→ 1991 published device: a "Graetzel cell", named after the inventer, achieved 10% efficiency at 1000 W/m² insolation at 25°C → which beat a-Si PV cells!

Grätzel

Advantages } $V_{oc} \sim 0.7V$, record efficiency is 15%

① low cost, non toxic materials

② relatively simple manufacturing

③ can be flexible and in many shapes - architectural applications

④ they work well in low and diffuse light applications indoors and outdoors

⑤ they work well in high ambient temperatures

Show Fig 2.35.

1. PV Modules and Arrays

a. How do we get from a single cell to a PV array?

Show Figures Poly-Si PV + Fig. 3.1

→ Si PV cell is thin and brittle → it must be sufficiently protected

① Life time: 20 - 30 years!

∴ PV array needs to survive in this environment:

① UV light → can damage some materials

② temperature extremes

③ moisture: corrosion, freezing/thawing, shorting potential, condensation

④ snow/ice loading

⑤ hail and sleet

Figure 3.1 A large array of PV modules on a rooftop in Switzerland (EPIA/BP Solar).

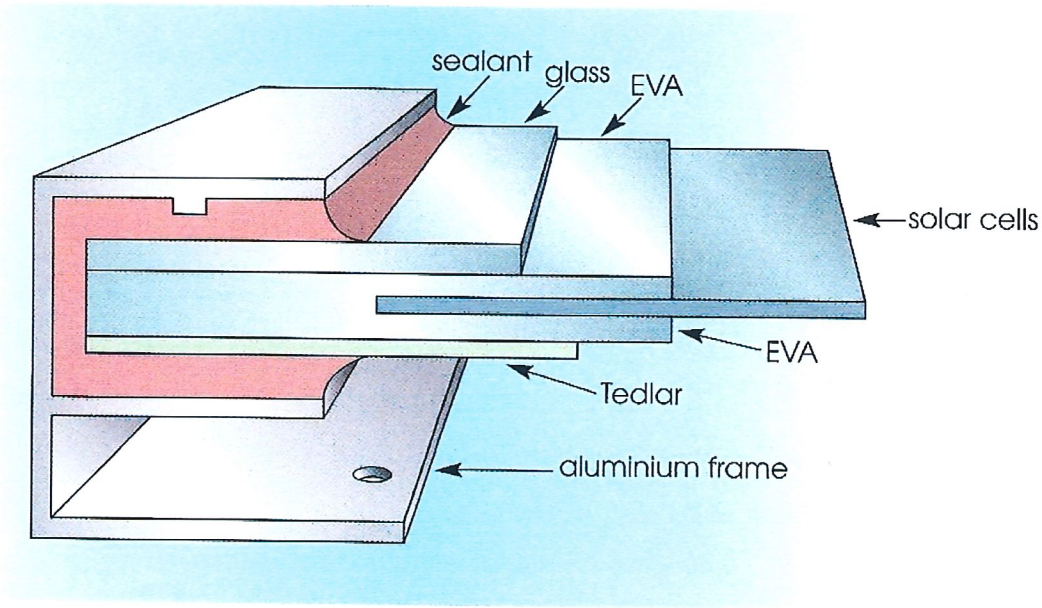


Figure 3.2 Typical construction of a conventional PV module.

⑥ wind

⑦ blowing dirt and sand

⑧ impact (dead limbs, kid's baseball or rock)

⑨ how to clean the panels off? / ⑩ salt spray, pollution

⑪ animals + birds

2. Typical Construction of a PV module

Show Fig 3.2 *

① For rigid crystalline Si PV cells:

→ cells are cushioned by airtight encapsulation in a layer of ethyl vinyl acetate (EVA) → so cell survives handling

→ Top Cover is a layer of tempered glass → strengthened compared to normal glass

* may have an antireflection coating (ARC)

→ underneath the EVA layer is a sheet of Tedlar (a light-weight synthetic polymer) that acts as a barrier to moisture and chemical attack

→ This assembly is fitted into a slotted aluminum frame and fixed in place with a sealant

