HBCU Clean Energy Education Seminar Series on Solar Energy

Extracting Solar Cell and Panel Parameters Using Particle Swarm Optimization

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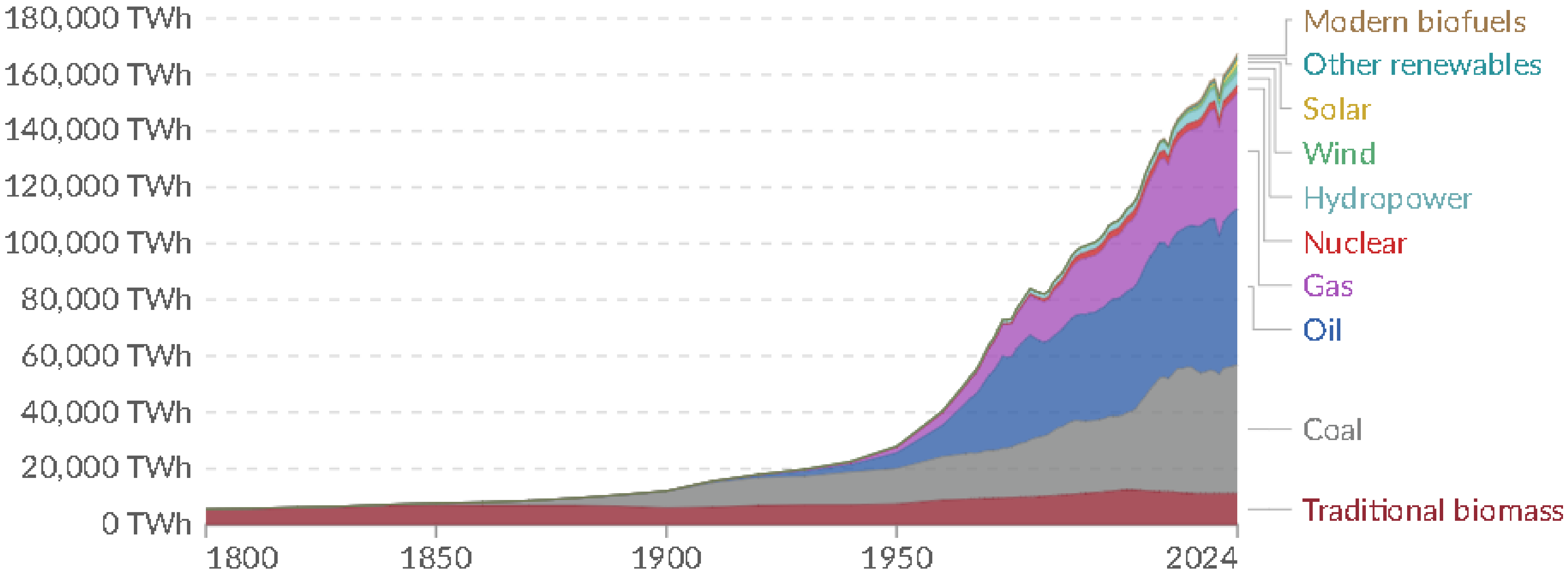
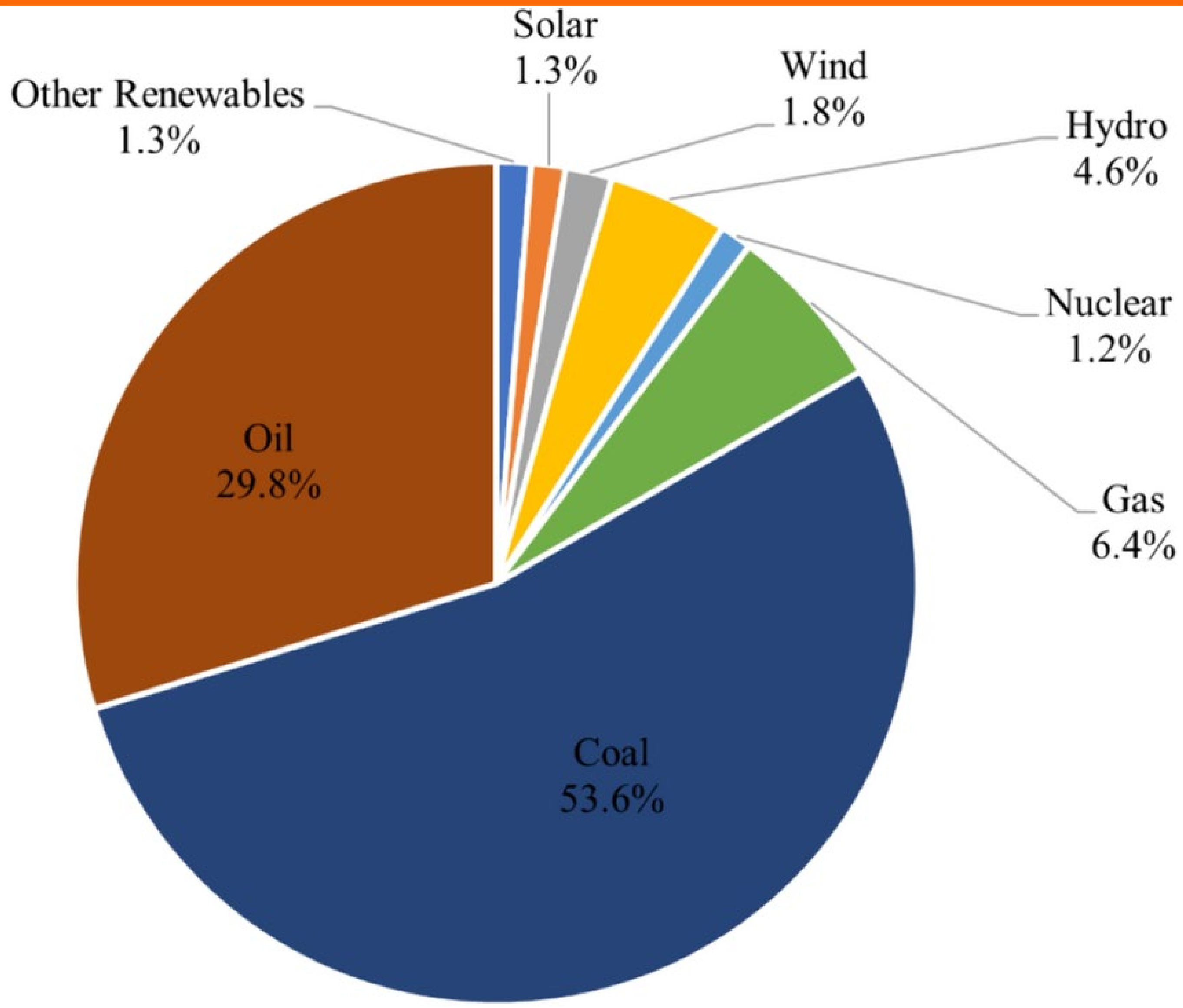
Global Energy Consumption



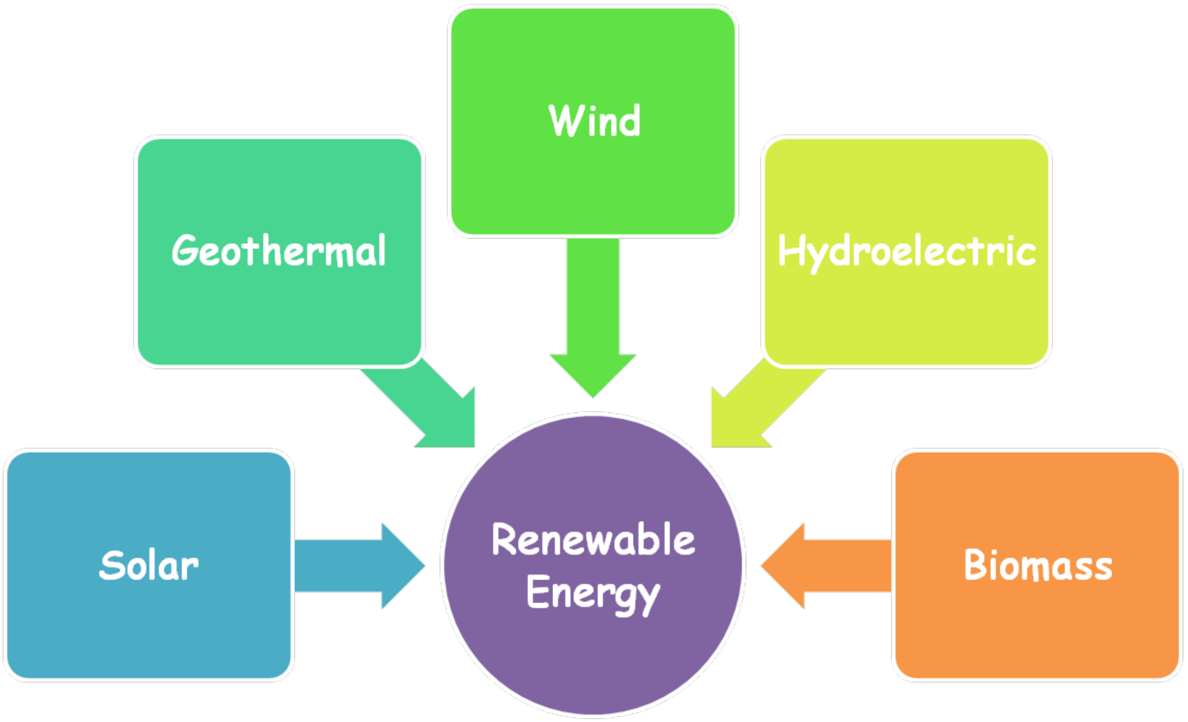
Data source: Energy Institute - Statistical Review of World Energy (2025);

