [A]	HSDA-1d	HSDA-2d
0.00	9.15	9.142474728	9.144265852	0.00752527	0.00573415
7.71	9.14	9.140400934	9.142770834	0.000400934	0.00277083
10.98	9.12	9.137620015	9.140166625	0.01762	0.0201666
14.55	9.11	9.124565823	9.127056264	0.0145658	0.0170563
16.36	9.10	9.103327792	9.105527906	0.00332779	0.00552791
18.00	9.07	9.060345878	9.061990344	0.00965412	0.00800966
19.15	9.02	9.003770589	9.004802569	0.0162294	0.0151974
20.04	8.95	8.935319406	8.935743217	0.0146806	0.0142568
20.87	8.86	8.842754185	8.842519963	0.0172458	0.01748
21.67	8.73	8.719167892	8.718257389	0.0108321	0.0117426
22.36	8.58	8.577976716	8.576494453	0.00202328	0.00350555
23.02	8.40	8.406356355	8.404386624	0.00635635	0.00438662
23.62	8.20	8.214791024	8.212472144	0.014791	0.0124721
24.15	8.00	8.011816997	8.009304561	0.011817	0.00930456
24.61	7.80	7.809882451	7.80730558	0.00988245	0.00730558
25.02	7.60	7.609097411	7.606552398	0.00909741	0.0065524
25.39	7.40	7.411616676	7.409170865	0.0116167	0.00917087
25.75	7.20	7.198020252	7.195771994	0.00197975	0.00422801
26.38	6.80	6.792404303	6.79062769	0.0075957	0.00937231
26.94	6.40	6.396186622	6.394946536	0.00381338	0.00505346
27.46	6.00	5.994312278	5.99366939	0.00568772	0.00633061
27.94	5.60	5.602439623	5.602346598	0.00243962	0.0023466
28.40	5.20	5.199908527	5.200378967	9.15E-05	0.000378967
28.84	4.80	4.793676385	4.79467023	0.00632361	0.00532977
29.25	4.40	4.414412502	4.415710301	0.0144125	0.0157103
29.66	4.00	4.002038999	4.003713185	0.002039	0.00371319
30.05	3.60	3.607295299	3.609140293	0.0072953	0.00914029
30.44	3.20	3.182212087	3.184265312	0.0177879	0.0157347
30.81	2.80	2.786050956	2.788019701	0.013949	0.0119803
31.17	2.40	2.396146519	2.397850259	0.00385348	0.00214974
31.52	2.00	2.016751545	2.017979665	0.0167515	0.0179797
31.88	1.60	1.579624191	1.580521888	0.0203758	0.0194781
32.22	1.20	1.192708156	1.192838655	0.00729184	0.00716134
32.55	0.80	0.826187325	0.825272536	0.0261873	0.0252725
32.89	0.40	0.400701779	0.39886434	0.000701779	0.00113566
33.22	0.00	−0.002355568	−0.005417337	0.00235557	0.00541734
AE				0.338598	0.338553

3.5 | STP6-120 photovoltaic panel

The STP6-120 photovoltaic panel has 36 polycrystalline silicon photovoltaic cells connected in series. Its *I*–*V* characteristic was measured at 1000 W/m^2 irradiance and 55 °C temperature. The (*I*,*V*) measured points [31], the values for the calculated ones with HSDA algorithm in both cases, one and two diode models, and the errors are presented in Table 17.

Table 18 shows the optimal parameters of the STP6-120 photovoltaic panel obtained using the HSDA algorithm for both one and two diode models and the lower and upper bound for each of them.

TABLE 14 The parameters of the Sharp ND-R250A5 photovoltaic panel for 1D and 2D

Algorithm	I_{ph} [A]	I_{o1} [μA]	n_1	R_s [Ω]	R_{sh} [Ω]	I_{o2} [μA]	n_2
HSDA 1D	9.1435605723	0.9981119333	72.40338150374	0.5913337981	5041.3845054		
Range set	0–10	E–6–E+1	1–2*60	0–1	0–5500		
HSDA 2D	9.1449255008	0.2569918588	72.90786057347	0.5894474996	8346.5465071	0.837347921325	72.79080498517
Range set	0–10	E–6–E+1	1–2*36	0–1	0–1000	E–6–E+1	1–2*36

TABLE 15 The statistical error tests for Sharp ND-R250A5 photovoltaic panel—1D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	1.140396039E−02	0.00940551	−1.84795E-7	9.58667E-5	0.999985
GCPSO [28]	1.153241392E−02	0.00955131	2.93882E-6	0.0015076	0.999985
MCSWOA [34]	1.186383988E−02	0.00982814	−0.000722863	0.361137	0.999984
5P [20]	8.342687861E−02	0.0606723	0.0536373	4.966	0.999220

The statistical error tests for the STP6-120 photovoltaic panel in both cases are presented in Table 19 for one diode model and in Table 20 for the two diode model. The HSDA algorithm has the best results for both diode models. The RMSE and the coefficient of determination calculated with HSDA algorithm for the one diode model are practically equal with the ones found using the EHA-NMS and Rcr-IJADE, but for the MBE and t-statistic the results are better. The variations between the STP6-120 photovoltaic panel parameters calculated with HSDA, EHA-NMS and Rcr-IJADE algorithms are very small which allows to say that it is the optimal solution that will be very difficult to improve in the future. High variations are found for the shunt resistance. which is around 22 Ω for the majority of the considered algorithms and 161 Ω for ABC and 991 Ω for BLPSO. Additionally, the reverse saturation current has a variation of 50% and the series resistance has a variation of 18% in the case of the BLPSO algorithm in comparison with HSDA algorithm. The values of the parameters taken into account for BLPSO algorithm are: 10.81803 μA for I_o and 0.00377 Ω.

There are few results for the parameters of the STP6-120 photovoltaic panel calculated using the two diode model. The values of the statistical error tests obtained with HSDA algorithm are less reliable for the optimum solution calculated with the two diode model than the one found with the one diode model. There are some differences between the parameters calculated with the three algorithms. In fact, there is an inversion between the values for the I_{01}, n_1 and I_{02}, n_2 for SDO and MCSWOA. Additionally, the series resistance has a difference of almost 10% between HSDA and SDO, the I_{o1} is 6.1168E − 08 A for SDO and 2.346E − 06 A for HSDA.

The I-V characteristics measured and calculated for the STP6-120 photovoltaic panel are presented in Figure 8. Additionally. it illustrates the distribution of the current for the three important (I,V) points calculated using the one and two diode model and the measured ones. The advantage is for all three in favour of the one diode model.

3.6 | Kyocera KC200GT photovoltaic panel

The Kyocera KC200GT photovoltaic panel has 54 multicrystalline silicon photovoltaic cells connected in series. It I–V

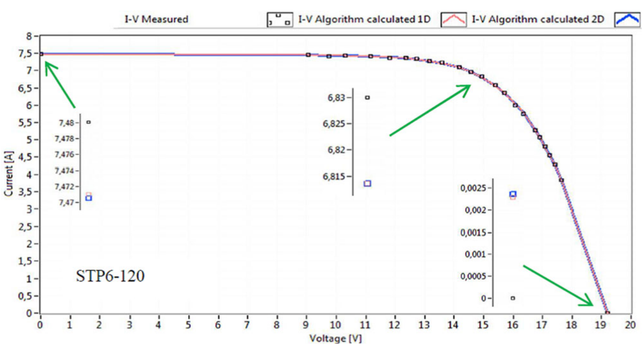

FIGURE 8 The I–V characteristics of STP6-120 photovoltaic panel

TABLE 16 The statistical error tests for Sharp ND-R250A5 photovoltaic panel—2D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	1.122145671E−02	0.00940425	1.17243E-6	0.000618121	0.9999859
GCPSO [28]	1.15324177E−02	0.00955131	3.13956E-6	0.00161058	0.9999851
MCSWOA [34]	1.18599272E−02	0.00982679	−0.00067675	0.338134	0.9999842

TABLE 17 (I, V) points of STP6-120 photovoltaic panel and results in current and errors using HSDA algorithm