② Rigid Thin film PV

→ Thin film PV cells are deposited directly onto glass

③ Flexible Thin Film PV

→ many module/array options exist

Show Fig. 3.3 *

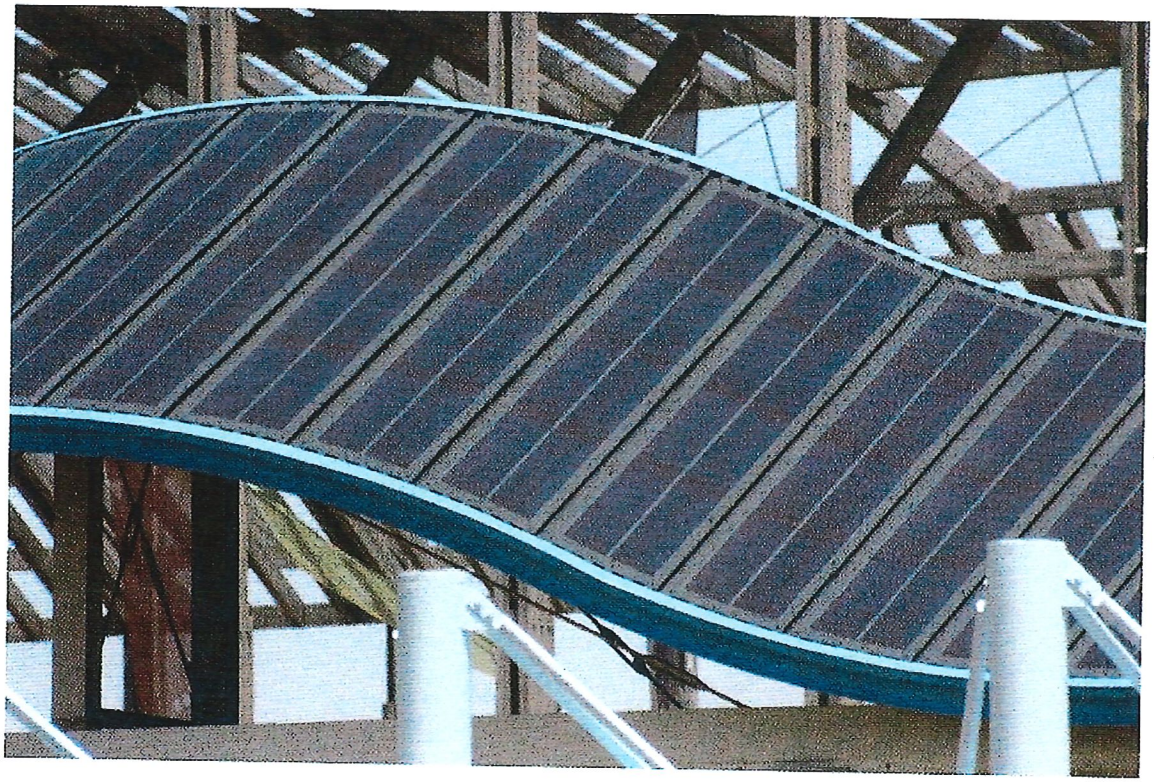


Figure 3.3 Innovative design: an example from Japan (IEA-PVPS).

3. Electrically Connecting PV cells and Modules

→ Each PV cell is a ~ low votage (~0.5V) and high current device

→ Connect in series to increase voltage

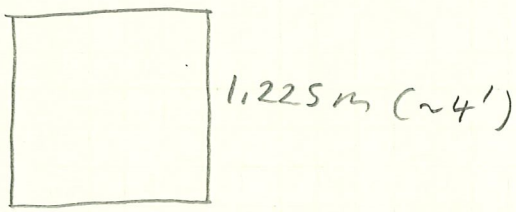
→ " " parallel " " current

a. Typical module output voltages:

① 36 series PV cells: ~ 18 V → suitable for charging 12V batteries
- ↳ V_{oc} ~ 20V
- ↳ V_{mpp} ~ 17V

② For grid connected PV systems
- → desire higher voltage
- → 72 in series → V_{mpp} ~ 35V
  - ↳ SC Si PV → 72 cells ~ 1.5 m^2 → yields up to ~ 200Wp

1.5 m^2 →



about 16 ft^2

→ or about 12.5W/ft^2 → 2000 ft^2 roof → ~ 25KW max

6hrs, 10¢/kWHr = ~ $15 × 150 days ~ $2250/yr

↓

ⓐ 3.16¢ per kWH ↳ $711

b. Connecting "Real" PV cells

→ "Real" PV cells are <u>not</u> identical

⇒ due to manufacturing differences, localized damage, partial shading, etc.