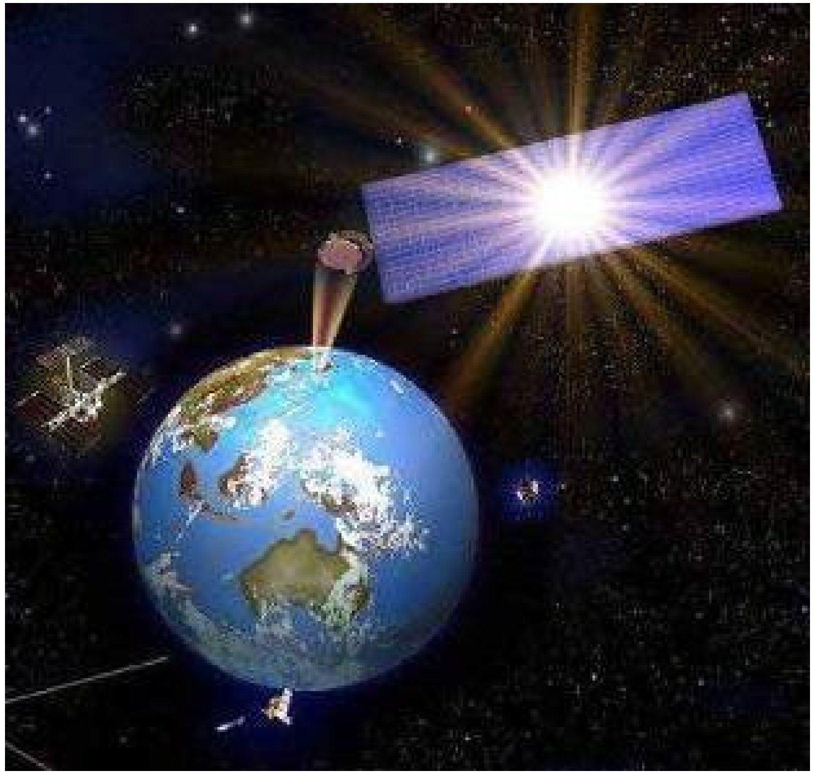
Energy Sources



Source: Our World in Data (2022)

Solar Energy

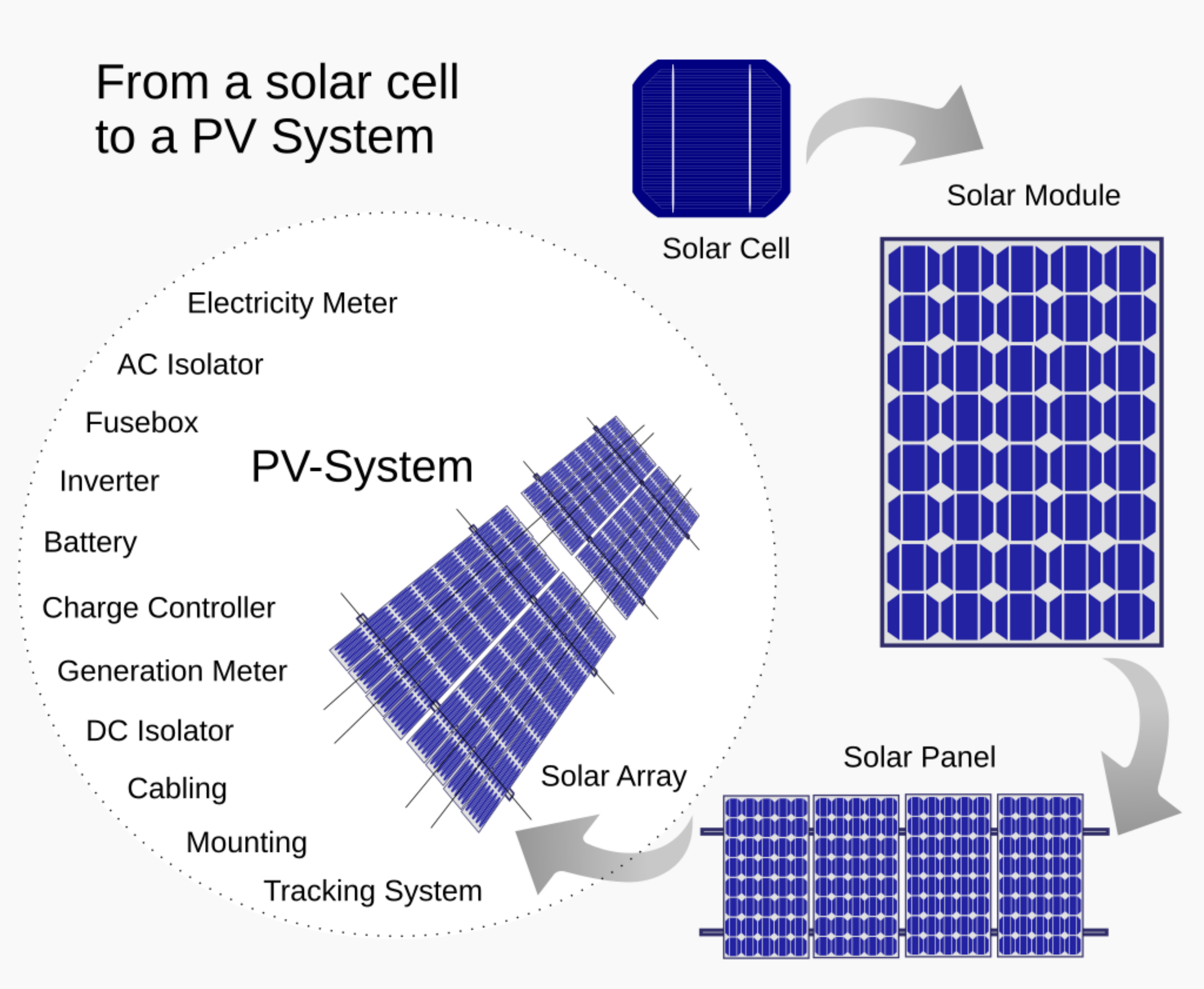




It would take **about 4,000 square miles of solar panels** to power the U.S. or a 63 by 63 mile area, or 12 Dougherty counties.

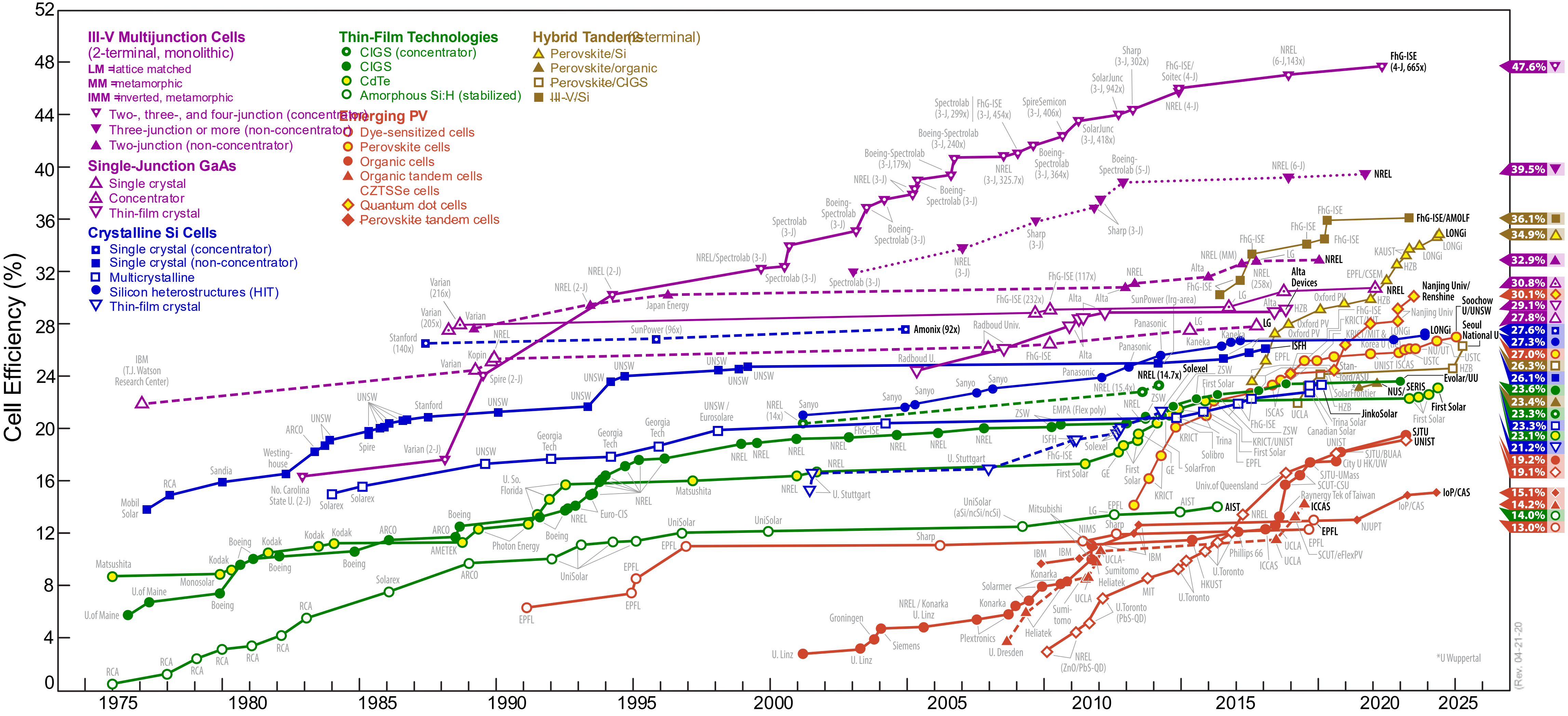
Solar irradiance on Earth's surface
on average 170 W/m² = 1490 kWh/m²/a
equals almost 1 barrel of oil per m²
= a total radiation flux of 87 PW (10^{15})
Solar irradiance is about **5 500 times** the current prime energy demand