Measured data		HSDA-1d	HSDA-2d	Error	Error
V [V]	I [A]	I_e [A]	I_e [A]	HSDA-1d	HSDA-2d
0	7.48	7.470979414	7.470591194	0.00902059	0.00940881
9.06	7.45	7.45254041	7.452552111	0.00254041	0.00255211
9.74	7.42	7.446762106	7.446797249	0.0267621	0.0267972
10.32	7.44	7.439089822	7.439142316	0.000910178	0.000857684
11.17	7.41	7.420315761	7.420386287	0.0103158	0.0103863
11.81	7.38	7.395999856	7.396076212	0.0159999	0.0160762
12.36	7.37	7.363183211	7.363257609	0.00681679	0.00674239
12.74	7.34	7.331345488	7.331413989	0.00865451	0.00858601
13.16	7.29	7.283999576	7.284056851	0.00600042	0.00594315
13.59	7.23	7.217384865	7.217425456	0.0126151	0.0125745
14.17	7.10	7.087575794	7.087586344	0.0124242	0.0124137
14.58	6.97	6.957709715	6.957695516	0.0122903	0.0123045
14.93	6.83	6.813611047	6.813575422	0.016389	0.0164246
15.39	6.58	6.566549907	6.566489165	0.0134501	0.0135108
15.71	6.36	6.347120904	6.347047732	0.0128791	0.0129523
16.08	6.00	6.044317977	6.044235204	0.044318	0.0442352
16.34	5.75	5.782597477	5.782517549	0.0325975	0.0325175
16.76	5.27	5.27482246	5.274763062	0.00482246	0.00476306
16.9	5.07	5.085578067	5.085527505	0.0155781	0.0155275
17.1	4.79	4.784400211	4.784370178	0.00559979	0.00562982
17.25	4.56	4.541148545	4.541136287	0.0188515	0.0188637
17.41	4.29	4.267337582	4.267344755	0.0226624	0.0226552
17.65	3.83	3.833347195	3.833380143	0.00334719	0.00338014
19.21	0	0.002282603	0.002369958	0.0022826	0.00236996
AE				0.317128	0.317472

TABLE 18 The parameters of the STP6-120 photovoltaic panel for 1D and 2D

Algorithm	I_{ph} [A]	I_{o1} [μA]	n_1	R_s [Ω]	R_{sh} [Ω]	I_{o2} [μA]	n_2
HSDA 1D	7.47252992	2.3349951	1.26010348	0.004594634591	22.219904		
Range set	0–10	E−6–E+1	1–2	0–0.005	0–50		
HSDA 2D	7.4720846882	2.3461292314	1.2605	0.004593007716	23.064174479	4.859387516975	49.885242868
Range set	0–10	E−6–E+1	1–2	0–0.005	0–50	E−6–E+1	1–50

characteristic was measured at 1000 W/m^2 irradiance and 25 °C temperature. The (I, V) points measured [39], the values for the calculated ones with HSDA algorithm in both cases. one and two diode models. and the errors are presented in Table 21.

Table 22 illustrates the optimal parameters of the Kyocera KC200GT photovoltaic panel obtained using the HSDA algorithm, for both one and two diode models, and the lower and upper bound for each of them.

The statistical error tests for the Kyocera KC200GT photovoltaic panel in both cases are presented in Table 23 for one diode model and in Table 24 for the two diode model. The HSDA algorithm has the best results for the one diode model in comparison with CS[38]. Also. it has better results in comparison with CS when the improved one diode model is used [39]. There are some papers where the dataset for Kyocera KC200GT photovoltaic panel is used. In the paper [47] it is referred, but perhaps there are some different (I, V) points because, there is a difference between the points and the plot, and the RMSE given is lower than the one we obtained using the values from paper [47]. The comparison of the datasheet values of Kyocera KC200GT photovoltaic panel shows only a difference between the short circuit current which is 8.21 A in [47]

TABLE 19 The statistical error tests for STP6-120 photovoltaic panel—1D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	1.6600603125087E−02	0.0132137	3.11478E-10	8.99845E-8	0.999906361
EHA-NMS [27]	1.6600603125090E−02	0.0132137	−5.06797E-9	1.46411E-6	0.999906361
Rcr-IJADE [31]	1.6600603125385E−02	0.0132137	−4.10595E-8	1.18619E-5	0.999906361
ISCE [25]	1.6601848135E−02	0.0132004	−0.000143677	0.0415061	0.999906347
MCSWOA [34]	1.6622559976E−02	0.0130677	0.000139469	0.0402402	0.999906113
BHCS [35]	1.6624900296E−02	0.0131412	−0.00062423	0.1802	0.999906087
BLPSO [36]	2.9751510085E−02	0.0238694	−0.00027505	0.0443389	0.999699236
ABC [33]	3.5482441067E−02	0.0283542	0.00192084	0.260004	0.999572206

TABLE 20 The statistical error tests for STP6-120 photovoltaic panel—2D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	1.6600887611E−02	0.013228	1.09127E-5	0.00315257	0.9999854
SDO [37]	1.6665802116E−02	0.0132356	0.00107599	0.310278	0.9999056
MCSWOA [34]	1.6698505417E−02	0.0132787	0.00129699	0.373625	0.9999053

and 8.29 A in [48], but there are high differences between the photovoltaic panel parameters. Additionally, the dataset from the paper [48] has some issue and it cannot be used.

The RMSE is reduced by more than 35%, when using the two diode model to calculate the parameters of the Kyocera KC200GT panel.

The I-V characteristics measured and calculated for the Kyocera KC200GT photovoltaic panel are presented in Figure 9. Additionally, it illustrates the distribution of the current for the three important (I, V) points calculated using the one and two diode model and the measured ones.

3.7 | PVM 752 GaAs photovoltaic panel

The I–V characteristic of the PVM 752 GaAs thin film photovoltaic panel was measured at 1000 W/m^2 irradiance and 25 °C temperature. The (I, V) measured points [32], the values for the

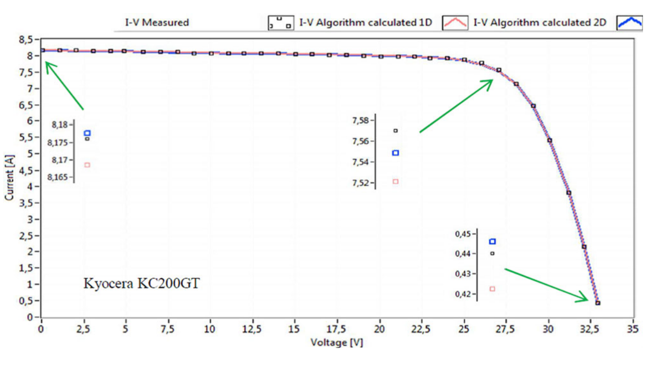

FIGURE 9 The I–V characteristics of Kyocera KC200GT photovoltaic panel

calculated ones with HSDA algorithm in both cases. one and two diode models, and the errors are presented in Table 25.

Table 26 illustrates the optimal parameters of the PVM 752 GaAs photovoltaic panel obtained using the HSDA algorithm, for both one and two diode models, and the lower and upper bound for each of them.

The statistical error tests for the PVM 752 GaAs thin film photovoltaic panel in both cases are presented in Table 27 for one diode model and in Table 28 for the two diode model, The HSDA algorithm has the best results for both diode models. There are three algorithms HSDA, SDO and ACT which calculate the parameters of the thin film photovoltaic panel with very small values for all statistical error tests, HSDA algorithm having the best values. The other three algorithms considered have the RMSE ten times higher than the first three. ELPSO has a very small coefficient of determination.

There are few results for the parameters of the PVM 752 GaAs photovoltaic panel, calculated using the two diode model. There are some significant differences between the parameters calculated with HSDA algorithm and EHHO algorithm. Thus. the difference for the shunt resistance is over 600%, for series resistance it is over 12%, for n_1 almost 100% and the I_{o1} is practically zero for the EHHO algorithm. The extracted values using the EHHO algorithm for the following parameters are: 100 Ω for R_{sh}, 0.5 Ω for R_s and 1.00599 for n_1.

The I–V characteristics, measured and calculated, for the PVM 752 GaAs photovoltaic panel are presented in Figure 10. The parameters calculated with HSDA algorithm using the two diode model are closer to real ones than those obtained using the one diode model, fact confirmed by the statistical error tests. In this case, using the two diode model is important to calculate the parameters of the thin film photovoltaic panel with very good accuracy.