ALABAMA POWER
A SOUTHERN COMPANY

RATE FD
FAMILY DWELLING-
RESIDENTIAL SERVICE

By order of the Alabama Public Service Commission dated October 20, 2008 in Docket # 24860.

The kWh charges shown reflect adjustment pursuant to Rates RSE and CNP for application to monthly bills effective for January 2016 billings.

PAGE	EFFECTIVE DATE	REVISION
1 of 2	January, 2009 Billings	Fourteenth

AVAILABILITY

Available in all areas served from the interconnected system of the Company.

APPLICABILITY

Applicable for service to single residences and individual family apartments. Service shall not be resold or shared with others except that when two or more family dwelling units are served through a single meter, all provisions of the rate and minimum shall be applied as though each dwelling unit has been separately metered and the actual metered consumption were divided equally between each unit.

CHARACTER OF SERVICE

Single phase service at approximately 120 or 120/240 volts will be provided hereunder. Three phase service can be provided in accordance with Alabama Power Company service regulations.

MONTHLY RATE

Base Charge:
$14.50 per customer; plus

Charge for Energy:

BILLING MONTHS JUNE - SEPTEMBER
9.0467¢ per kWh for the first 1000 kWh,
plus
9.2996¢ per kWh for all over 1000 kWh.

BILLING MONTHS OCTOBER - MAY
9.0467¢ per kWh for the first 750 kWh,
plus
7.8467¢ per kWh for all over 750 kWh.

MINIMUM BILL

No monthly bill shall be less than $14.50 plus applicable provisions of Rate T.

BUDGET BILLING

See Alabama Power Company's Rules and Regulations for Electric Service governing application to this rate.

ALABAMA POWER
A SOUTHERN COMPANY

RATE PAE
PURCHASE OF ALTERNATE ENERGY

By order of the Alabama Public Service Commission dated May 5, 2015 in Docket # 18005.

PAGE	EFFECTIVE DATE	REVISION
1 of 4	June, 2015 Billings	Thirty-Sixth

AVAILABILITY

Available on any distribution line of the Company.

APPLICABILITY

Applicable for any Customer who has installed an electric generating facility that has a nameplate capacity of not more than 100 KW for Customer's own use and desires a permanent electrical connection with the Company's system in order to sell alternate electrical energy to the Company.

RATE FOR PURCHASE OF ALTERNATE ENERGY

The Customer may choose among Option A, Option B, or Option C, subject to eligibility that shall be determined based on the rate under which the Customer currently receives electric service. Customers not taking service under Time Advantage rates may choose between Option A and Option B. Customers taking service under Time Advantage rates may choose between Option A and Option C. The Monthly Base Charge shall be paid by the Customer to the Company to cover the cost of meter configuration, meter reading, data processing and miscellaneous expenses necessary for the proper accounting of electrical energy sold to the Company by the Customer. The payment for energy is the per kWh payment by the Company to the Customer for energy purchased by the Company from the Customer.

OPTION A – STANDARD RATE

Monthly Base Charge:

Single Phase Service	$0.82 per customer
Three Phase Service	$1.35 per customer

Payment for Energy:

BILLING MONTHS JUNE – SEPTEMBER	BILLING MONTHS OCTOBER - MAY
3.16¢ per kWh for all kWh	2.88¢ per kWh for all kWh

→ ∴ the module's output is limited by the PV cell with the <u>lowest</u> output, i.e. the "weakest link in the chain"

→ The resulting power loss is called <u>"Mismatch Loss"</u>

① Mismatch Loss from manufacturing tolerances

→ small, of little concern

② Mismatch Loss from partial shading

→ potentially problematic, should be avoided

③ Mismatch Loss from a bad PV cell

→ Bad!

→ Bad cell now acts as a load (→ reverse biased P-N junction in breakdown) if it cannot produce current

→ it consumes power and produces heat, which can further damage the array → solder joint melting, etc.