From Solar Cell to Photovoltaic System

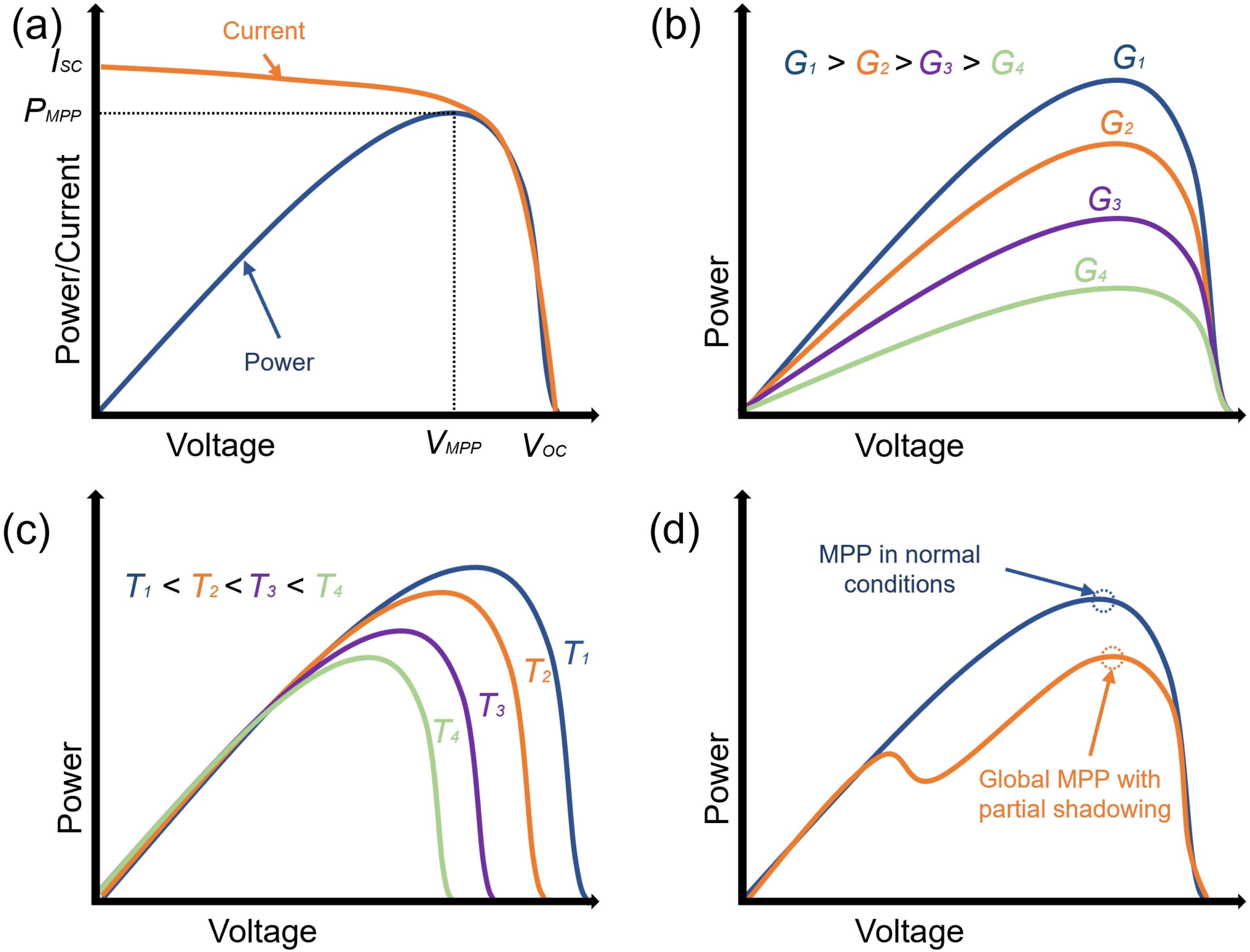


https://en.wikipedia.org/wiki/Solar_cell#/media/File:From_a_solar_cell_to_a_PV_system.svg

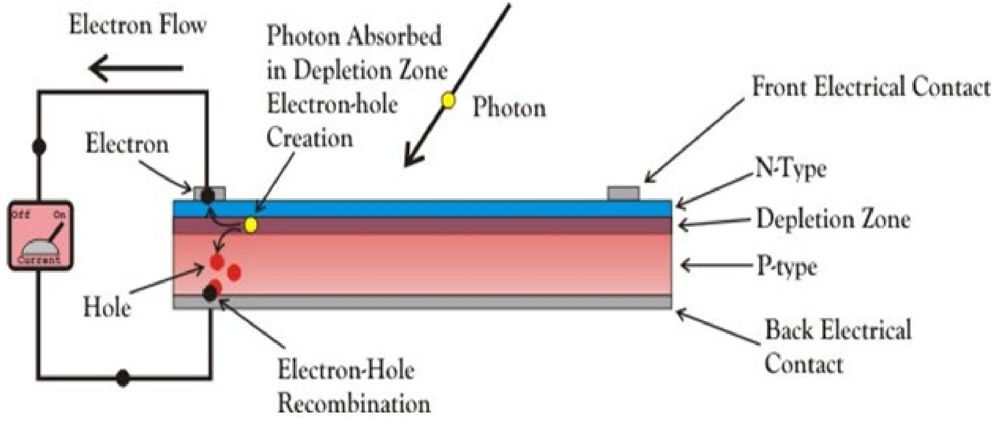
Best Research-Cell Efficiencies

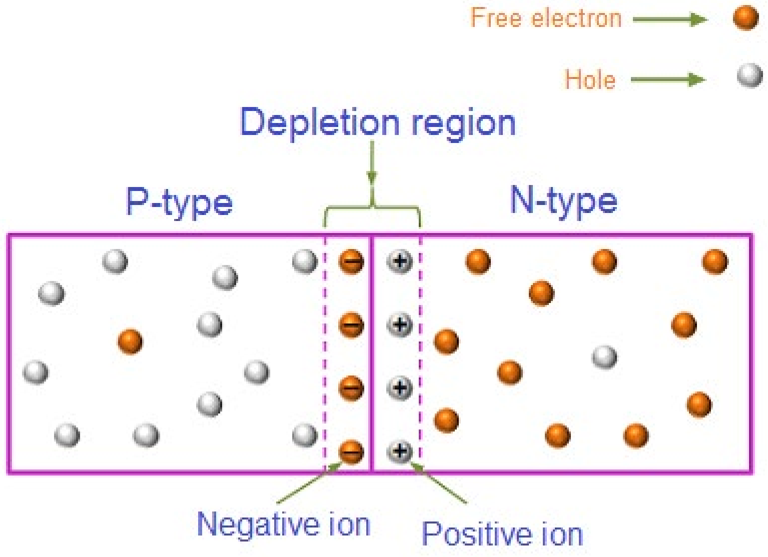


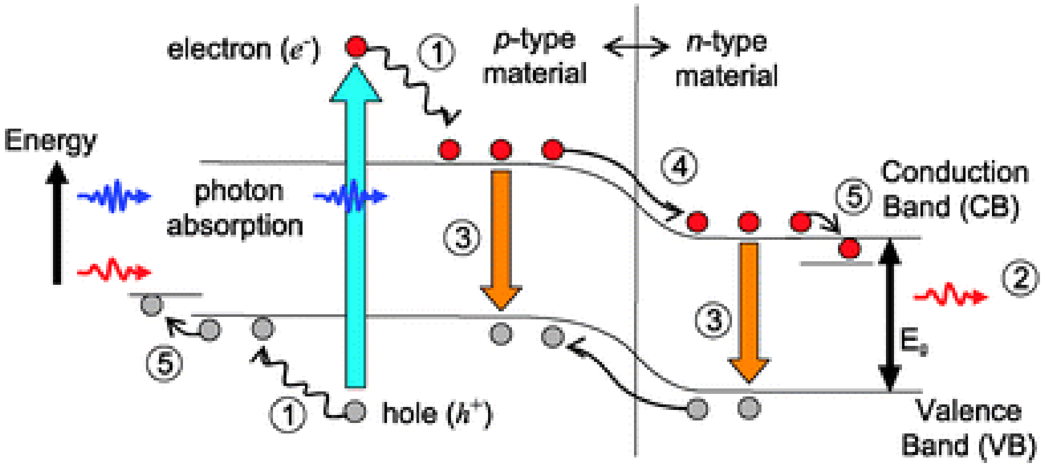
Maximum Power Point (MPP)