TABLE 21 (I,V) points of Kyocera KC200GT photovoltaic panel and results in current and errors using HSDA algorithm

Measured data		HSDA-1d	HSDA-2d	Error	Error
V [V]	I [A]	I_e [A]	I_e [A]	HSDA-1d	HSDA-2d
0.0409	8.1761	8.168506402	8.177597927	0.0075936	0.00149793
1.0472	8.1761	8.160493753	8.168452598	0.0156062	0.0076474
2.0534	8.1761	8.152481897	8.159308177	0.0236181	0.0167918
3.0707	8.1364	8.144465571	8.150166802	0.00806557	0.0137668
4.0769	8.1364	8.136453702	8.141022371	5.37E-05	0.00462237
4.9082	8.1364	8.129834461	8.133467438	0.00656554	0.00293256
6.0129	8.1178	8.121077547	8.123476488	0.00327755	0.00567649
7.0192	8.1178	8.113064754	8.114331071	0.00473525	0.00346893
8.0255	8.1178	8.105051808	8.105185565	0.0127482	0.0126144
9.0427	8.0781	8.097035673	8.096044746	0.0189357	0.0179447
10.049	8.0781	8.089021763	8.086898695	0.0109218	0.00879869
11.0662	8.0781	8.080919688	8.077652815	0.00281969	0.000447185
11.974	8.0781	8.073686679	8.069400036	0.00441332	0.00869996
12.9912	8.0595	8.065616161	8.060198489	0.00611616	0.000698489
13.9975	8.0595	8.057582224	8.051041091	0.00191778	0.00845891
15.0147	8.0385	8.049483074	8.041826358	0.0109831	0.00332636
16.021	8.0385	8.041380069	8.032628134	0.00288007	0.00587187
17.0272	8.0199	8.033223043	8.023421778	0.013323	0.00352178
18.0445	8.0199	8.024736287	8.013937587	0.00483629	0.00596241
19.0507	8.0012	8.015980614	8.004341229	0.0147806	0.00314123
20.0679	7.9802	8.006297238	7.994069767	0.0260972	0.0138698
21.0742	7.9802	7.994948415	7.982609947	0.0147484	0.00240995
22.0805	7.9616	7.98016232	7.968567631	0.0185623	0.00696763
22.9993	7.9219	7.960730418	7.951058351	0.0388304	0.0291584
24.0165	7.9219	7.925278344	7.919964966	0.00337834	0.00193503
25.0227	7.8823	7.862341438	7.864614532	0.0199586	0.0176855
26.029	7.7844	7.744693568	7.758294045	0.0397064	0.026106
27.0462	7.5699	7.521620945	7.548750802	0.0482791	0.0211492
28.0525	7.1385	7.12718053	7.164001776	0.0113195	0.0255018
29.0697	6.4717	6.443158097	6.474429725	0.0285419	0.00272973
30.076	5.4155	5.415799292	5.422289993	0.000299292	0.00678999
31.1807	3.8091	3.834297113	3.806573489	0.0251971	0.00252651
32.0995	2.1443	2.162865473	2.133716443	0.0185655	0.0105836
32.9198	0.44	0.422331064	0.446068671	0.0176689	0.00606867
AE				0.485344	0.309372

TABLE 22 The parameters of the Kyocera KC200GT photovoltaic panel for 1D and 2D

Algorithm	I_{ph} [A]	I_{o1} [μA]	n_1	R_s [Ω]	R_{sh} [Ω]	I_{o2} [μA]	n_2
HSDA 1D	8.1861146203	3.9544490582E-4	54.332817131	0.265468560011	125.5889522415		
Range set	0–10	$E-6$–$E+1$	1–128	0–0.5	0–500		
HSDA 2D	8.1993730800	3.72439771494E-4	62.807993415	0.288048638147	110.0343402669	3.9374261E-5	49.461034082
Range set	0–10	$E-6$–$E+1$	1–128	0–0.5	0–500	$E-6$–$E+1$	1–128

TABLE 23 The statistical error tests for Kyocera KC200GT photovoltaic panel—1D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	1.8439334177147E−02	0.0142748	1.68232E-8	5.24106E-6	0.999890269
CS [38]	1.9741113849075E−02	0.0159929	0.000841057	0.244966	0.999874228
CS [39]	2.3626486347225E−02	0.0167132	0.00777703	2.00251	0.999819848
WDO [44]	1.6121180114611E−01	0.100538	-0.0357129	1.305	0.991612471
PS [44]	1.5121019219095E−01	0.116131	-0.047096	1.88286	0.992620915

TABLE 24 The statistical error tests for Kyocera KC200GT photovoltaic panel—2D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	1.190362421737E-2	0.00909918	−0.000106163	0.051235	0.99995427
PSDA [44]	1.198170902546 E-2	0.00895609	−3.29509E-5	0.0157982	0.99995366

3.8 | Leibold solar module LSM 20 photovoltaic panel

The I–V characteristic of the Leibold solar module LSM 20 photovoltaic panel, with 20 monocrystalline silicon photovoltaic cells connected in series, was measured at 360 W/m^2 irradiance and 24 °C temperature. The (I, V) measured points [40], the values for the calculated ones with HSDA algorithm in both cases, one and two diode models, and the errors are presented in Table 29.

Table 30 illustrates the optimal parameters of the LSM 20 photovoltaic panel obtained using the HSDA algorithm for both one and two diode models and the lower and upper bound for each of them.

The statistical error tests for the LSM 20 photovoltaic panel in both cases are presented in Table 31 for one diode model and in Table 32 for the two diode model. The HSDA algorithm has better results for one diode model than ACT algorithm, the RMSE is improved with 1.5%. The ACT algorithm was used only for one diode model [40].

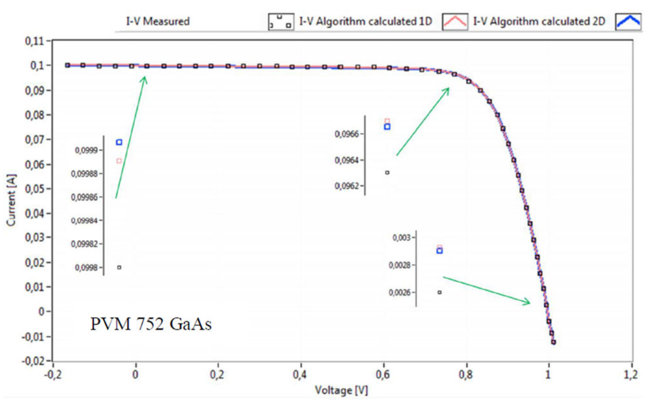

FIGURE 10 The I–V characteristics of PVM 752 GaAs photovoltaic panel

The I–V characteristics measured and calculated for the LSM 20 photovoltaic panel are presented in Figure 11.

3.9 | Leybold solar module STE 4/100 photovoltaic panel

The I–V characteristic of the Leybold Solar Module STE 4/100 photovoltaic panel, with 4 polycrystalline silicon photovoltaic cells connected in series, was measured at 900 W/m^2 irradiance and 22 °C temperature. The (I, V) measured points [40], the values for the calculated ones with HSDA algorithm in both cases, one and two diode models, and the errors are presented in Table 33.

Table 34 illustrates the optimal parameters of the STE 4/100 photovoltaic panel obtained using the HSDA algorithm for both one and two diode models and the lower and upper bound for each of them.

