**Estimation of parameters for solar cells with S–shaped current–voltage characteristics using meta–heuristic algorithms**

Oleg Olikh

*Taras Shevchenko National University of Kyiv, 64/13, Volodymyrska Street, Kyiv, 01601, Ukraine*

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| Fig.S1. Fitting results (lines) for the simulated current-voltage characteristic (symbols). The values *I*01= 1.6⋅10-6 mA, *n*1= 1.92, *R*p1 = 190 Ω, *I*02 = 0.16 mA, *n*2= 1.92, *R*p2 =190 Ω, *R*s = 45 Ω, *I*ph = 8 mA were assumed under simulation. | | |

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| Fig.S2. Fitting results (lines) for the simulated current-voltage characteristic (symbols). The parameters values from Sec.2.2.2 were assumed under simulation. | | |

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| Fig.S2. Comparison of *I*01 value estimation by different algorithms on the IV curve set. Circles represent the *I*01 values, which have been used in IV curve simulations, squares represent the median values, and stars represent the mean values. The colored regions correspond to the IQR. The lines only serve as guide to the eye. | | |

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| Fig.S2. Comparison of *n*1 value estimation by different algorithms on the IV curve set. Circles represent the *n*1 values, which have been used in IV curve simulations, squares represent the median values, and stars represent the mean values. The colored regions correspond to the IQR. The lines only serve as guide to the eye. | | |

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| Fig.S2. Comparison of *R*p1 value estimation by different algorithms on the IV curve set. Circles represent the *R*p1 values, which have been used in IV curve simulations, squares represent the median values, and stars represent the mean values. The colored regions correspond to the IQR. The lines only serve as guide to the eye. | | |

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| Fig.S2. Comparison of *I*02 value estimation by different algorithms on the IV curve set. Circles represent the *I*02 values, which have been used in IV curve simulations, squares represent the median values, and stars represent the mean values. The colored regions correspond to the IQR. The lines only serve as guide to the eye. | | |

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| Fig.S2. Comparison of *n*2 value estimation by different algorithms on the IV curve set. Circles represent the *n*2 values, which have been used in IV curve simulations, squares represent the median values, and stars represent the mean values. The colored regions correspond to the IQR. The lines only serve as guide to the eye. | | |

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| Fig.S2. Comparison of *R*p2 value estimation by different algorithms on the IV curve set. Circles represent the *R*p2 values, which have been used in IV curve simulations, squares represent the median values, and stars represent the mean values. The colored regions correspond to the IQR. The lines only serve as guide to the eye. | | |

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| Fig.S2. Comparison of *R*s value estimation by different algorithms on the IV curve set. Circles represent the *R*s values, which have been used in IV curve simulations, squares represent the median values, and stars represent the mean values. The colored regions correspond to the IQR. The lines only serve as guide to the eye. | | |

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| Fig.S2. Comparison of *I*ph value estimation by different algorithms on the IV curve set. Circles represent the *I*ph values, which have been used in IV curve simulations, squares represent the median values, and stars represent the mean values. The colored regions correspond to the IQR. The lines only serve as guide to the eye. | | |

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| Fig.S2. Comparison of RMSPE value for different algorithms, applied to the IV curve set. Squares represent the median values, and stars represent the mean values. The colored regions correspond to the IQR. The lines only serve as guide to the eye. | | |

