GS+I 東京大学総括寄付講座「太陽光を機軸とした持続可能グローバルエネルギーシステム」
GLOBAL SOLAR+ INITIATIVE. THE UNIVERSITY OF TOKYO

Sustainable Global Energy Systems Based on Solar Power

R&D of ultra-high efficiency solar cells and GS+I's mission

Yoshiaki Nakano

RCAST, The University of Tokyo, Co-chair of GS+I

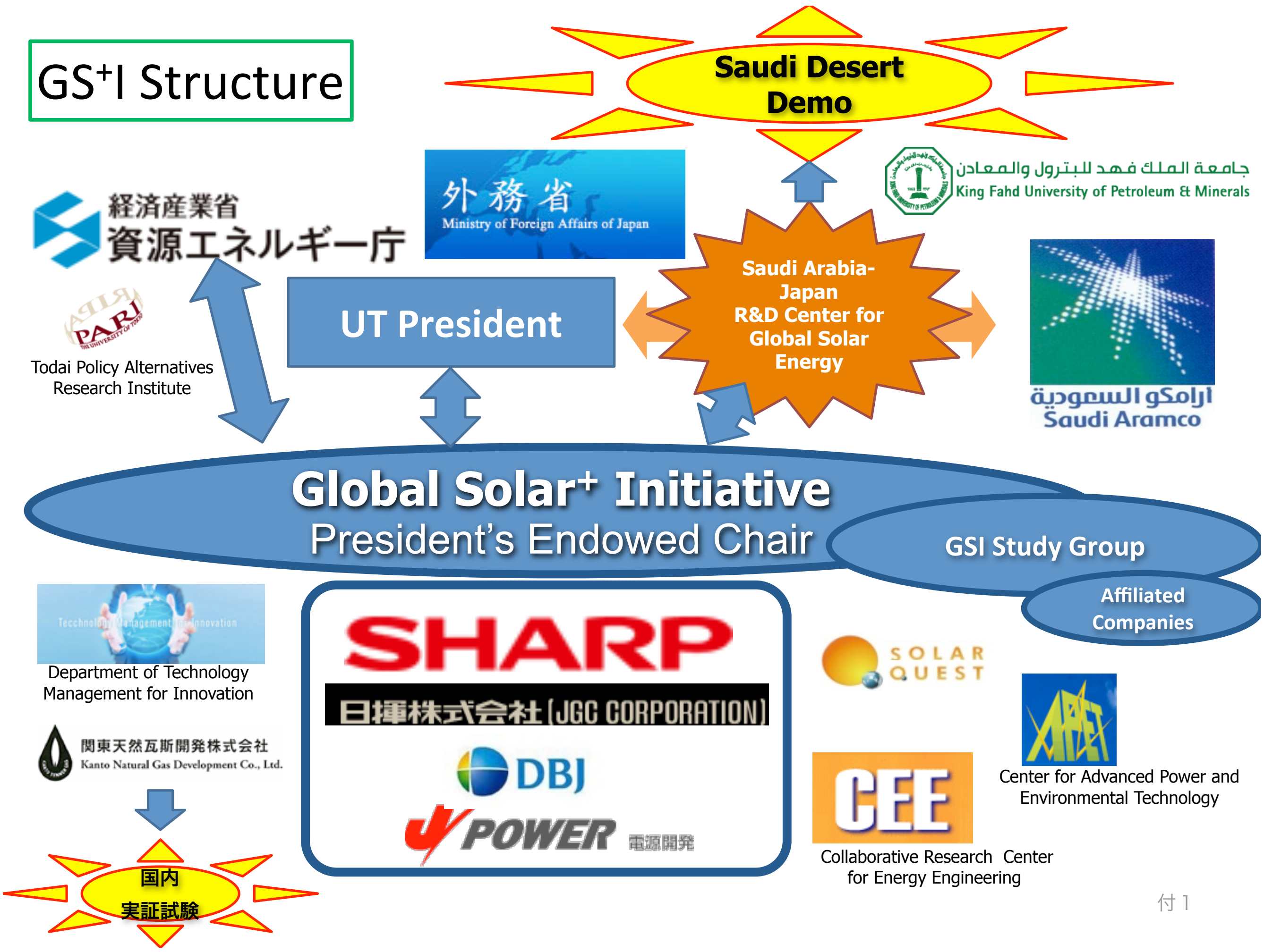
2012.9.28 UT-KFUPM Workshop @ ENEOS Hall, RCAST