Solar Cell







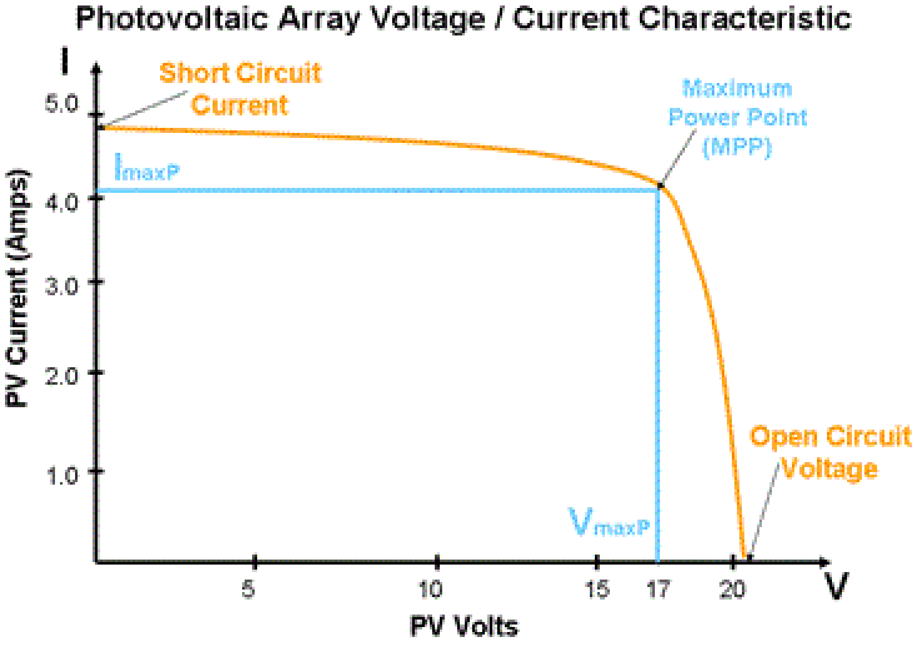
$$J = J_0[\exp(\frac{qV}{kT}) - 1]$$

$$J_0 = q[\frac{D_n n_i^2}{L_n N_A} + \frac{D_p n_i^2}{L_p N_D}]$$

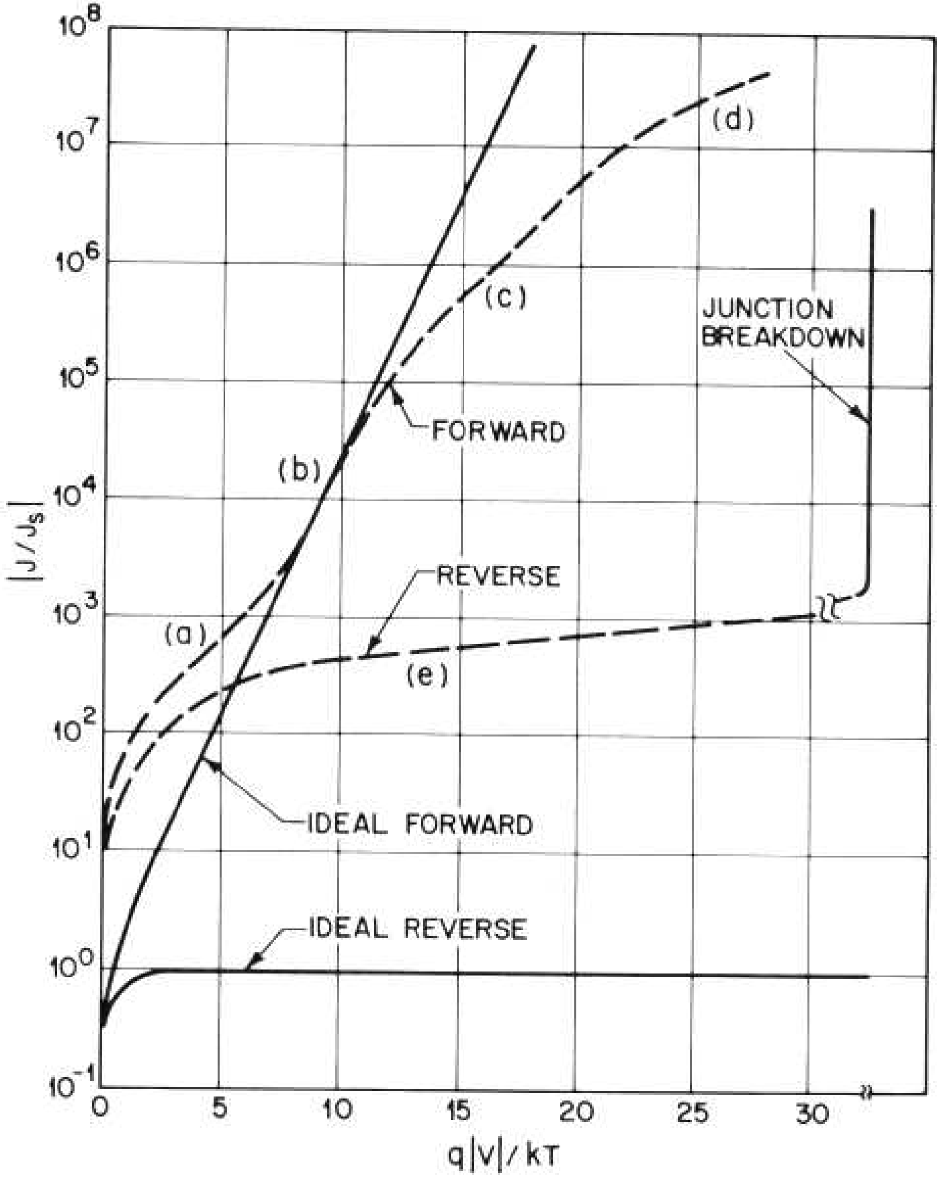
$$J = J_0[\exp(\frac{V - JR_s}{nkT/q}) - 1]$$

The Theory of *p-n* Junctions in Semiconductors and *p-n* Junction Transistors

Solar Cell I-V Analysis



Current-voltage characteristic of a "real" silicon diode.
(a) Generation-recombination region.
(b) "Ideal" or Shockley diffusion current region.
(c) High-injection current region.
(d) Series resistance effect.
(e) Reverse leakage current due to generation-recombination and surface effects.
(From Simon M. Sze, *Physics of Semiconductor Devices*)



Why extract solar cell/panel parameters from I–V curves?

✓Performance Characterization

- The I–V curve provides direct insight into efficiency, power output, and operating behavior under given illumination and temperature conditions.

✓Determination of Key Device Parameters

- Parameters such as Voc, Isc, FF, Rs, Rsh, and the diode ideality factor reveal how the device converts light into electrical power and where losses occur.

✓Identifying Loss Mechanisms

- Series resistance indicates ohmic losses (contacts, wiring, bulk resistance).
- Shunt resistance reveals leakage pathways or defects.
- Ideality factor points to recombination pathways (surface, bulk, or junction).

✓Quality Control and Manufacturing Diagnostics

- Deviations in parameters can indicate material defects, processing issues, or degradation during fabrication.

Why extract solar cell/panel parameters from I–V curves?

✓ Modeling and Simulation

- Extracted parameters feed into equivalent circuit models (single-diode, double-diode, etc.) enabling device performance prediction under varying conditions.

✓ System-Level Optimization

- Helps to optimize panel arrangements, MPPT operation, and system efficiency for solar installations.

✓ Aging, Reliability, and Degradation Analysis

- Tracking I–V curves over time reveals performance decline modes such as corrosion, encapsulation failure, or light-induced degradation (e.g., LID in Si).

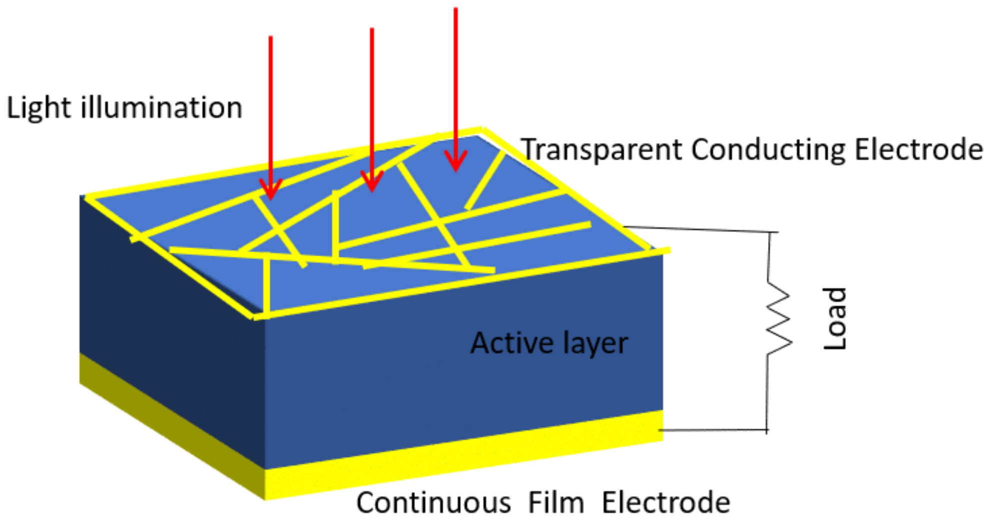
✓ Comparative Evaluation

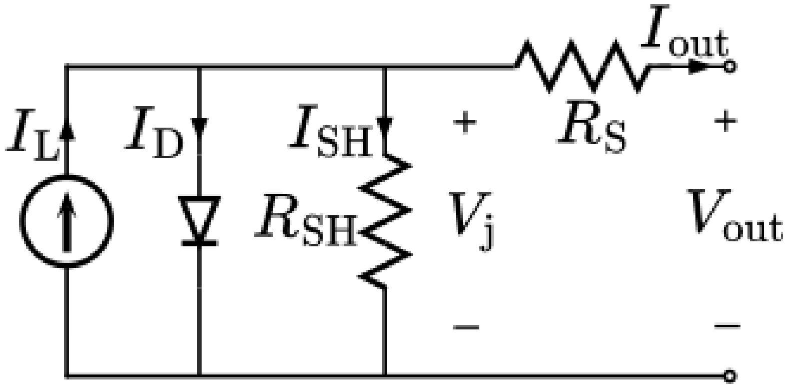
- Enables fair comparison across devices, materials, or fabrication recipes by providing standardized performance metrics.

✓ Understanding Physics of Operation

- Analysis of curve shape provides insights into charge transport, recombination, carrier collection, and interface quality.

Equivalent circuit of a solar cell





$$I_{out} = I_L - I_D - I_{SH}$$

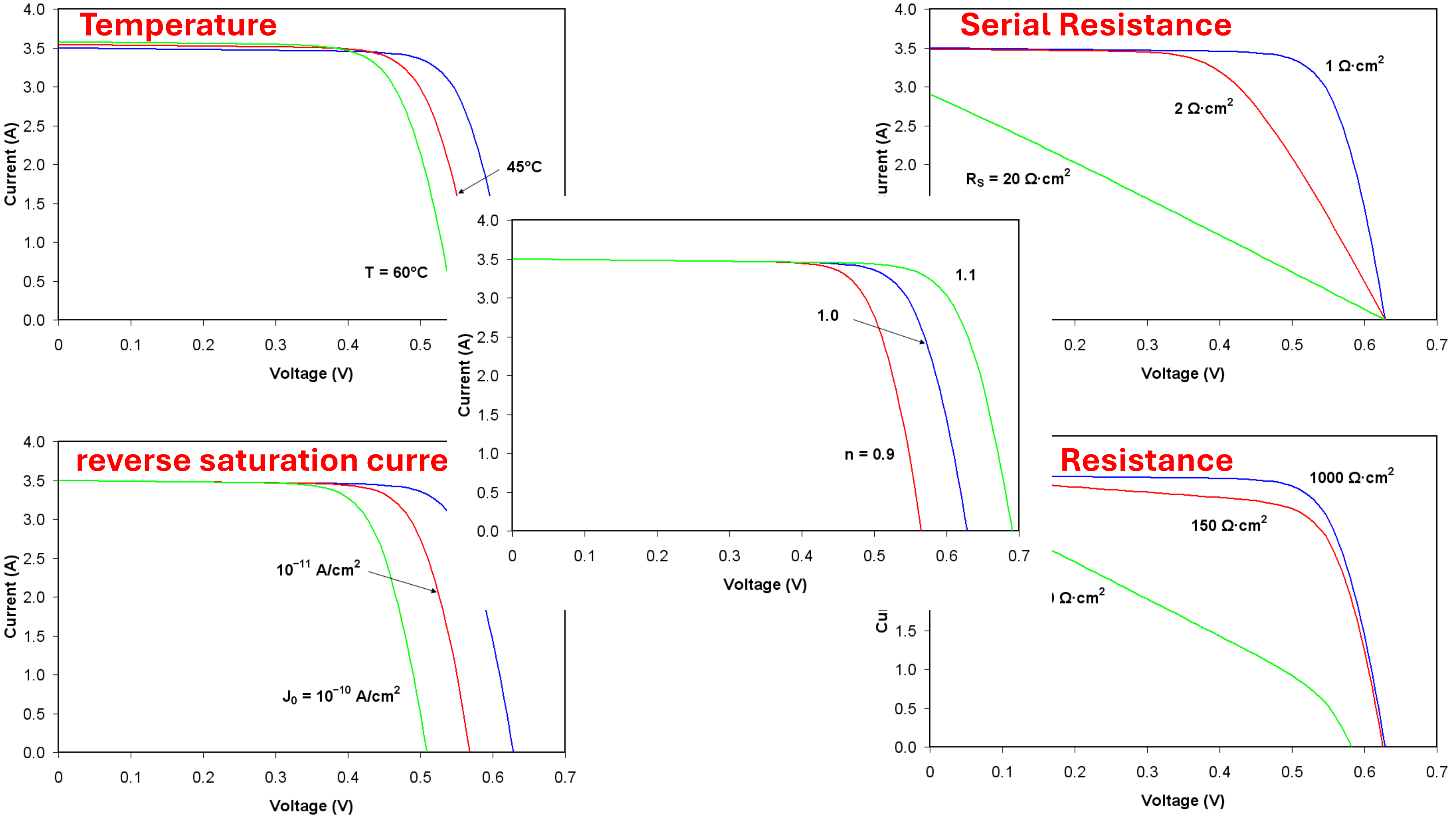
$$V_j = R_S I_{out} + V_{out} = R_{SH} I_{SH}$$

$$J = J_{ph} - J_0\{\exp[\frac{q(V + JR_s)}{nkT}] - 1\} - \frac{V + JR_s}{R_{sh}}$$