The statistical error tests for the STE 4/100 photovoltaic panel in both cases are presented in Table 35 for one diode model and in Table 36 for the two diode model. The HSDA algorithm has better results for one diode model than ACT

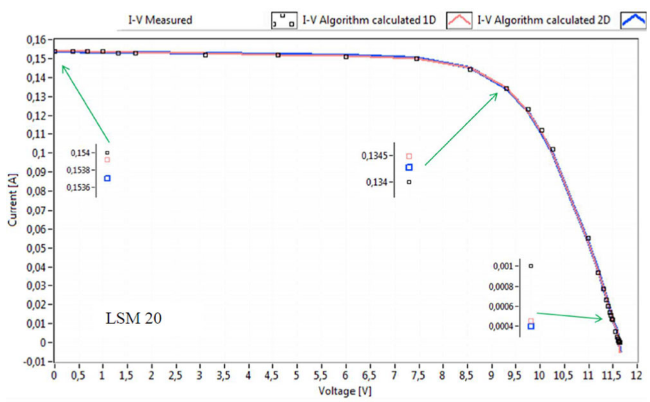

FIGURE 11 The I–V characteristics of LSM 20 photovoltaic panel

TABLE 25 (*I*,*V*) points of PVM 752 GaAs photovoltaic panel and results in current and errors using HSDA algorithm

Measured data		HSDA-1d	HSDA-2d	Error	Error
V [V]	*I* [A]	I_e [A]	I_e [A]	HSDA-1d	HSDA-2d
−0.1659	0.1001	0.10017618	0.100212005	7.62E-05	0.000112005
−0.1281	0.1	0.100120536	0.100152495	0.000120536	0.000152495
−0.0888	0.0999	0.10006268	0.100090619	0.00016268	0.000190619
−0.049	0.0999	0.10000399	0.100027849	0.00010399	0.000127849
−0.0102	0.0999	0.099946775	0.099966656	4.68E-05	6.67E-05
0.0275	0.0998	0.099891278	0.099907303	9.13E-05	0.000107303
0.0695	0.0999	0.099829249	0.099840958	7.08E-05	5.90E-05
0.1061	0.0998	0.099775374	0.099783339	2.46E-05	1.67E-05
0.146	0.0998	0.099716536	0.099720409	8.35E-05	7.96E-05
0.1828	0.0997	0.099662366	0.099662471	3.76E-05	3.75E-05
0.223	0.0997	0.099603083	0.099599058	9.69E-05	0.000100942
0.26	0.0996	0.099548611	0.099540787	5.14E-05	5.92E-05
0.3001	0.0997	0.099489363	0.099477384	0.000210637	0.000222616
0.3406	0.0996	0.099429684	0.099413494	0.000170316	0.000186506
0.3789	0.0995	0.099373176	0.099352939	0.000126824	0.000147061
0.4168	0.0994	0.099317077	0.099292721	8.29E-05	0.000107279
0.4583	0.0994	0.099255014	0.099225895	0.000144986	0.000174105
0.4949	0.0993	0.099199237	0.099165559	0.000100763	0.000134441
0.537	0.0993	0.099131549	0.099091897	0.000168451	0.000208103
0.5753	0.0992	0.099062101	0.099016028	0.000137899	0.000183972
0.6123	0.099	0.098977196	0.098923822	2.28E-05	7.62E-05
0.6546	0.0988	0.098825269	0.098762679	2.53E-05	3.73E-05
0.6918	0.0983	0.098573078	0.098504018	0.000273078	0.000204018
0.7318	0.0977	0.097987461	0.097920182	0.000287461	0.000220182
0.7702	0.0963	0.096695718	0.096652138	0.000395718	0.000352138
0.8053	0.0937	0.094116317	0.094125709	0.000416317	0.000425709
0.8329	0.09	0.090307454	0.090376421	0.000307454	0.000376421
0.855	0.0855	0.085459791	0.08557175	4.02E-05	7.18E-05
0.8738	0.0799	0.079738726	0.079869113	0.000161274	3.09E-05
0.8887	0.0743	0.073952307	0.07407544	0.000347693	0.00022456
0.9016	0.0683	0.068086146	0.068189138	0.000213854	0.000110862
0.9141	0.0618	0.061475863	0.061541092	0.000324137	0.000258908
0.9248	0.0555	0.055190974	0.05521686	0.000309026	0.00028314
0.9344	0.0493	0.049074059	0.049062906	0.000225941	0.000237094
0.9445	0.0422	0.042211401	0.04216675	1.14E-05	3.33E-05
0.9533	0.0357	0.035767146	0.035694512	6.71E-05	5.49E-06
0.9618	0.0291	0.029189699	0.029097473	8.97E-05	2.53E-06
0.9702	0.0222	0.022457991	0.022363564	0.000257991	0.000163564
0.9778	0.0157	0.016133973	0.016052633	0.000433973	0.000352633
0.9852	0.0092	0.009706717	0.009650402	0.000506717	0.000450402
0.9926	0.0026	0.002926255	0.00290338	0.000326255	0.00030338
0.9999	−0.004	−0.004127752	−0.004108619	0.000127752	0.000108619
1.0046	−0.0085	−0.008528464	−0.008454168	2.85E-05	4.58E-05
1.0089	−0.0124	−0.013091372	−0.012989266	0.000691372	0.000589266
AE				0.00800002	0.00743812

TABLE 26 The parameters of the PVM 752 GaAs photovoltaic panel for 1D and 2D

Algorithm	I_{ph} [A]	I_{o1} [μA]	n_1	R_s [Ω]	R_{sh} [Ω]	I_{o2} [μA]	n_2
HSDA 1D	0.1000275091	5.9443224E-6	1.646690262776	0.650143443909	678.14612332		
Range Set	0–1	E−6–E+1	1–2	0–1	0–1000		
HSDA 2D	0.1000559745	7.2694093E-5	2.002608024691	0.669003416666	634.06199495	6.225529666E-7	1.5147908024
Range Set	0–1	E−6–E+1	1–2.5	0–1	0–1000	E−6–E+1	1–2

TABLE 27 The statistical error tests for PVM 752 GaAs photovoltaic panel—1D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	2.3469677491907E-4	0.000181819	4.21357E-9	0.000117727	0.9999584
SDO [37]	2.3699803913041E-4	0.000188993	3.2839E-5	0.917463	0.9999576
ACT [40]	3.4361680140958E-4	0.00024677	2.37078E-5	0.453511	0.9999108
EHHO [41]	2.2610170949847E-3	0.00196237	5.64302E-6	0.016366	0.9961378
ABC [40]	2.8210677059958E-3	0.00216911	0.000695827	1.66898	0.9939876
ELPSO [32]	2.5591450030227E-2	0.0214164	6.91387E-5	0.0177159	0.5018068

algorithm, the RMSE is improved with almost 9%. The ACT algorithm was used only for one diode model [40].

The I–V characteristics measured and calculated for the STE 4/100 photovoltaic panel are presented in Figure 12.

3.10 | Monocrystalline commercial 3 × 3 photovoltaic cell

The I–V characteristic of the monocrystalline commercial silicon photovoltaic cell, 3 × 3 cm sizes, was measured at 1000 W/m^2 irradiance and 27 °C temperature. The (I, V) points measured, the values for the calculated ones with HSDA algorithm in both cases one and two diode models and the errors are presented in Table 37.

Table 38 illustrates the optimal parameters of the mSi 3 × 3 photovoltaic cell obtained using the HSDA algorithm for both one and two diode models and the lower and upper bound for each of them.

The statistical error tests for the mSi 3 × 3 photovoltaic cell in both cases are presented in Table 39 for one diode model and in Table 40 for the two diode model. The HSDA algorithm has the best results for one diode model, giving better solutions in comparison with SDA algorithm and 5P.

The I–V characteristics measured and calculated for the mSi 3 × 3 photovoltaic cell are presented in Figure 13.

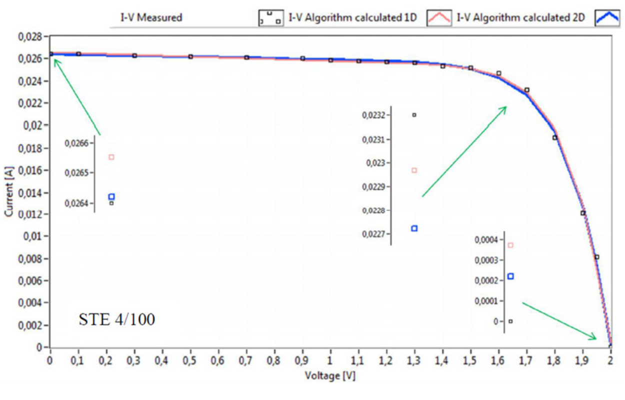

FIGURE 12 The I–V characteristics of STE 4/100 photovoltaic panel

3.11 | Amorphous silicon aSi:H photovoltaic cell

The I–V characteristic of the aSi:H amorphous silicon photovoltaic cell, 1 cm^2 area, was measured at 1000 W/m^2 irradiance and 25 °C temperature, using LOT Oriel class A solar simulator and 4200A-SCS Keitley analyser. The (I, V) measured points [50], the values for the calculated ones with HSDA algorithm in