→ This is known as <u>"Hot-Spot Formation"</u>

<u>Show Fig 3.4 *</u>

a. Series chain → full voltage from good cells across reverse biased bad cell → leads to breakdown and hot spot formation

b. circuit drawing of (a.)

c. <u>Bypass diodes</u> added to small groups of PV cells to prevent hot spots from bad cells

→ trade off: bypass diode will take out all good cells in a group with one bad cell

→ typically: one bypass diode for every 10 or fewer PV cells

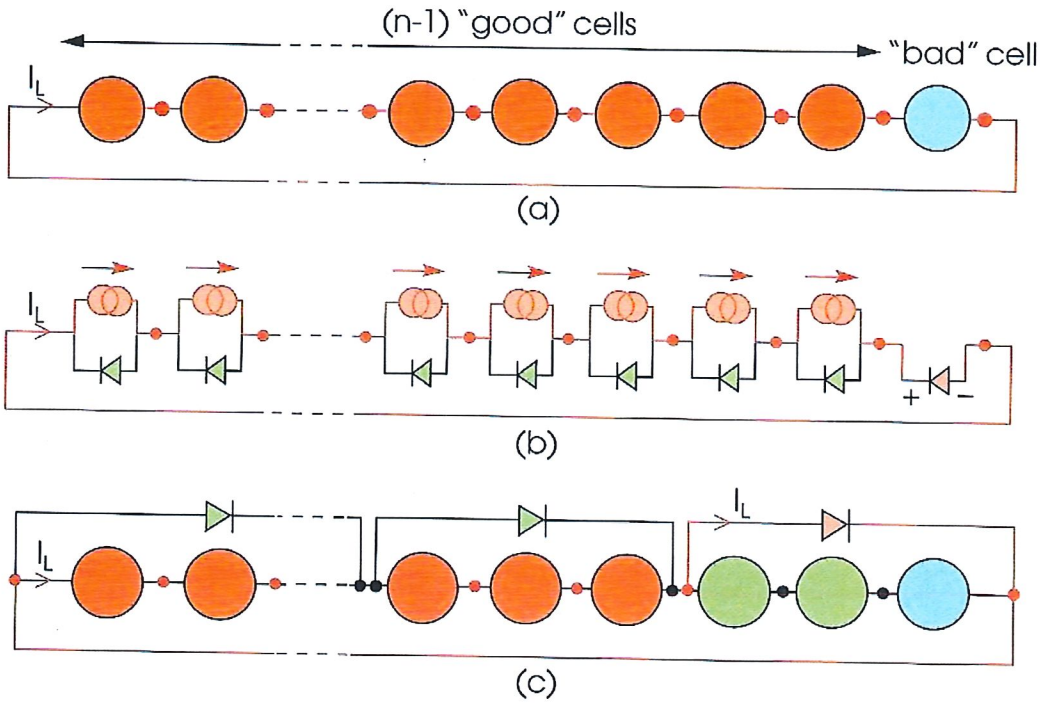


Figure 3.4 (a) A string of cells including one 'bad' cell; (b) equivalent circuit; (c) addition of bypass diodes.

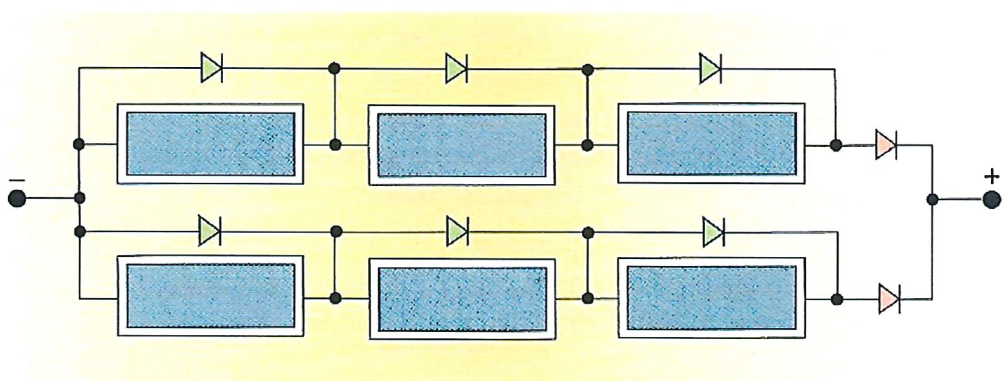


Figure 3.5 An array of 6 modules.

c. Modules

→ Modules are also characterized by V_{oc}, I_{sc} and P_{mpp}

→ Modules can be connected in series and parallel too

show Fig 3.5

Note: do not connect modules from different manufactures due to different I-V characteristics and spectral response → might result in extra mismatch losses

→ Bypass diodes also added to modules: 1 per module

→ Diodes added in series with modules are called "Blocking Diodes"

→ these diodes ensure current only flows out of the modules

→ typically used with battery charging PV systems to prevent batteries from discharging through the modules at night