I_L, photogenerated current
I_0, reverse saturation current
I_D represents recombination losses
n, diode ideality factor (1 for an ideal diode)
q, elementary charge
k, Boltzmann constant
T, absolute temperature

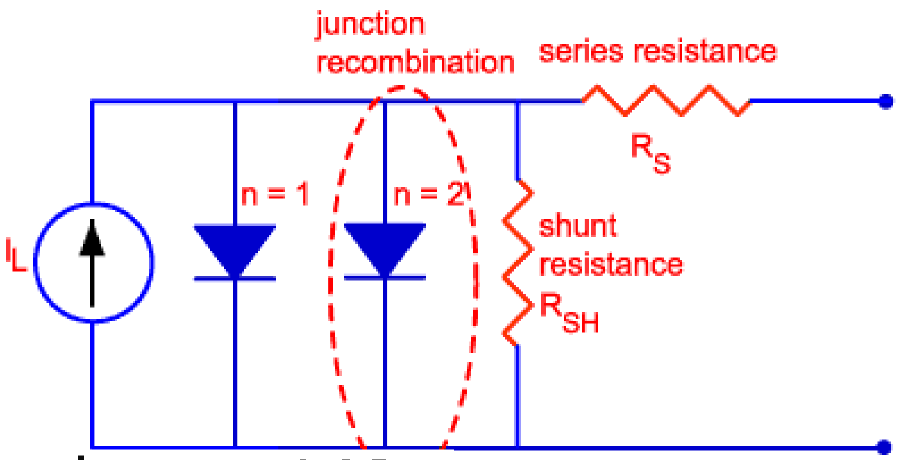
Effect of Physical Size

$$J = J_{ph} - J_0\{\exp[\frac{q(V+JR_s)}{nkT}] - 1\} - \frac{V+JR_s}{R_{sh}}$$



https://en.wikipedia.org/wiki/Theory_of_solar_cells

Double diode model



Double Diode Model (DDM) — circuit equation (steady-state I–V)

$$I(V) = I_{ph} - I_{01}\left(e^{\frac{q(V+IR_s)}{n_1 kT}} - 1\right) - I_{02}\left(e^{\frac{q(V+IR_s)}{n_2 kT}} - 1\right) - \frac{V+IR_s}{R_{sh}}.$$

Variables / parameters

- $I(V)$: output current at terminal voltage V
- I_{ph}: photocurrent (light-generated current)
- I_{01}, I_{02}: saturation currents for the two diodes (diffusion & recombination)
- n_1, n_2: ideality factors (≈1 for diffusion, ≈2 for recombination via defects)
- R_s: series resistance (contacts, grid, bulk resistivity)
- R_{sh}: shunt resistance (leakage paths)
- q: elementary charge, k: Boltzmann constant, T: temperature

The J-V Equation of Solar Cell

$$J = J_{ph} - J_{01}[e^{\frac{q(V+JR_s)}{n_1 kT}} - 1] - J_{02}[e^{\frac{q(V+JR_s)}{n_2 kT}} - 1] - \frac{V + JR_s}{R_{sh}}$$

At V_{oc} point, J=0:

$$J_{ph} = J_{01}(e^{\frac{qV_{oc}}{n_1 kT}} - 1) + J_{02}(e^{\frac{qV_{oc}}{n_2 kT}} - 1) + \frac{V_{oc}}{R_{sh}}$$

If the recombination in space charge region is negligible :

$$J_{ph} = J_{01}(e^{\frac{qV_{oc}}{n_1 kT}} - 1) + \frac{V_{oc}}{R_{sh}}$$

If the R_{sh} is big enough and V_{oc}/R_{sh} is negligible :

$$J_{ph} = J_0(e^{\frac{qV_{oc}}{n_1 kT}} - 1)$$

And this express is equal to:

$$V_{oc} = \frac{n_1 kT}{q} \ln(\frac{J_{ph}}{J_0} + 1)$$

Solar Cell Equation Analysis

Then assuming $J_{sc} \approx J_{ph}$, $\exp\left(\frac{qV_{oc}}{n_1 kT}\right) \gg 1$:

$$J_{sc} = J_0 e^{\frac{qV_{oc}}{nkT}}$$

Equal to:

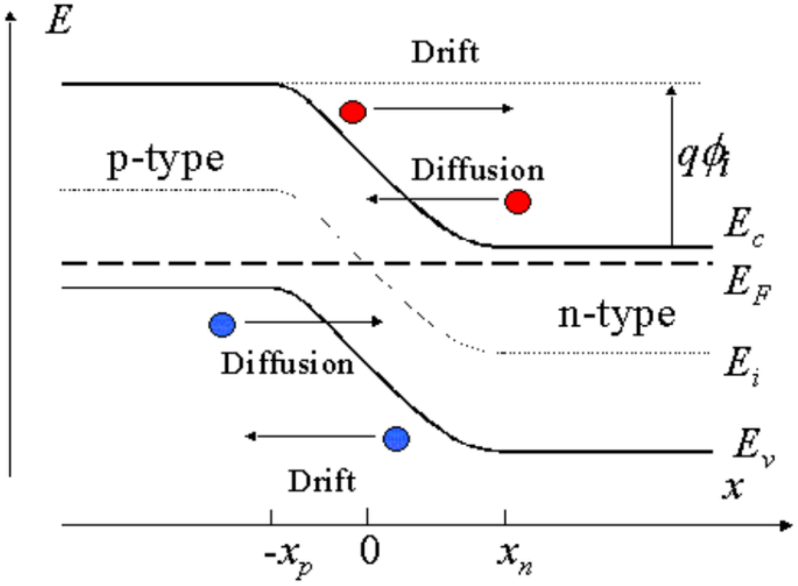
$$\ln J_{sc} = \ln J_0 + \frac{q}{nkT} V_{oc}$$

$$V_{oc} = \frac{nkT}{q} \ln(\frac{J_{ph}}{J_0} + 1)$$

Considering the expression of J_0 :

$$J_0 = J_{00} e^{-\frac{\Phi_b}{nkT}}$$

$$V_{oc} = \frac{\Phi_b}{q} - \frac{nkT}{q} \ln \frac{J_{ph}}{J_{00}}$$



Complexity of Solving Solar Cell Equation:

$$J = J_{ph} - J_0\{\exp[\frac{q(V+JR_s)}{nkT}] - 1\} - \frac{V+JR_s}{R_{sh}}$$

- Implicit functional equations;
- nonlinearity;
- multivariables

Common optimization algorithms include:

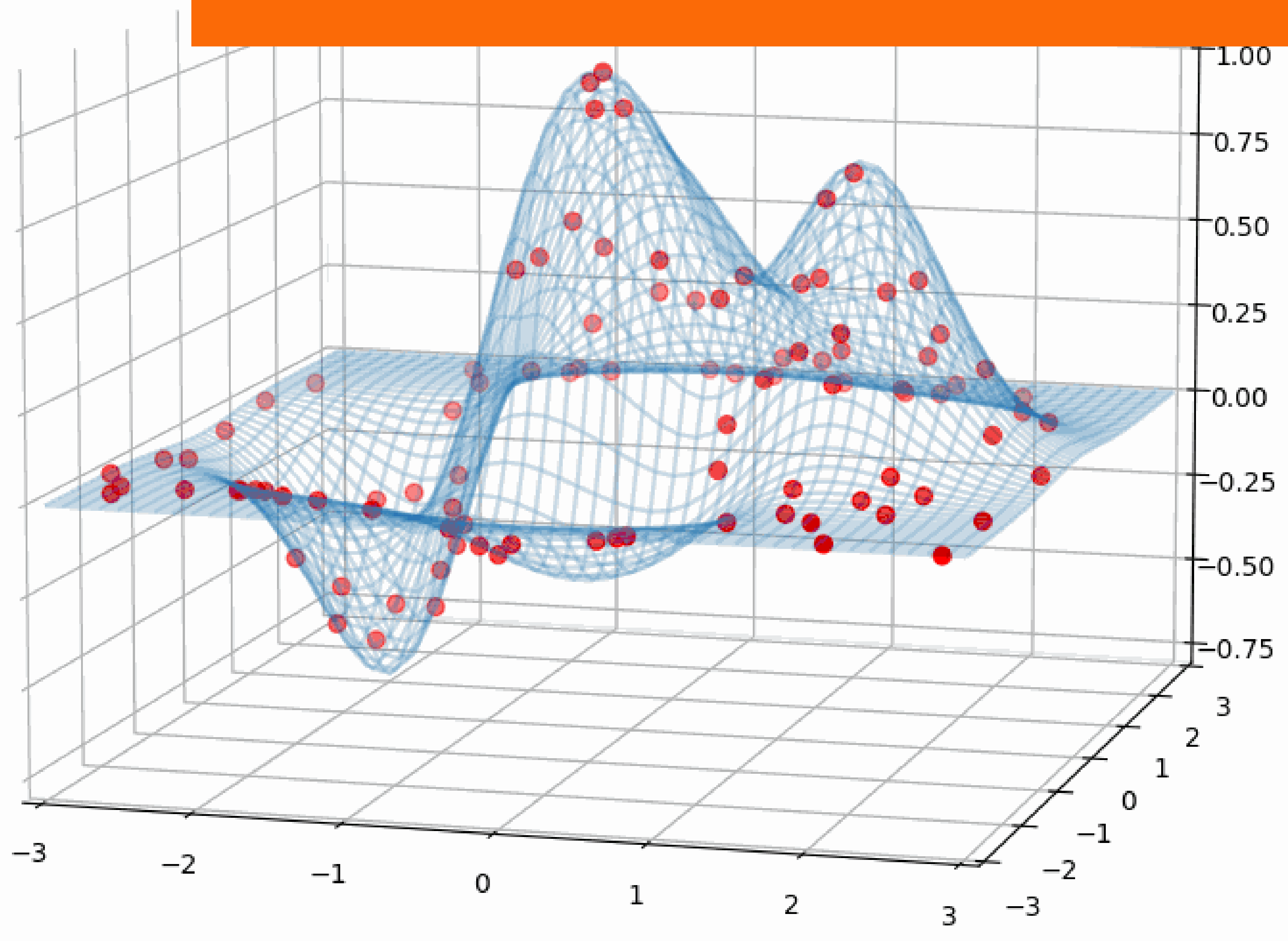
1. Gradient Descent (Stiffest Descent Method)
2. Newton's Method / Quasi-Newton Method
3. Conjugate Gradient Method