Outline

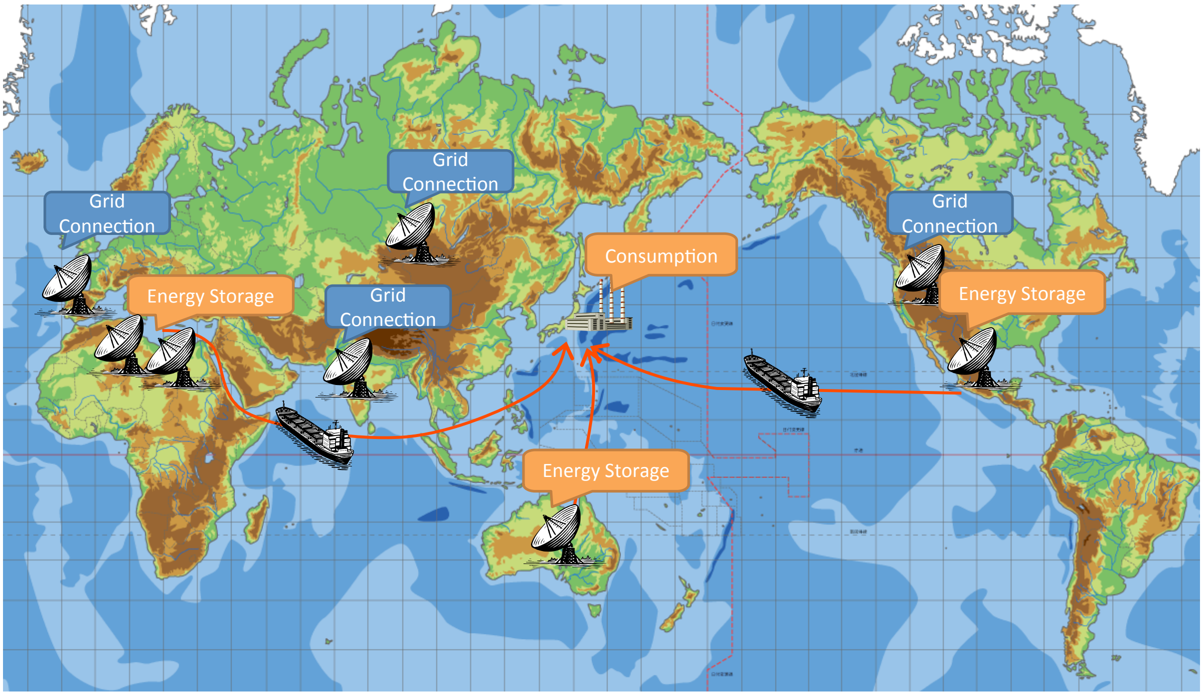
1. GS+I Mission
2. Potential of Sunlight Energy
3. Solar Energy Harvesting: H or E?
4. Current R&D Status of High-Efficiency PV Cells
5. Solar Energy Storage and Transport