TABLE 28 The statistical error tests for PVM 752 GaAs photovoltaic panel - 2D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	2.1306175254689E-4	0.000169048	−1.77149E-7	0.00545216	0.9999657
SDO [37]	2.2313102275034E-4	0.000169756	−6.18891E-5	1.89309	0.9999624
EHHO [41]	2.2610170949847E-3	0.00196237	5.64302E-6	0.016366	0.9961378

TABLE 29 (I,V) points of LSM 20 photovoltaic panel and results in current and errors using HSDA algorithm

Measured data		HSDA-1d	HSDA-2d	Error	Error
V [V]	I [A]	I_e [A]	I_e [A]	HSDA-1d	HSDA-2d
0	0.154	0.153918454	0.153699987	8.15E-05	0.000300013
0.37	0.154	0.153769379	0.153591101	0.000230621	0.000408899
0.67	0.154	0.153648504	0.153502806	0.000351496	0.000497194
0.99	0.154	0.153519561	0.153408611	0.000480439	0.000591389
1.31	0.153	0.153393195	0.153316209	0.000393195	0.000316209
1.67	0.153	0.153248093	0.153210169	0.000248092	0.000210169
3.1	0.152	0.152673338	0.152789255	0.000673338	0.000789255
4.6	0.152	0.152056575	0.152329944	5.66E-05	0.000329944
6	0.151	0.151391532	0.151784568	0.000391532	0.000784568
7.45	0.15	0.149850691	0.150227905	0.000149309	0.000227905
8.55	0.144	0.145008553	0.14509898	0.00100855	0.00109898
9.3	0.134	0.13449098	0.13428015	0.00049098	0.00028015
9.75	0.123	0.121908759	0.121632185	0.00109124	0.00136782
10.04	0.112	0.110548532	0.11032334	0.00145147	0.00167666
10.26	0.102	0.099836064	0.099714081	0.00216394	0.00228592
10.99	0.055	0.05313578	0.053403983	0.00186422	0.00159602
11.2	0.037	0.038041924	0.038219239	0.00104192	0.00121924
11.31	0.0281	0.0285902	0.02876331	0.0004902	0.00066331
11.37	0.0227	0.023783631	0.023902365	0.00108363	0.00120236
11.41	0.019	0.020601775	0.020672417	0.00160177	0.00167242
11.44	0.016	0.018454981	0.018465451	0.00245498	0.00246545
11.46	0.0142	0.016741639	0.016731412	0.00254164	0.00253141
11.48	0.0127	0.014606277	0.014606098	0.00190628	0.0019061
11.5	0.012	0.011347838	0.011443716	0.000652162	0.000556284
11.55	0.006	0.008890751	0.008771463	0.00289075	0.00277146
11.58	0.003	0.006549938	0.006362935	0.00354994	0.00336293
11.6	0.002	0.003531533	0.003409322	0.00153153	0.00140932
11.61	0.001	0.002726095	0.002580864	0.0017261	0.00158086
11.62	0.001	0.000449688	0.000395378	0.000550312	0.000604622
11.63	0.0006	−0.001264432	−0.001271893	0.00186443	0.00187189
11.632	0.0003	−0.001281269	−0.001305013	0.00158127	0.00160501
11.633	0.0002	−0.001364252	−0.001390291	0.00156425	0.00159029
11.636	0.0001	−0.001912584	−0.00192204	0.00201258	0.00202204
11.64	0.0001	−0.002847481	−0.002818815	0.00294748	0.00291881
11.65	0	−0.005057074	−0.004943104	0.00505707	0.0049431
AE				0.0481749	0.049658

TABLE 30 The parameters of the LSM 20 photovoltaic panel for 1D and 2D

Algorithm	I_{ph} [A]	I_{o1} [μA]	n_1	R_s [Ω]	R_{sh} [Ω]	I_{o2} [μA]	n_2
HSDA 1D	0.1543170769	2.6509530E-3	1.272131128842	6.424783439254	2482.1422144		
Range set	0–1	E−6–E+1	1–2	0–10	0–5000		
HSDA 2D	0.1539796183	2.9919159E-3	1.333644224220	6.170727347669	3398.5971878	3.089392126E-3	1.3336845722
Range set	0–1	E−6–E+1	1–2	0–10	0–5000	E−6–E+1	1–2

TABLE 31 The statistical error tests for LSM 20 photovoltaic panel—1D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	1.7640056788688E-3	0.00137642	3.66602E-7	0.00121181	0.999302
ACT [40]	1.7907070790738E-3	0.00138492	−7.75688E-6	0.0252584	0.999280

TABLE 32 The statistical error tests for LSM 20 photovoltaic panel—2D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	1.7584869412758E-3	0.0014188	3.97536E-7	0.00131819	0.999306
PSDA [44]	1.75889 E-3	0.0014258	−1.40082E-5	0.0464372	0.999306

TABLE 33 (I, V) points of STE 4/100 photovoltaic panel and results in current and errors using HSDA algorithm

Measured data		HSDA-1d	HSDA-2d	Error	Error
V [V]	I [A]	I_e [A]	I_e [A]	HSDA-1d	HSDA-2d
0.00	0.0264	0.026552231	0.026419736	0.000152231	1.97E-05
0.10	0.0264	0.026478313	0.026372319	7.83E-05	2.77E-05
0.30	0.0263	0.026330637	0.026277506	3.06E-05	2.25E-05
0.50	0.0262	0.026182941	0.026182522	1.71E-05	1.75E-05
0.70	0.0261	0.026035109	0.026086744	6.49E-05	1.33E-05
0.90	0.026	0.025886378	0.025987298	0.000113622	1.27E-05
1.00	0.0259	0.025810656	0.025933056	8.93E-05	3.31E-05
1.10	0.0258	0.025731831	0.025870827	6.82E-05	7.08E-05
1.20	0.0257	0.025645006	0.025791272	5.50E-05	9.13E-05
1.30	0.0256	0.025537557	0.025674029	6.24E-05	7.40E-05
1.40	0.0253	0.025377857	0.025475159	7.79E-05	0.000175159
1.50	0.0252	0.025081111	0.025096093	0.000118889	0.000103907
1.60	0.0247	0.024440977	0.024326669	0.000259023	0.000373331
1.70	0.0232	0.022969194	0.022722991	0.000230806	0.000477009
1.80	0.0189	0.019728598	0.019442624	0.000828598	0.000542624
1.90	0.0121	0.012834507	0.012794207	0.000734507	0.000694207
1.95	0.0081	0.006903773	0.007226841	0.00119623	0.000873159
2.00	0	0.000373262	0.000219779	0.000373262	0.000219779
AE				0.00455087	0.00384171

TABLE 34 The parameters of the STE 4/100 photovoltaic panel for 1D and 2D

Algorithm	I_{ph} [A]	I_{o1} [μA]	n_1	R_s [Ω]	R_{sh} [Ω]	I_{o2} [μA]	n_2
HSDA 1D	0.0265952366	1.4121163E-4	1.035670610803	2.203791071239	1352.8567829		
Range set	0–0.1	$E-6$–$E+1$	1–2	0–5	0–2000		
HSDA 2D	0.0264345331	7.4687521E-5	1.069983607677	1.182091387200	2109.2480021	4.910183730E-3	1.2999453589
Range set	0–0.1	$E-6$–$E+1$	1–2	0–5	0–2000	$E-6$–$E+1$	1–2

TABLE 35 The statistical error tests for STE 4/100 photovoltaic panel - 1D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	4.0852924995122E-4	0.000252826	3.3492E-9	3.3802E-5	0.99693
ACT [40]	4.4789891725246E-4	0.000258011	−7.01989E-5	0.654298	0.99631

TABLE 36 The statistical error tests for STE 4/100 photovoltaic panel—2D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	3.3480413907454E-4	0.000213428	1.82614E-8	0.000224889	0.99794

TABLE 37 (I, V) points of mSi 3 × 3 photovoltaic cell and results in current and errors using HSDA algorithm