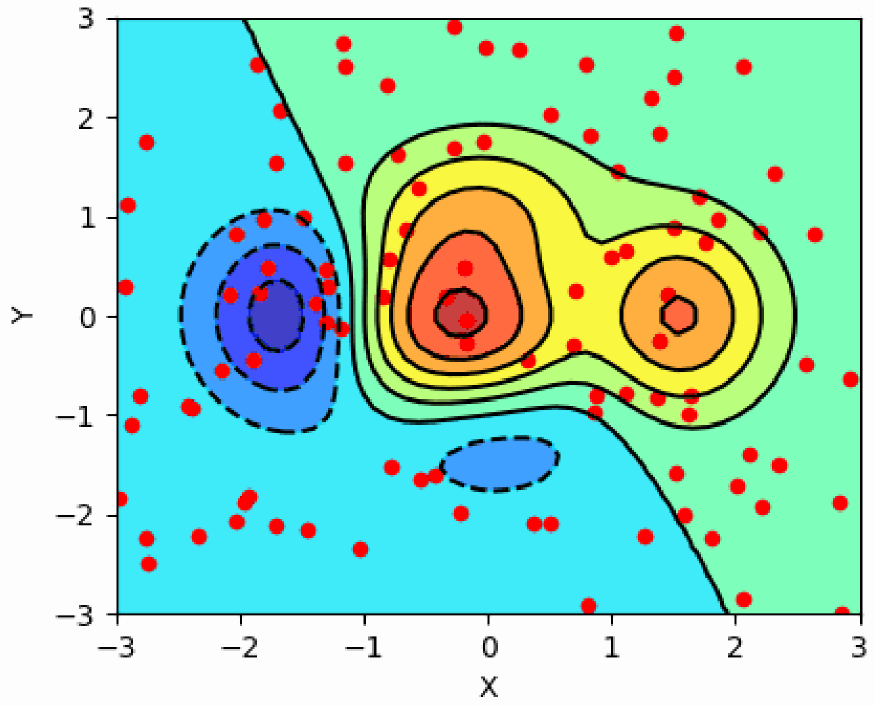
Particle Swarm Optimization （PSO）

"Particle swarm optimization (PSO) is a population based stochastic optimization technique developed by Dr. Eberhart and Dr. Kennedy in 1995, inspired by social behavior of bird flocking or fish schooling."

Compared with other intelligent algorithms, the PSO algorithm has the following advantages: It is simple and easy to implement; it has good global convergence; and it is fast and robust.

A particle swarm searching for the global minimum of a function

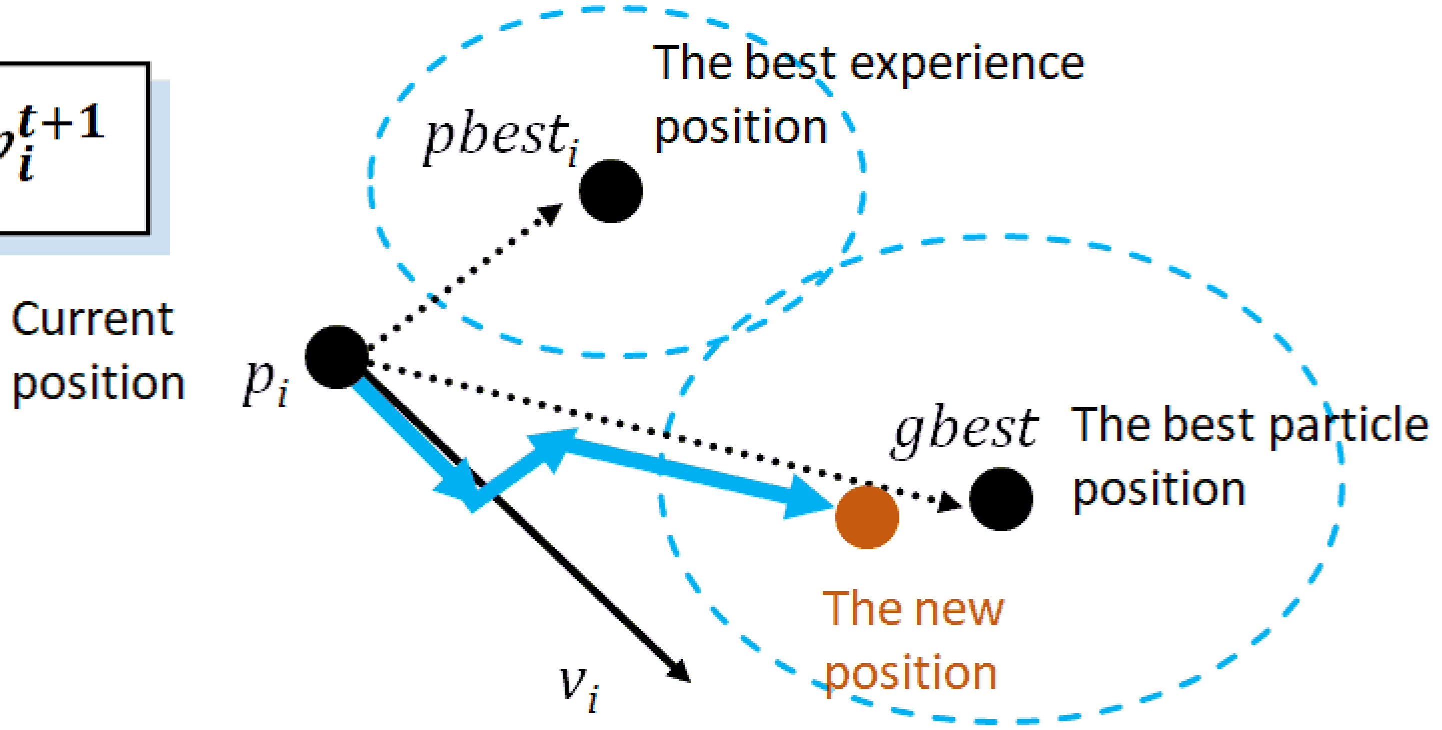




PSO is a population-based technique.

$$v_i^{t+1} = \underbrace{v_i^t}_{\text{Inertia}} + \underbrace{c_1 r_1 (pbest_i^t - p_i^t)}_{\text{Personal influence}} + \underbrace{c_2 r_2 (gbest^t - p_i^t)}_{\text{Social influence}}$$

$$p_i^{t+1} = p_i^t + v_i^{t+1}$$



Parameters used in PSO fitting

The main parameters used to model the PSO are:

- $S(n) = \{s_1, s_2, \ldots, s_n\}$: a swarm of n particles
- s_i: an individual in the swarm with a position p_i and velocity v_i, $i \in [|1, n|]$
- p_i: the position of a particle s_i
- v_i: the velocity of a particle p_i
- $pbest_i$: the best solution of a particle
- $gbest$: the best solution of the swarm (Global)
- f: fitness function
- c_1, c_2: acceleration constants (cognitive and social parameters)
- r_1, r_2: random numbers between 0 and 1
- t: the iteration number