Global Solar Plus Initiative

-Endowed Chair for Sustainable Global Energy System Driven by Sunlight



Sustainable Global Energy System



Generation and Storage under Strong Sun
then Energy Shipping to Remote Location

Necessary Technologies

High-efficiency PV/CPV/CSP

Energy Storage and Transportation

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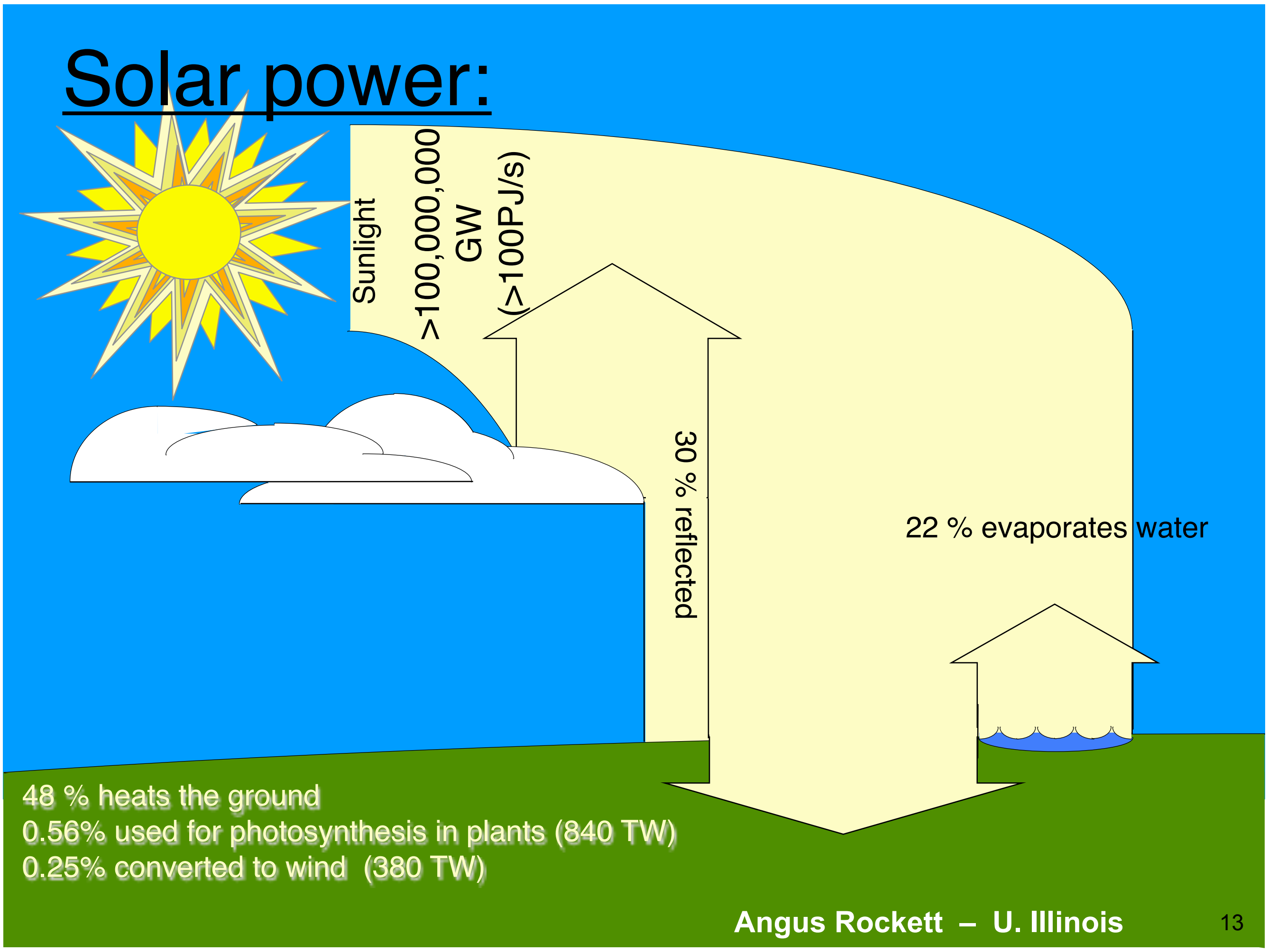