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| **Table S1.** Results of the comparative algorithm on single IV curve | | | | | | | | | | |
|  |  | Parameter | | | | | | | | |
|  |  | *I*01 (A) | *n*1 | *R*p1 (Ω) | *I*02 (A) | *n*2 | *R*p2 (Ω) | *R*s (Ω) | *I*ph (A) | RMSPE |
|  | true value | 1.6e-9 | 1.92 | 190 | 1.6e-4 | 1.92 | 190 | 45 | 8e-3 |  |
| DE | MEAN | 4.30612E-7 | 2.29342 | 273.866 | 8.17387E-4 | 8.08356 | 217.375 | 23.6714 | 0.00793327 | 0.202896 |
| MEDIAN | 6.31239E-9 | 2.09479 | 200.493 | 3.843E-4 | 4.91355 | 106.342 | 14.1994 | 0.00776123 | 0.177838 |
| STD | 9.79424E-7 | 0.819543 | 327.208 | 0.00101283 | 8.7304 | 448.313 | 22.4509 | 8.7897E-4 | 0.0818108 |
| IQR | 2.47897E-7 | 1.18701 | 73.9815 | 0.00118424 | 6.42196 | 73.1935 | 36.6225 | 0.00105832 | 0.12722 |
| EBLSHADE | MEAN | 4.89016E-8 | 1.99143 | 191.859 | 1.90839E-4 | 2.09441 | 257.032 | 42.8834 | 0.00795469 | 0.112344 |
| MEDIAN | 1.59673E-9 | 1.91973 | 189.998 | 1.59904E-4 | 1.91936 | 189.951 | 45.0092 | 0.00800011 | 0.111803 |
| STD | 2.94351E-7 | 0.302862 | 7.06297 | 1.42778E-4 | 0.749826 | 408.471 | 8.42013 | 1.76013E-4 | 0.00378624 |
| IQR | 2.45E-17 | 2E-9 | 1E-7 | 4E-13 | 2.5E-9 | 2.5E-7 | 5E-8 | 2E-12 | 0 |
| ADELI | MEAN | 1.59673E-9 | 1.91973 | 189.998 | 1.59904E-4 | 1.91936 | 189.951 | 45.0092 | 0.00800011 | 0.111803 |
| MEDIAN | 1.59673E-9 | 1.91973 | 189.998 | 1.59904E-4 | 1.91936 | 189.951 | 45.0092 | 0.00800011 | 0.111803 |
| STD | 2.24774E-17 | 1.8407E-9 | 8.14411E-8 | 2.26085E-12 | 1.09586E-8 | 1.29649E-6 | 8.3637E-8 | 1.67527E-12 | 5.60747E-17 |
| IQR | 2.5E-17 | 2E-9 | 1E-7 | 8E-13 | 6E-9 | 3.5E-7 | 6.5E-8 | 2E-12 | 0 |
| NDE | MEAN | 2.96195E-7 | 2.42087 | 217.047 | 4.32932E-4 | 4.1948 | 572.088 | 31.1402 | 0.00768983 | 0.150002 |
| MEDIAN | 1.97951E-8 | 2.31401 | 205.507 | 2.7074E-4 | 2.82514 | 247.163 | 33.9332 | 0.00765711 | 0.111897 |
| STD | 1.06531E-6 | 0.585381 | 81.8273 | 3.94921E-4 | 6.46811 | 902.42 | 16.9948 | 3.9184E-4 | 0.149461 |
| IQR | 1.28566E-7 | 0.782389 | 32.2484 | 5.10535E-4 | 2.85309 | 341.063 | 30.0524 | 6.3894E-4 | 2.59792E-4 |
| MABC | MEAN | 1.87007E-6 | 3.23398 | 517.263 | 0.00116959 | 14.9942 | 881.309 | 25.5168 | 0.0101761 | 0.404887 |
| MEDIAN | 3.78613E-8 | 3.00104 | 141.578 | 2.22821E-4 | 6.65565 | 82.0348 | 12.4381 | 0.00855776 | 0.169928 |
| STD | 3.35158E-6 | 3.38085 | 2492.2 | 0.00255612 | 17.4695 | 2269.68 | 27.1128 | 0.00447919 | 0.313895 |
| IQR | 1.56208E-6 | 2.81682 | 158.743 | 7.57854E-4 | 23.8231 | 151.829 | 47.2398 | 0.00357495 | 0.608581 |
| TLBO | MEAN | 4.76305E-9 | 1.91592 | 189.79 | 2.17925E-4 | 2.14102 | 494.417 | 44.2879 | 0.00801613 | 0.111834 |
| MEDIAN | 1.59673E-9 | 1.91973 | 189.998 | 1.59904E-4 | 1.91936 | 189.951 | 45.0092 | 0.00800011 | 0.111803 |
| STD | 1.1263E-8 | 0.237052 | 9.96477 | 2.26679E-4 | 1.05125 | 1239.57 | 9.34268 | 2.38013E-4 | 9.91547E-5 |
| IQR | 3.78381E-11 | 0.00312336 | 0.131118 | 2.10985E-8 | 0.00210025 | 0.0325284 | 0.0313024 | 1.92458E-6 | 2.0801E-6 |
| **Table S1** (*continued*) | | | | | | | | | | |
|  |  | *I*01 (A) | *n*1 | *R*p1 (Ω) | *I*02 (A) | *n*2 | *R*p2 (Ω) | *R*s (Ω) | *I*ph (A) | RMSPE |