https://www.baeldung.com/cs/pso

PSO algorithm for optimization problem of d-dimensional decision variables

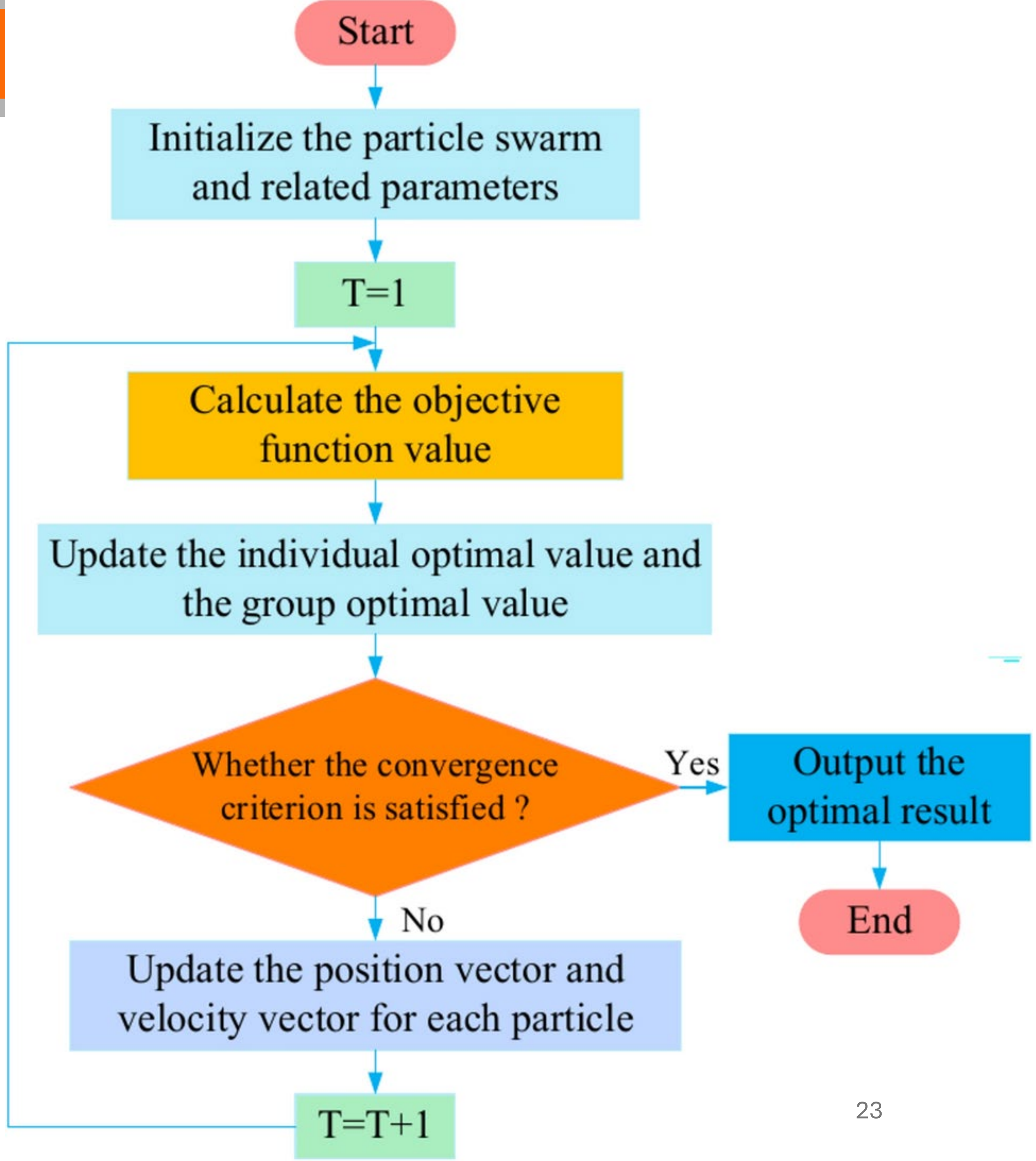
1. Initialize *P* number of particles with some random position;
2. Evaluate the fitness function of particles;
3. *gbest* = global best solution;
4. **For** l = 1 to maximum number of iterations **do**
5. **For** j = 1 to *P* **do**
6. Update the velocity and position for the j^{th} particle using Equations (1) and (2), respectively;
7. Evaluate the fitness function of j^{th} particle;
8. Update the personal best (*pbest*) of j^{th} particle;
9. Update the *gbest*;
10. Keep *gbest* as the best problem solution;
11. **End for**
12. **End for**

The portion highlighted in red can be accelerated using OpenMP.

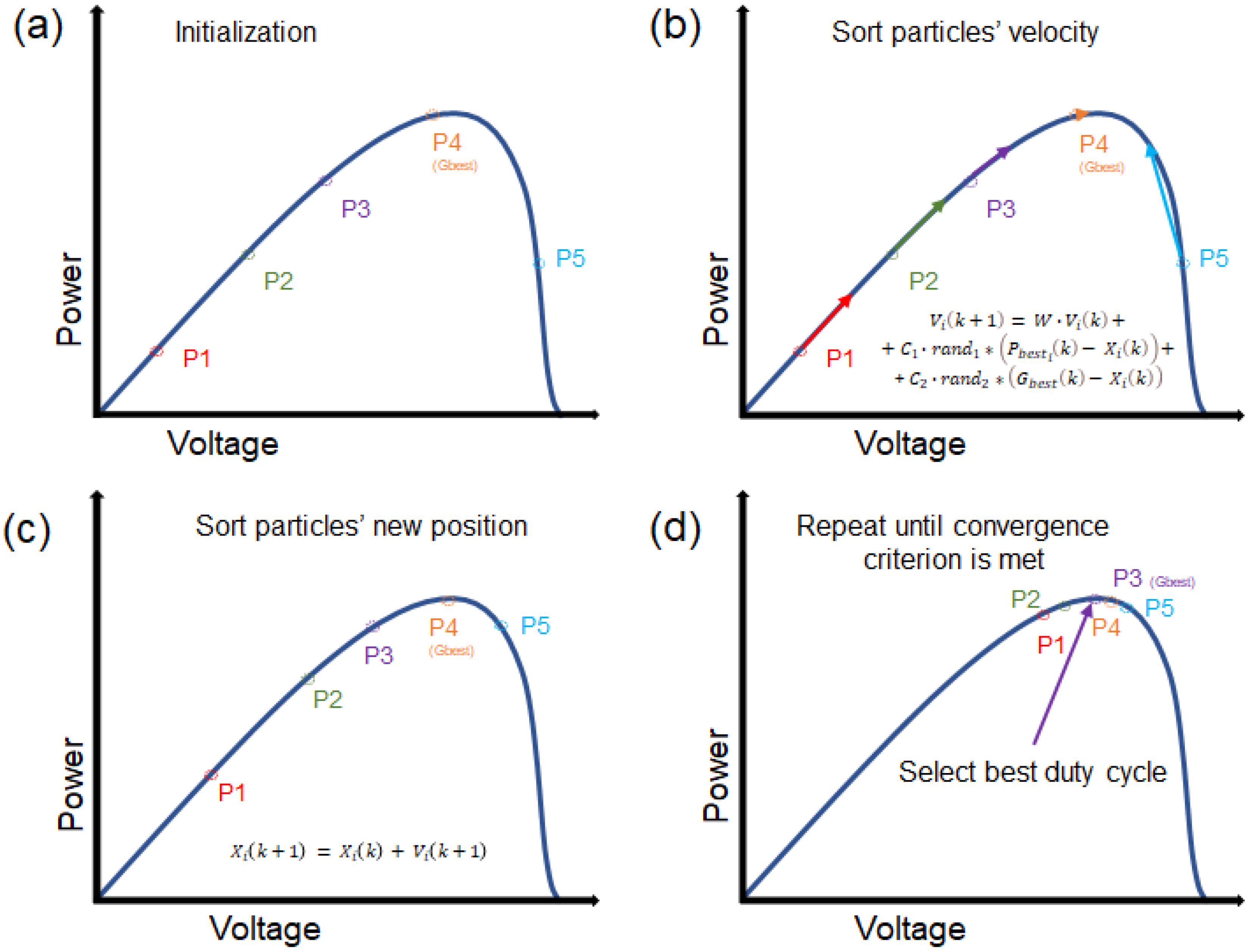
Steps and Flowchart

The PSO execution steps:

1. Initialize algorithm constants.
2. Initialize the solution from the solution space (initial values for position and velocity).
3. Evaluate the fitness of each particle.
4. Update individual and global bests (and).
5. Update the velocity and position of each particle.
6. Go to step 3 and repeat until the termination condition.



MPPT



(a)
Initialization
P1
P2
P3
P4
(Gbest)
P5
Power
Voltage
(b)
Sort particles' velocity
P1
P2
P3
P4
(Gbest)
P5
$V_i(k+1) = W \cdot V_i(k) +$
$+ C_1 \cdot rand_1 * (P_{best_i}(k) - X_i(k)) +$
$+ C_2 \cdot rand_2 * (G_{best}(k) - X_i(k))$
Power
Voltage
(c)
Sort particles' new position
P1
P2
P3
P4
(Gbest)
P5
$X_i(k+1) = X_i(k) + V_i(k+1)$
Power
Voltage
(d)
Repeat until convergence
criterion is met
P3 (Gbest)
P2
P5
P1
P4
Select best duty cycle
Power
Voltage

The characteristics of intelligent optimization algorithms:

1. Based on the simulation of biological intelligence or physical processes;

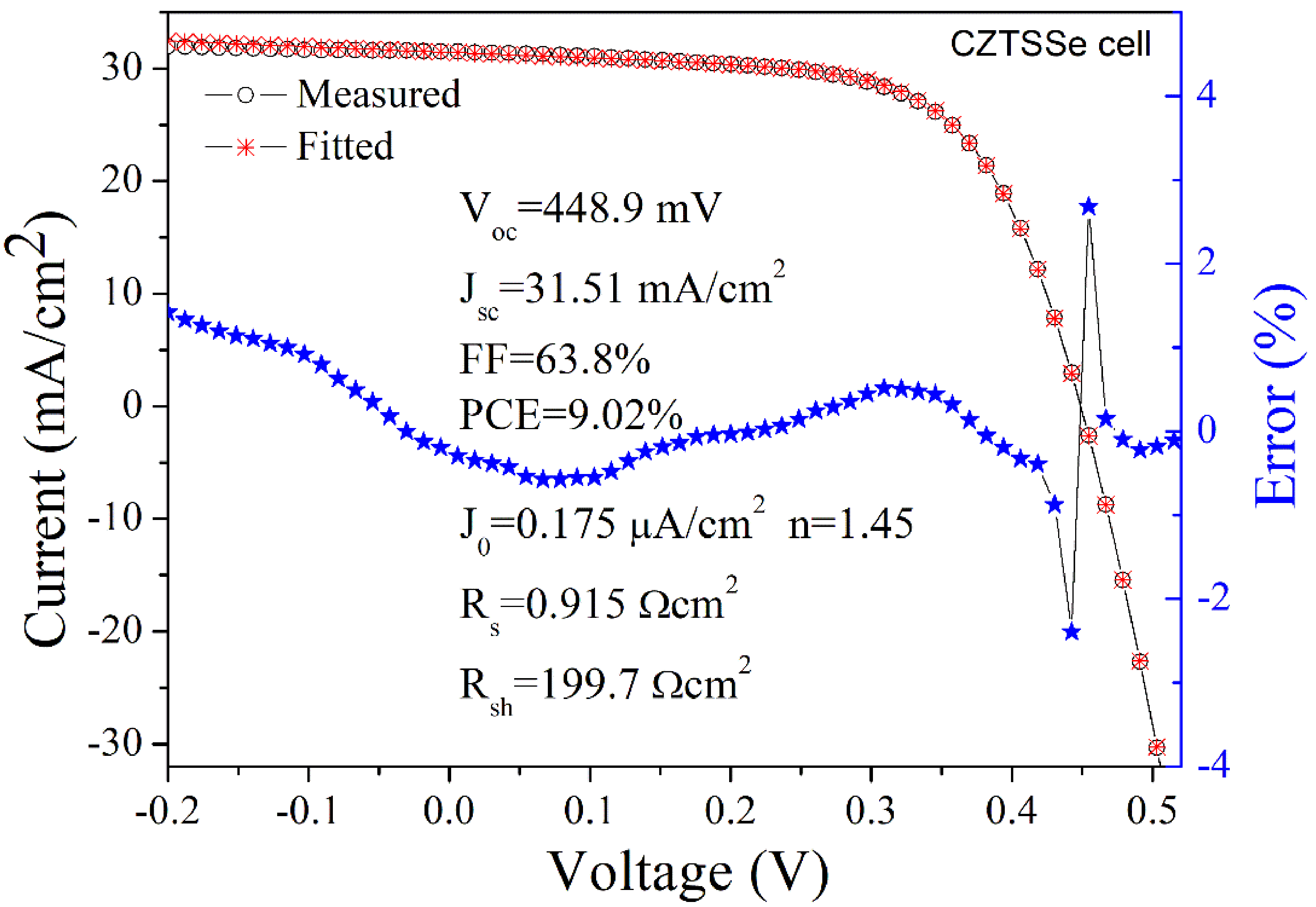
2. A probabilistic global optimization algorithm, with a higher chance of finding the global optimum and better global convergence;