Measured data		HSDA-1d	HSDA-2d	Error	Error
V [V]	I [A]	I_e [A]	I_e [A]	HSDA-1d	HSDA-2d
0	0.424809	0.425360823	0.425365533	0.000551823	0.000556533
0.011822	0.424796	0.425241118	0.425250622	0.000445118	0.000454622
0.020097	0.424785	0.425157259	0.425170077	0.000372259	0.000385076
0.053199	0.424745	0.4248209	0.424846518	7.59E-05	0.000101518
0.098122	0.424649	0.424359791	0.424400925	0.000289209	0.000248075
0.111718	0.424643	0.424218133	0.424263308	0.000424867	0.000379692
0.14009	0.42448	0.423916715	0.42396885	0.000563285	0.00051115
0.20984	0.423716	0.423087411	0.423142513	0.000628589	0.000573487
0.265994	0.422752	0.422105861	0.422137414	0.000646139	0.000614586
0.300869	0.421397	0.421052342	0.421052436	0.000344658	0.000344564
0.322739	0.420192	0.420002819	0.419976692	0.000189181	0.000215309
0.350521	0.417588	0.417860152	0.417796743	0.000272152	0.000208743
0.396036	0.409474	0.410247802	0.410136645	0.000773802	0.000662645
0.413769	0.403773	0.404661339	0.404547772	0.000888339	0.000774772
0.453963	0.380558	0.381072631	0.381011711	0.000514631	0.000453711
0.481745	0.350061	0.349896403	0.349905945	0.000164597	0.000155055
0.493567	0.331099	0.331313782	0.331351087	0.000214782	0.000252087
0.49534	0.328027	0.328182228	0.328222673	0.000155228	0.000195673
0.517211	0.282367	0.28158437	0.281636685	0.00078263	0.000730315
0.531988	0.24221	0.241051033	0.241079653	0.00115897	0.00113035
0.536717	0.227086	0.226666767	0.226688771	0.000419233	0.000397229
0.539081	0.219305	0.219144141	0.219161655	0.000160859	0.000143345
0.559179	0.14596	0.146386518	0.146353079	0.000426518	0.000393079
0.563907	0.126391	0.127192354	0.12715456	0.000801354	0.00076356
0.573956	0.082714	0.083300831	0.083261084	0.000586831	0.000547084
0.579276	0.05794	0.058724404	0.058701842	0.000784404	0.000761842
0.582231	0.044104	0.044367767	0.044352505	0.000263767	0.000248505
0.588734	0.012269	0.011928244	0.011952874	0.000340756	0.000316126
0.591211	0	−0.001024099	−0.000983475	0.0010241	0.000983475
AE				0.0142648	0.0135022

TABLE 38 The parameters of the mSi 3 × 3 photovoltaic panel for 1D and 2D

Algorithm	I_{ph} [A]	I_{o1} [μA]	n_1	R_s [Ω]	R_{sh} [Ω]	I_{o2} [μA]	n_2
HSDA 1D	0.4257531602	0.5162416132	1.679334065220	0.091328987389	99.075980176		
Range set	0–1	E−6–E+1	1–2	0–1	0–200		
HSDA 2D	0.4257480777	0.2402586324	1.606285751590	0.092861056153	103.52271354	1.030135254319	2.0918681454
Range set	0–1	E−6–E+1	1–2	0–1	0–200	E−6–E+1	1–3

TABLE 39 The statistical error tests for mSi 3 × 3 photovoltaic panel—1D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	5.6309870446516E-4	0.000491861	3.50364E-7	0.00329241	0.999985
SDA [12]	6.2839209496693E-4	0.000498157	0.000175553	1.53958	0.999982
5P [20]	2.2469147549724E-3	0.00163766	0.000213079	0.504074	0.999767

TABLE 40 The statistical error tests for mSi 3 × 3 photovoltaic panel - 2D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	5.3057797215484 E-4	0.000465593	−5.75799E-7	0.0057425	0.999987

both cases, one and two diode models, and the errors are presented in Table 41.

Table 42 illustrates the optimal parameters of the aSi:H photovoltaic cell obtained using the HSDA algorithm for both one and two diode models and the lower and upper bound for each of them.

The statistical error tests for the aSi:H photovoltaic cell in both cases are presented in Table 43 for one diode model and in Table 44 for the two diode model. The results obtained using HSDA algorithm are compared with the ones obtained using SDA algorithm and 5P method for one diode model. The shunt resistance calculated with 5P differs with over 50% from the one obtained with HSDA algorithm, but the difference is higher for series resistance where we have 1.725 Ω for 5P and 0.04 Ω for HSDA. In this case, the analytical method shows its limits.

The *I–V* characteristics measured and calculated using both one and two diode models for the aSi:H photovoltaic cell are presented in Figure 14.

The necessary time to extract the parameters when the parallel implementation of HSDA was used, were six times smaller in mean for DD model, using an i7 processor with 4 cores and 8 threads at 1.9 GHz.

Table 45 illustrates the improvements in RMSE for each photovoltaic cell or panel. The improvements brought by the HSDA algorithm in comparison with the best algorithm considered from the specialised literature for one diode model are shown in the first column, and for two diode model, in the second column, respectively. The third column shows if there is an improvement in RMSE when the two diode model is used in comparison with the one diode model for the HSDA algorithm and in the last column this improvement in percentage is listed.

4 | CONCLUSIONS

Eleven reliable datasets are considered and presented, eight for photovoltaic panels and three for photovoltaic cells. Nine of them are collected from specialised literature and two new ones are for a monocrystalline commercial cell and for an amorphous silicon cell. The photovoltaic cells and panels considered are manufactured from different materials. such as: mono and polycrystalline silicon, amorphous silicon and GaAs. The HDSA algorithm is described and used to calculate the parameters of the photovoltaic cells and panels using one and two diode model. The HSDA algorithm proved its performance as follows: for fifteen of the cases, the HSDA algorithm extracts the parameters of the photovoltaic cells and panels with the smallest values for the statistical error tests, for four algorithms, the results are the same with the ones given by other algorithms

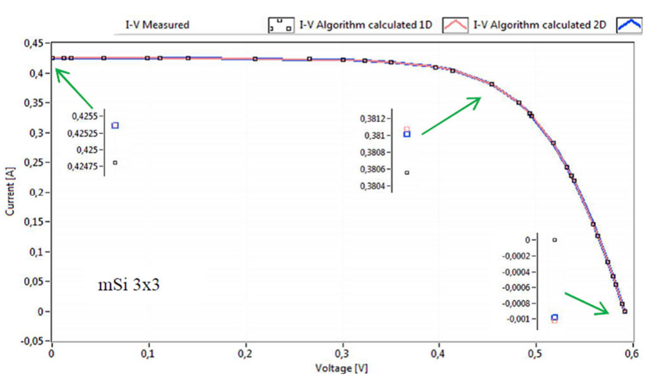

FIGURE 13 The *I–V* characteristics of mSi 3 × 3 photovoltaic cell

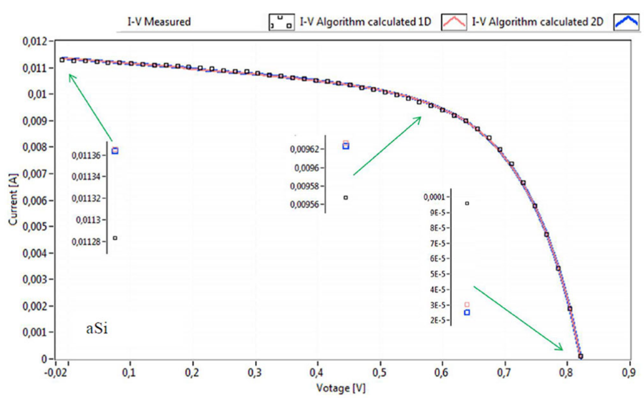

FIGURE 14 The *I–V* characteristics of aSi:H photovoltaic cell

TABLE 41 (I,V) points of aSi:H photovoltaic cell and results in current and errors using HSDA algorithm