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|  | true value | 1.6e-9 | 1.92 | 190 | 1.6e-4 | 1.92 | 190 | 45 | 8e-3 |  |
| GOTLBO | MEAN | 1.71767E-6 | 9.57122 | 11628.3 | 7.92397E-4 | 20.2703 | 128.312 | 24.659 | 0.0228366 | 0.639726 |
| MEDIAN | 1.03447E-8 | 3.41832 | 69.094 | 7.71914E-7 | 14.2566 | 74.3327 | 8.80183 | 0.0142995 | 0.81521 |
| STD | 3.34406E-6 | 11.018 | 44234.6 | 0.00216328 | 14.115 | 417.298 | 29.8185 | 0.0197114 | 0.282839 |
| IQR | 1.36228E-6 | 15.8671 | 216.793 | 2.4192E-4 | 23.5098 | 64.4833 | 43.6466 | 0.0237021 | 0.493468 |
| STLBO | MEAN | 1.59673E-9 | 1.91973 | 189.998 | 1.59904E-4 | 1.91936 | 189.951 | 45.0092 | 0.00800011 | 0.111803 |
| MEDIAN | 1.59673E-9 | 1.91973 | 189.998 | 1.59904E-4 | 1.91936 | 189.951 | 45.0092 | 0.00800011 | 0.111803 |
| STD | 3.10035E-17 | 2.53498E-9 | 1.09935E-7 | 7.54905E-13 | 5.08363E-9 | 3.95897E-7 | 7.27714E-8 | 2.265E-12 | 5.60747E-17 |
| IQR | 3.6E-17 | 2.5E-9 | 1E-7 | 1.15E-12 | 7.5E-9 | 6E-7 | 1E-7 | 3E-12 | 0 |
| PSO | MEAN | 3.14227E-6 | 16.6587 | 180118 | 0.00271538 | 36.2226 | 1271.15 | 41.1715 | 0.0386418 | 0.554837 |
| MEDIAN | 1E-16 | 3.52665 | 106.144 | 1E-10 | 50 | 22.0427 | 0.409733 | 0.00899564 | 0.836124 |
| STD | 4.55814E-6 | 22.0702 | 388032 | 0.00438738 | 21.3176 | 3258.81 | 45.3494 | 0.0350568 | 0.350233 |
| IQR | 1E-5 | 49.083 | 163.924 | 0.00643173 | 40.2401 | 100.011 | 92.3135 | 0.0667872 | 0.724107 |
| IJAYA | MEAN | 4.22388E-7 | 2.24164 | 311.312 | 6.00966E-4 | 6.98969 | 296.131 | 13.8104 | 0.00757605 | 0.137686 |
| MEDIAN | 9.73093E-9 | 2.19089 | 210.625 | 4.10043E-4 | 5.6748 | 159.549 | 3.75794 | 0.00761625 | 0.123026 |
| STD | 1.1024E-6 | 0.833675 | 469.522 | 9.60642E-4 | 5.94046 | 532.266 | 18.5512 | 6.09311E-4 | 0.0351445 |
| IQR | 1.12926E-7 | 1.11574 | 61.1361 | 5.19021E-4 | 3.36356 | 169.582 | 18.6422 | 8.92576E-4 | 0.0320204 |
| ISCA | MEAN | 1.15274E-6 | 10.4396 | 22799 | 5.06103E-4 | 15.9083 | 152.337 | 12.3251 | 0.0178729 | 0.740415 |
| MEDIAN | 2.08898E-8 | 3.5363 | 102.061 | 6.45362E-7 | 12.4266 | 76.6075 | 2.41391 | 0.0104324 | 0.830527 |
| STD | 2.29412E-6 | 12.3668 | 98896.9 | 0.00127207 | 11.5125 | 585.368 | 23.4796 | 0.0187227 | 0.239125 |
| IQR | 1.16327E-6 | 11.1835 | 413.555 | 9.58418E-5 | 16.2615 | 68.6495 | 7.87543 | 0.0101581 | 0.282537 |
| NNA | MEAN | 4.86072E-7 | 17.7241 | 7704.75 | 7.60416E-4 | 26.175 | 181.643 | 7.19023 | 0.0194113 | 0.776483 |
| MEDIAN | 4.09834E-12 | 13.7798 | 75.4677 | 6.53373E-6 | 24.3121 | 74.7187 | 1.47635 | 0.0127364 | 0.833512 |
| STD | 1.37597E-6 | 15.7707 | 23975 | 0.00178214 | 12.9398 | 643.998 | 14.9043 | 0.01764 | 0.233516 |
| IQR | 2.55487E-8 | 28.9827 | 126.308 | 4.49047E-4 | 21.3311 | 63.1188 | 3.89105 | 0.0132889 | 0.0740081 |
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| **Table S1** (*continued*) | | | | | | | | | | |
|  |  | *I*01 (A) | *n*1 | *R*p1 (Ω) | *I*02 (A) | *n*2 | *R*p2 (Ω) | *R*s (Ω) | *I*ph (A) | RMSPE |
|  | true value | 1.6e-9 | 1.92 | 190 | 1.6e-4 | 1.92 | 190 | 45 | 8e-3 |  |
| CWOA | MEAN | 1.91016E-6 | 19.7767 | 27364.9 | 0.00115056 | 30.3776 | 400.515 | 27.5457 | 0.026159 | 0.746787 |
| MEDIAN | 5.94422E-10 | 17.2753 | 56.5524 | 6.44204E-9 | 34.0434 | 52.5507 | 9.03927 | 0.0141445 | 0.854377 |
| STD | 3.8446E-6 | 17.5006 | 145161 | 0.00303351 | 17.6242 | 1479.81 | 32.8588 | 0.0257545 | 0.300868 |
| IQR | 5.44157E-7 | 30.0379 | 70.4671 | 9.36563E-5 | 32.9741 | 74.873 | 53.057 | 0.0233644 | 0.0649151 |
| WW | MEAN | 2.25657E-6 | 6.01898 | 1815.69 | 3.60402E-4 | 45.528 | 79.1659 | 16.1267 | 0.0242362 | 0.802633 |
| MEDIAN | 4.28549E-7 | 4.43733 | 94.2486 | 1E-10 | 50 | 31.019 | 1.15863 | 0.00961191 | 0.853405 |
| STD | 3.10815E-6 | 7.02418 | 7319.67 | 0.00147962 | 11.7448 | 227.327 | 25.8349 | 0.0246133 | 0.124962 |
| IQR | 3.2253E-6 | 3.28317 | 58.5468 | 5.44421E-5 | 0 | 61.1333 | 15.4329 | 0.0241842 | 0.0583219 |