3. A parallel algorithm;

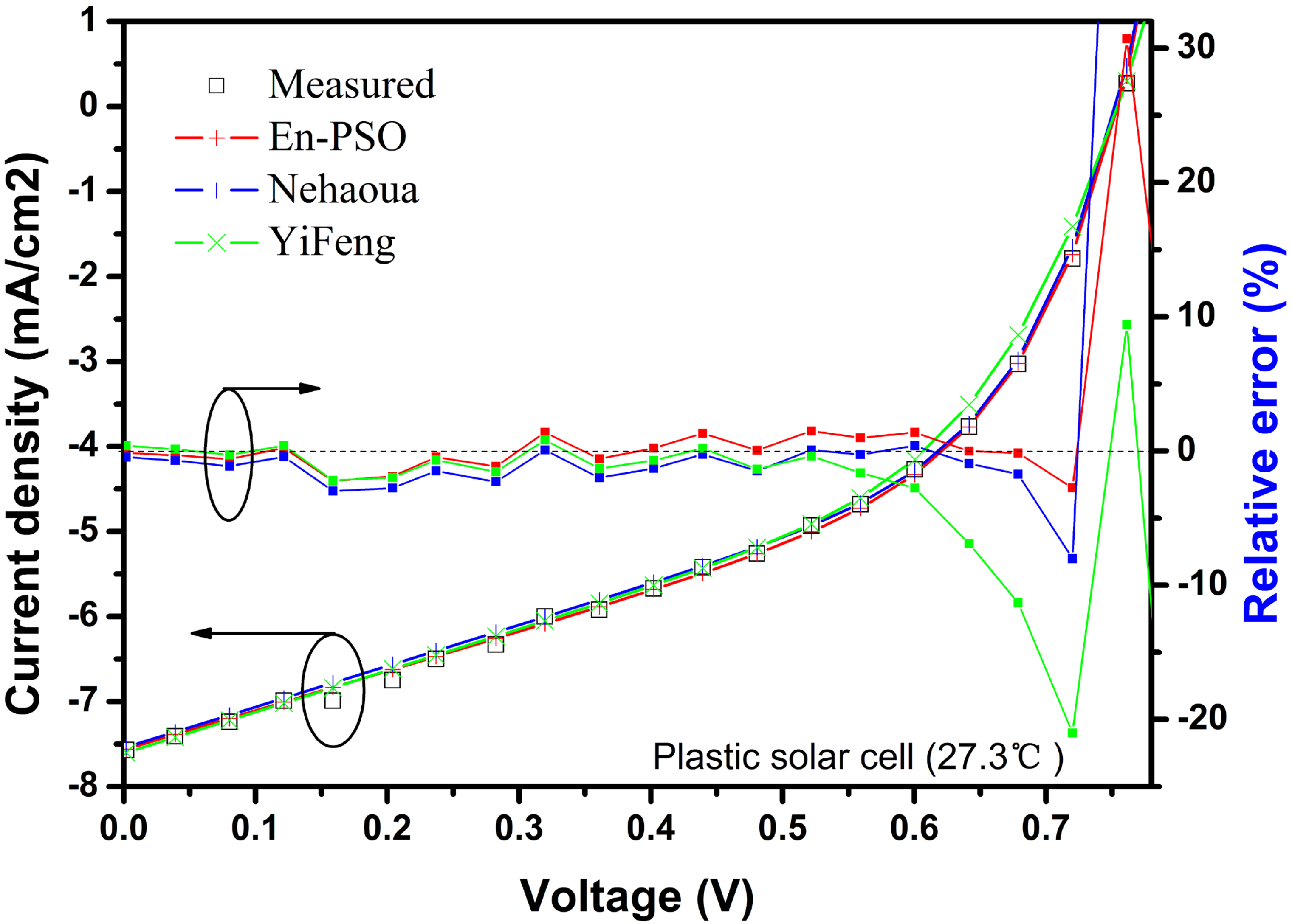
4. Robust algorithm

https://github.com/zhongrui7/Particle-Swarm-Optimization-approach/blob/main/pso_PVIV_fit0.c

PSO Fitting Results of a thin-film CZTSSe Solar Cell



Analysis of Organic Photovoltaics



Fitting results from I-V data of organic solar cells:

I-V fitting parameters of organic solar cells (25°C)

NO.	R_s (Ωcm^2)	R_{sh} (Ωcm^2)	J_0 ($nAcm^{-2}$)	n	J_{ph} ($mAcm^{-2}$)	Error
a	8.588	197.27	13.63	2.31	7.94	-
b	0.755	215.88	85.83	2.71	7.59	0.13% (RMSE)
c	3.16	204.92	12.08	2.29	7.66	1.806% (RMSE)

Result a: From A. Ortiz-Conde et al. [1992] and Yifeng Lei et al. [2025]
Result b: From this tool.
Result c: From N. Nehaoua, Y. Chergui and D. E. Mekki (2011). A new model for extracting physical parameters from I-V curves of organic and inorganic solar cells.

Summary

PSO Advantages: Simple to implement; Derivative-free and uses very few parameters; Efficient global search

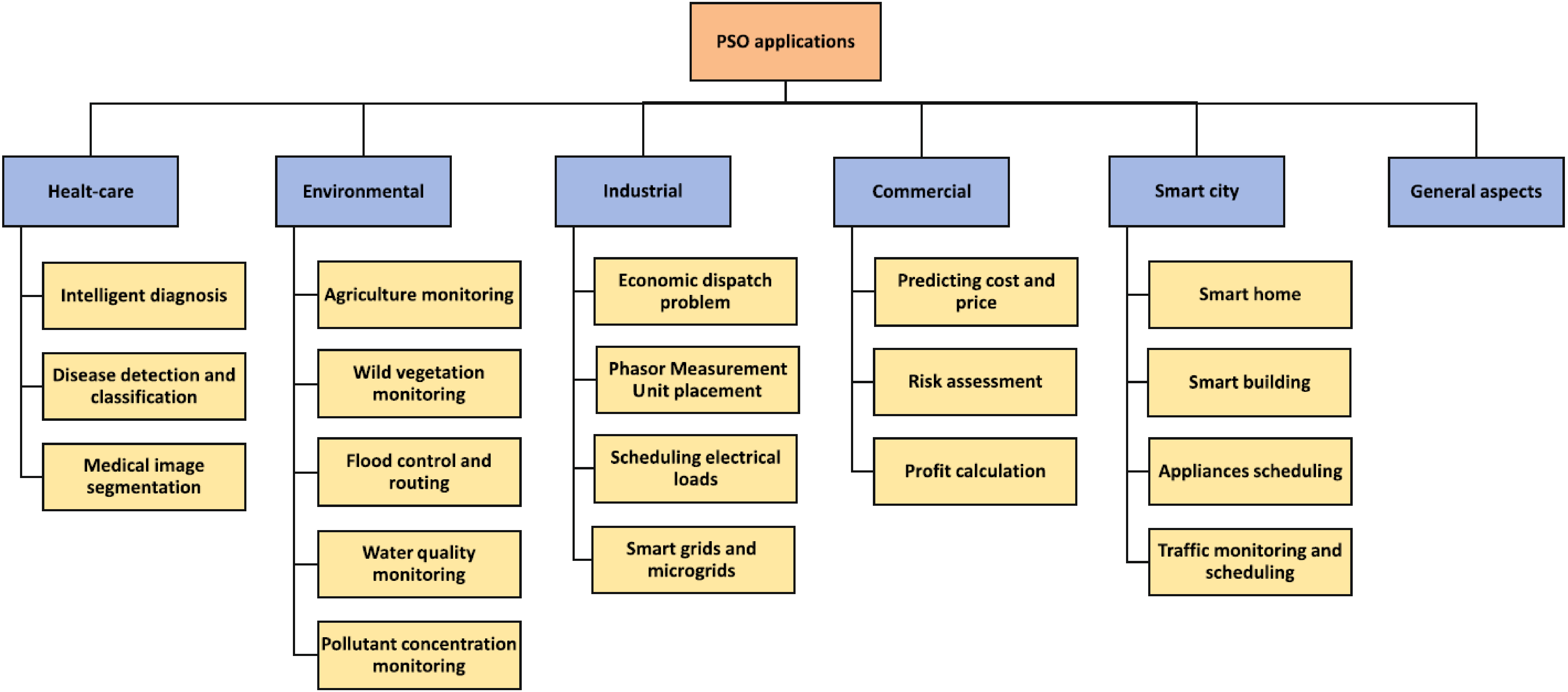
Solar Cell Parameter Extraction and Modeling: Non-linear power curves; Avoids local maxima; Robust

Solar Panel Maximum Power Point Tracking (MPPT): Partial shading; Fast-changing weather; Handles rapidly fluctuating irradiance

Category	What PSO Optimizes
Parameter Extraction	I_0, n, R_s, R_{sh}, DDM/TDM parameters
Device Design	Thickness, doping, trap densities
MPPT Control	Operating voltage/power point
System Deployment	Tilt, spacing, array layout
Energy Management	Dispatch of PV + battery + grid
Materials / Light Trapping	Structure geometry, band gap

Thank you!

Q&A


PSO applications
Healt-care
Environmental
Industrial
Commercial
Smart city
General aspects
Intelligent diagnosis
Disease detection and classification
Medical image segmentation
Agriculture monitoring
Wild vegetation monitoring
Flood control and routing
Water quality monitoring
Pollutant concentration monitoring
Economic dispatch problem
Phasor Measurement Unit placement
Scheduling electrical loads
Smart grids and microgrids
Predicting cost and price
Risk assessment
Profit calculation
Smart home
Smart building
Appliances scheduling
Traffic monitoring and scheduling