Measured data		HSDA-1d	HSDA-2d	Error	Error
V [V]	**I [A]**	**I_e [A]**	**I_e [A]**	**HSDA-1d**	**HSDA-2d**
−0.01	0.0112831	0.011365428	0.011363934	−8.23E-05	8.08E-05
0.00848	0.0112656	0.011329745	0.011328705	−6.41E-05	6.31E-05
0.026955	0.0112425	0.011294035	0.011293438	−5.15E-05	5.09E-05
0.045435	0.0112236	0.011258271	0.011258099	−3.47E-05	3.45E-05
0.063915	0.0112024	0.011222452	0.011222687	−2.01E-05	2.03E-05
0.08239	0.0111931	0.011186572	0.011187191	6.53E-06	5.91E-06
0.10087	0.0111547	0.0111506	0.011151588	4.10E-06	3.11E-06
0.11935	0.0111104	0.011114523	0.011115855	−4.12E-06	5.45E-06
0.137825	0.011099	0.011078323	0.011079959	2.07E-05	1.90E-05
0.156305	0.0110782	0.011041952	0.011043862	3.62E-05	3.43E-05
0.174785	0.0110397	0.011005381	0.011007534	3.43E-05	3.22E-05
0.19326	0.011007	0.010968572	0.010970924	3.84E-05	3.61E-05
0.21175	0.0109816	0.010931424	0.010933928	5.02E-05	4.77E-05
0.2302	0.0109413	0.010893976	0.010896588	4.73E-05	4.47E-05
0.2487	0.0108962	0.010855954	0.010858622	4.02E-05	3.76E-05
0.26715	0.010861	0.010817449	0.010820111	4.36E-05	4.09E-05
0.28565	0.0108375	0.010778112	0.010780703	5.94E-05	5.68E-05
0.30415	0.0107773	0.010737876	0.010740343	3.94E-05	3.70E-05
0.3226	0.0107235	0.010696635	0.010698908	2.69E-05	2.46E-05
0.3411	0.0106896	0.010653898	0.0106559	3.57E-05	3.37E-05
0.35955	0.0106237	0.01060957	0.010611244	1.41E-05	1.25E-05
0.37805	0.0105959	0.010562995	0.010564257	3.29E-05	3.16E-05
0.3965	0.0105226	0.010513926	0.010514732	8.67E-06	7.87E-06
0.415	0.0104671	0.010461462	0.010461746	5.64E-06	5.35E-06
0.4335	0.0104073	0.010404954	0.01040467	2.35E-06	2.63E-06
0.45195	0.0103272	0.010343608	0.010342738	−1.64E-05	1.55E-05
0.47045	0.0102575	0.01027589	0.010274413	−1.84E-05	1.69E-05
0.4889	0.0101725	0.010200693	0.010198631	−2.82E-05	2.61E-05
0.5074	0.0100598	0.010115773	0.010113186	−5.60E-05	5.34E-05
0.52585	0.009967	0.010019312	0.010016261	−5.23E-05	4.93E-05
0.54435	0.0098534	0.009907973	0.009904584	−5.46E-05	5.12E-05
0.56285	0.0097021	0.009778504	0.009774968	−7.64E-05	7.29E-05
0.5813	0.0095669	0.009626993	0.009623476	−6.01E-05	5.66E-05
0.5998	0.0093838	0.009447275	0.009444054	−6.35E-05	6.03E-05
0.61825	0.0092011	0.009233682	0.00923097	−3.26E-05	2.99E-05
0.63675	0.0089748	0.008976841	0.008974912	−2.04E-06	1.12E-07
0.6552	0.0086853	0.008668002	0.008667131	1.73E-05	1.82E-05
0.6737	0.0083376	0.00829287	0.008293222	4.47E-05	4.44E-05
0.69215	0.007911	0.007837927	0.00783955	7.31E-05	7.15E-05
0.71065	0.0073725	0.007281415	0.00728422	9.11E-05	8.83E-05
0.72915	0.006665	0.006600576	0.006604454	6.44E-05	6.05E-05
0.7476	0.005787	0.0057683	0.005772802	1.87E-05	1.42E-05
0.7661	0.0047014	0.004743608	0.004748044	−4.22E-05	4.66E-05

(Continues)

TABLE 41 (Continued)

Measured data		HSDA-1d	HSDA-2d	Error	Error
V [V]	I [A]	I_e [A]	I_e [A]	HSDA-1d	HSDA-2d
0.78455	0.0034034	0.003487069	0.003490263	−8.37E-05	8.69E-05
0.80305	0.0018769	0.001936075	0.001936162	−5.92E-05	5.93E-05
0.8215	9.58E-05	3.04E-05	2.51E-05	6.54E-05	7.07E-05
AE				0.00182372	0.00176117

TABLE 42 The parameters of the aSi photovoltaic panel for 1D and 2D

Algorithm	I_{ph} [A]	I_{o1} [μA]	n_1	R_s [Ω]	R_{sh} [Ω]	I_{o2} [μA]	n_2
HSDA 1D	0.011347	0.7047542	3.353834	0.040283	520.065069		
Range set	0–0.1	E−6–E+1	1–5	0–0.5	0–1000		
HSDA 2D	0.0113491493	0.2221958520	3.079462129749	0.198793857050	528.10082632	1.060530428020	4.0991152170
Range set	0–0.1	E−6–E+1	1–5	0–0.5	0–1000	E−6–E+1	1–5

TABLE 43 The statistical error tests for aSi photovoltaic panel—1D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	4.6194563185752E-5	3.96462E-5	4.13577E-7	0.0600605	0.999665
SDA [12]	4.6330023708607E-5	3.98306E-5	−4.39431E-7	0.0636288	0.999663
5P [20]	2.0863145086178E-4	0.000189952	−0.000144047	6.40262	0.993170

TABLE 44 The statistical error tests for aSi photovoltaic panel—2D for different algorithms

Algorithm	RMSE	MAE	MBE	t-statistic	R^2
HSDA	4.497351894588E-5	3.82863E-5	2.63015E-8	0.00392311	0.999683

TABLE 45 The improvements

	Improvements			
Photovoltaic cell or panel	1D [%]	2D [%]	Yes or no (of 2D from 1D)	2D from 1D [%]
RTC	0	0.03	Yes	0.4
PWP201	0	1.6	No	–
STM6-40	0	7.5	Yes	0.5
Sharp ND-R250A5	1.1	2.7	Yes	1.6
STP6-120	0	0.4	No	–
Kyocera KC200GT	6.6	0.7	Yes	35.5
PVM 752 GaAs	1	4,5	Yes	9.2
Leibold solar module LSM 20	1,5	0.02	Yes	0.35
Leybold solar module STE 4/100	8.8	–	Yes	18
Monocrystalline commercial 3 × 3	10.4	–	Yes	5.8
Amorphous silicon aSi:H	0.3	–	Yes	2.56

and for three it is applied for the first time. The values of statistical error tests are improved if the two diode model is used for nine devices under test, and only for two panels they are not: PWP201 and STP6-120. This proved that the second mechanism is important in order to explain the behaviour of these photovoltaic cells and panels. The time to extract the parameters of the photovoltaic cells is reduced more than six time using HSDA algorithm when the parallel implementation is used.

The analysis and the calculus achieved proved that the HSDA algorithm is an important tool to:

- Extract the parameters of photovoltaic cells and panels with very high accuracy. It can be successfully used for all types of photovoltaic cells and panels.
- Prove if a solution is optimised or it can be still optimised using the refining process.

Using the HSDA algorithm for extracting the parameters of concentrated photovoltaic cells (CPV) and using the three diode model are the aims of further work and research.