The sun made all

Fossil Fuel
-saved sunlight energy

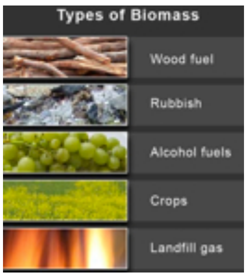

Petroleum


Coal

Natural Gas

Renewable Energy
-current sunlight energy

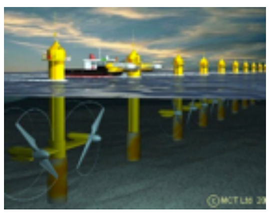
Indirect



Biomass


Wind power


Hydropower


Wave power

Direct

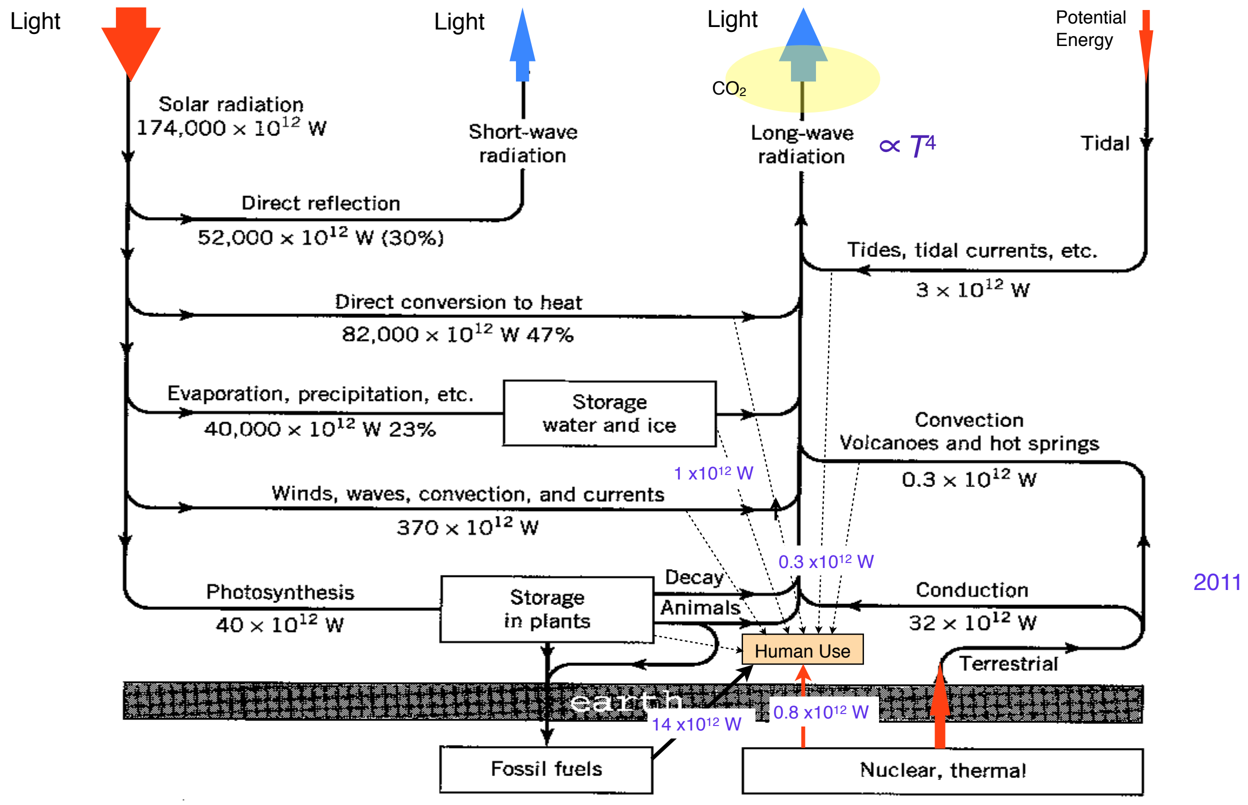

PV


Solar thermal

- Cost is very different from region to region
- Best mix also differs

GS+I University of Tokyo

Energy Flow on the Earth



US Atomic Energy Commission Publication TID --25857, 1972

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Barstow Scheme

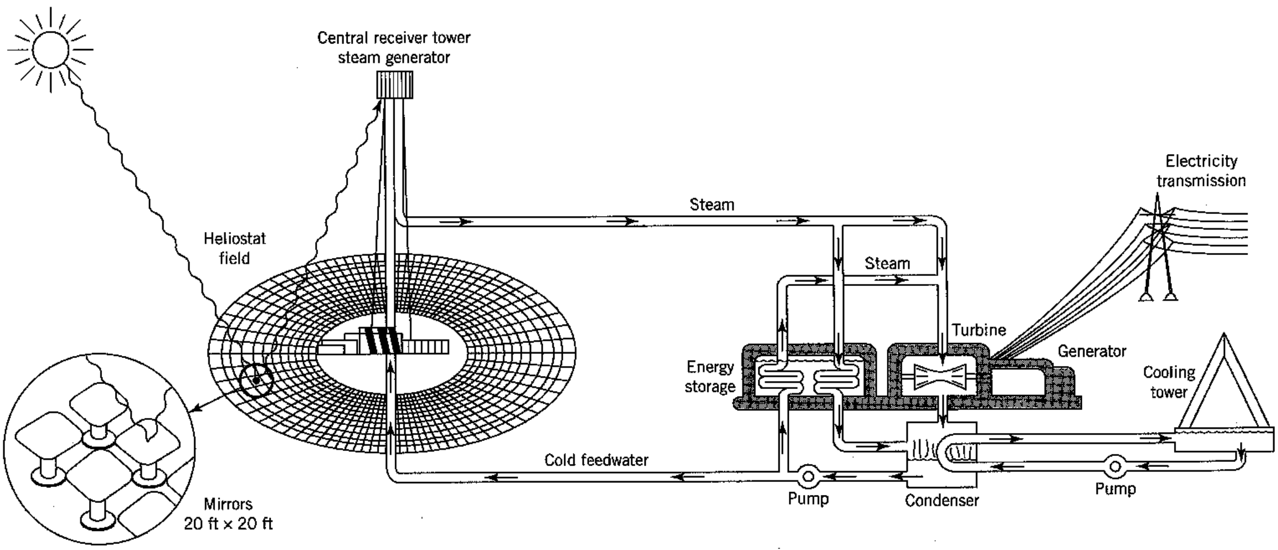

Figure 4.11 A schematic view of a 10 MW_e solar-thermal power plant near Barstow, California. The receiver and boiler that absorb the sunlight reflected from 1900 heliostats are at the top of a 90 meter tower. The heliostats are each steered by computer control to reflect the sunlight onto the receiver. The steam