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| **Table S1.** The statistical significance of the null hypothesis in Friedman, Friedman Aligned, and Quade tests and the Iman–Davenport extension | | | | | | | | | | | |
| Test | *p*-value | | | | | | | | | | |
| Single IV case | | | | | | | | | | IV-set case |
| *I*01 | *n*1 | *R*p1 | *I*02 | *n*2 | *R*p2 | *R*s | *I*ph | RMSPE | Comp |  |
| Friedman | 4.9664E-07 | 0.0000E+00 | 0.0000E+00 | 3.0381E-07 | 0.0000E+00 | 6.8597E-07 | 2.3210E-06 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 2.2964E-06 |
| Iman- Davenport | 0.0000E+00 | 1.4774E-09 | 1.4310E-09 | 0.0000E+00 | 1.3797E-09 | 0.0000E+00 | 1.5223E-09 | 1.4438E-09 | 1.2472E-09 | 0.0000E+00 | 0.0000E+00 |
| Friedman Aligned | 4.0411E-07 | 5.9524E-07 | 2.7010E-05 | 1.4847E-06 | 0.0000E+00 | 4.9647E-06 | 0.0000E+00 | 5.0555E-07 | 0.0000E+00 | 4.3982E-04 | 0.0000E+00 |
| Quade | 1.1191E-09 | 0.0000E+00 | 0.0000E+00 | 1.1432E-09 | 0.0000E+00 | 1.0869E-09 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 8.3247E-06 | 0.0000E+00 |