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REFERENCES

1. Wolf, M., Rauschenbach, H.: Series resistance effects on solar cell measurements. Advanced Energy Conversion 3(2), 455–479 (1963)
2. Bashahu, M., Habyarimana, A.: Review and test of methods for determination of the solar cell series resistance. Renewable Energy 6(2), 129–238 (1995)
3. Bashahu, M., Nkundabakura, P.: Review and tests of methods for the determination of the solar cell junction ideality factors. Sol. Energy 81(7), 856–863 (2007).
4. Cotfas, D.T., Cotfas, P.A., Kaplanis, S.: Methods to determine the dc parameters of solar cells: a critical review. Renewable Sustainable Energy Rev. 28, 588–596 (2013)
5. Cotfas, D.T., Cotfas, P.A., Kaplanis, S.: Methods and techniques to determine the dynamic parameters of solar cells: review. Renewable Sustainable Energy Rev. 61, 213–221 (2016)
6. Humada, A.M., et al.: Solar cell parameters extraction based on single and double-diode models: A review. Renewable Sustainable Energy Rev. 56, 494–509 (2016)
7. Jervase, J.A., Bourdoucen, H., Al-Lawati, A.: Solar cell parameter extraction using genetic algorithms. Meas. Sci. Technol. 12(11), 1922–1925 (2001)
8. Pillai, D.S., Rajasekar, N.: Metaheuristic algorithms for PV parameter identification: A comprehensive review with an application to threshold setting for fault detection in PV systems. Renewable Sustainable Energy Rev. 82(3), 3503–3525 (2018)
9. Oliva, D., et al.: A review on meta-heuristics methods for estimating parameters of solar cells. J. Power Sources 435, 126683 (2019)
10. Yanga, B., et al.: Comprehensive overview of meta-heuristic algorithm applications on PV cell parameter identification. Energy Convers. Manage. 208, 112595 (2020)
11. Selem, S.I., El-Fergany, A.A., Hasanien, H.M.: Artificial electric field algorithm to extract nine parameters of triple-diode photovoltaic model. Int. J. Energy Res. 45, 590–604 (2020)
12. Cotfas, D.T., Deaconu, A.M., Cotfas, P.A.: Application of successive discretization algorithm for determining photovoltaic cells parameters. Energy Convers. Manage. 196, 545–556 (2019)
13. Oliva, D., El Aziz, M.A., Hassanien, A.E.: Parameter estimation of photovoltaic cells using an improved chaotic whale optimization algorithm. Appl. Energy 200, 141–154 (2017)
14. Guo, L., et al.: Parameter identification and sensitivity analysis of solar cell models with cat swarm optimization algorithm. Energy Convers. Manage. 108, 520–528 (2016)
15. Hamid, N.F.A., Rahim, N.A., Selvaraj, J.: Solar cell parameters identification using hybrid Nelder–Mead and modified particle swarm optimization. J. Renewable Sustainable Energy 8, 015502 (2016)
16. Niu, Q., Zhang, H., Li, K.: An improved TLBO with elite strategy for parameters identification of PEM fuel cell and solar cell models. Int. J. Hydrogen Energy 39, 3837–3854 (2014)
17. Alam, D.F., Yousri, D.A., Eteiba, M.B.: Flower pollination Algorithm based solar PV parameter estimation. Energy Convers. Manage. 101, 410–422 (2015)
18. Huang, W., et al.: Extracting solar cell model parameters based on chaos particle swarm algorithm. In: 2011 International Conference on Electric Information and Control Engineering, pp. 398–402. IEEE, Piscataway, NJ (2011).
19. Yuan, X.F., Xiang, Y.Z., He, Y.Q.: Parameter extraction of solar cell models using mutative- scale parallel chaos optimization algorithm. Sol. Energy 108, 238–251 (2014)
20. Chan, D.S.H., Phillips, J.R., Phang, J.C.H.: A comparative study of extraction methods for solar cell model parameters. Solid-State Electronics 29(3), 329–337 (1986)
21. Cotfas, P.A., Cotfas, D.T.: Design and implementation of RELab system to study the solar and wind energy. Measurement 93, 94–101 (2016)
22. AlHajri, M.F., et al.: Optimal extraction of solar cell parameters using pattern search. Renewable Energy 44, 238–245 (2012)
23. Cotfas, D.T., Cotfas, P.A., Cataron, A.: Using the genetic algorithm to determine the parameters of photovoltaic cells and panels. In: International Symposium on Electronics and Telecommunications 2018, pp. 1–4. IEEE, Piscataway, NJ (2018)
24. Askarzadeh, A., Rezazadeh, A.: Parameter identification for solar cell models using harmony search-based algorithms. Sol. Energy 86(11), 3241–3249 (2012)
25. Gao, X., et al.: Parameter extraction of solar cell models using improved shuffled complex evolution algorithm. Energy Convers. Manage. 157, 460–479 (2018)
26. Gnetchejo, P.J., et al.: Important notes on parameter estimation of solar photovoltaic cell. Energy Convers. Manage. 197, 111870 (2019)
27. Chen, Z., et al.: Parameters identification of photovoltaic models using hybrid adaptive Nelder–Mead simplex algorithm based on eagle strategy. Appl. Energy 182, 47–57 (2016)
28. Nunes, H.G.G., et al.: A new high performance method for determining the parameters of PV cells and modules based on guaranteed convergence particle swarm optimization. Appl. Energy 211, 774–791 (2018)
29. Nunes, H.G.G., et al.: Collaborative swarm intelligence to estimate PV parameters. Energy Convers. Manage. 185, 866–890 (2019)
30. Jordehi, A.R.: Time varying acceleration coefficients particle swarm optimisation (TVACPSO): a new optimisation algorithm for estimating parameters of PV cells and modules. Energy Convers Manage 129, 262–274 (2016)
31. Gong, W., Cai, Z.: Parameter extraction of solar cell models using repaired adaptive differential evolution. Sol Energy 94, 209–220 (2013)
32. Jordehi, A.R.: Enhanced leader particle swarm optimisation (ELPSO): An efficient algorithm for parameter estimation of photovoltaic (PV) cells and modules. Sol. Energy 159, 78–87 (2018)
33. Oliva, D., et al.: A chaotic improved artificial bee colony for parameter estimation of photovoltaic cells. Energies 10(7), 865 (2017)
34. Xiong, G., et al.: Modified search strategies assisted crossover whale optimization algorithm with selection operator for parameter extraction of solar photovoltaic models. Remote Sensing 11(23), 2795 (2019)

35. Chen, X., Yu, K.: Hybridizing cuckoo search algorithm with biogeography-based optimization for estimating photovoltaic model parameters. Sol. Energy 180, 192–206 (2019)
36. Chen, X., et al.: Biogeography-based learning particle swarm optimization. Soft Computing 21, 7519–7541 (2017).
37. Xiong, G., et al.: Application of supply-demand-based optimization for parameter extraction of solar photovoltaic models. Complexity 2019, 3923691 (2019)
38. Ma, J., et al.: Parameter estimation of photovoltaic models via cuckoo search. J. Appl. Math. 2013, 362619 (2013)
39. Ma, J.: Optimization approaches for parameter estimation and maximum power point tracking (MPPT) of photovoltaic systems. Ph.D. Thesis, University of Liverpool (2014)
40. Muhammad, F.F., et al.: Simple and efficient estimation of photovoltaic cells and modules parameters using approximation and correction technique. PLoS One 14(5), e0216201 (2019)
41. Jiao, S., et al.: Orthogonally adapted Harris hawks optimization for parameter estimation of photovoltaic models. Energy 203, 117804 (2020)
42. Zhang, Y., Ma, M., Jin, Z.: Comprehensive learning Jaya algorithm for parameter extraction of photovoltaic models. Energy 211, 118644 (2020)
43. Elkholy, M.M., El-Hameed, M.A., El-Fergany, A.A.: Artificial ecosystem-based optimizer to electrically characterize PV generating systems under various operating conditions reinforced by experimental validations. IET Renewable Power Gener. 15(3), 701–715 (2021)
44. Deaconu, A.M., Cotfas, D.T., Cotfas, P.A.: Calculation of seven photovoltaic cells parameters using parallelized successive discretization algorithm, Int. J. Photoenergy 2020, 6669579 (2020)
45. Stone, R.J.: Improved statistical procedure for the evaluation of solar radiation estimation models. Sol. Energy 51(4), 298–291 (1993)
46. Easwarakhanthan, T., Bottin, J., Bouhouch, I., Boutrit, C.: Nonlinear minimization algorithm for determining the solar cell parameters with microcomputers. Int J Sol. Energy 4(1), 1 (1986)
47. Derick, M., et al.: An improved optimization technique for estimation of solar photovoltaic parameters. Sol. Energy 157, 116–124 (2017).
48. Ram, P.J., et al.: A new hybrid bee pollinator flower pollination algorithm for solar parameter estimation. Energy Convers. Manage. 135, 463–476 (2017)
49. Babu, T.S., et al.: Parameter extraction of two diode solar PV model using fireworks algorithm. Sol. Energy 140, 265–276 (2016)
50. Martínez, A.L., et al.: Solar photovoltaic technology on rough low carbon steel substrates for building integrated photovoltaics: A complete fabrication sequence panel. Sol. Energy 124, 216–226 (2016)

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