from the boiler can be either delivered directly to the turbine and generator or to storage. The storage system can provide steam for 4 hours of generation at a level of 7 MW_e without sunlight. (Figure supplied by the Solar Energy Research Institute.)

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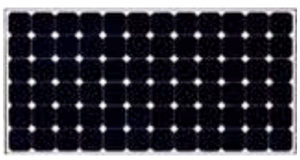
Light into Electricity: PV

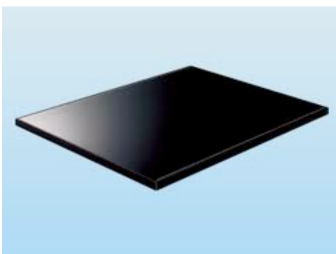
Poly-crystalline Si

Thin film Si

Dye-sensitized, Organic



Single crystalline Si



Thin film compound

PV Technology Options

Flat plates (~94% of today's market)

- **Crystalline silicon**
  - Single crystal
  - Polycrystalline
- **Thin films**
  - CdTe
  - Amorphous Si
  - $CuInGaSe_2$
- **New technologies**
  - Organic
  - Multiple others

Concentrators

- **Silicon**
  - Linear focus
  - Point focus
  - 2–200x
- **Multijunctions (III-Vs)**
  - Point focus
  - 250 to >1000x

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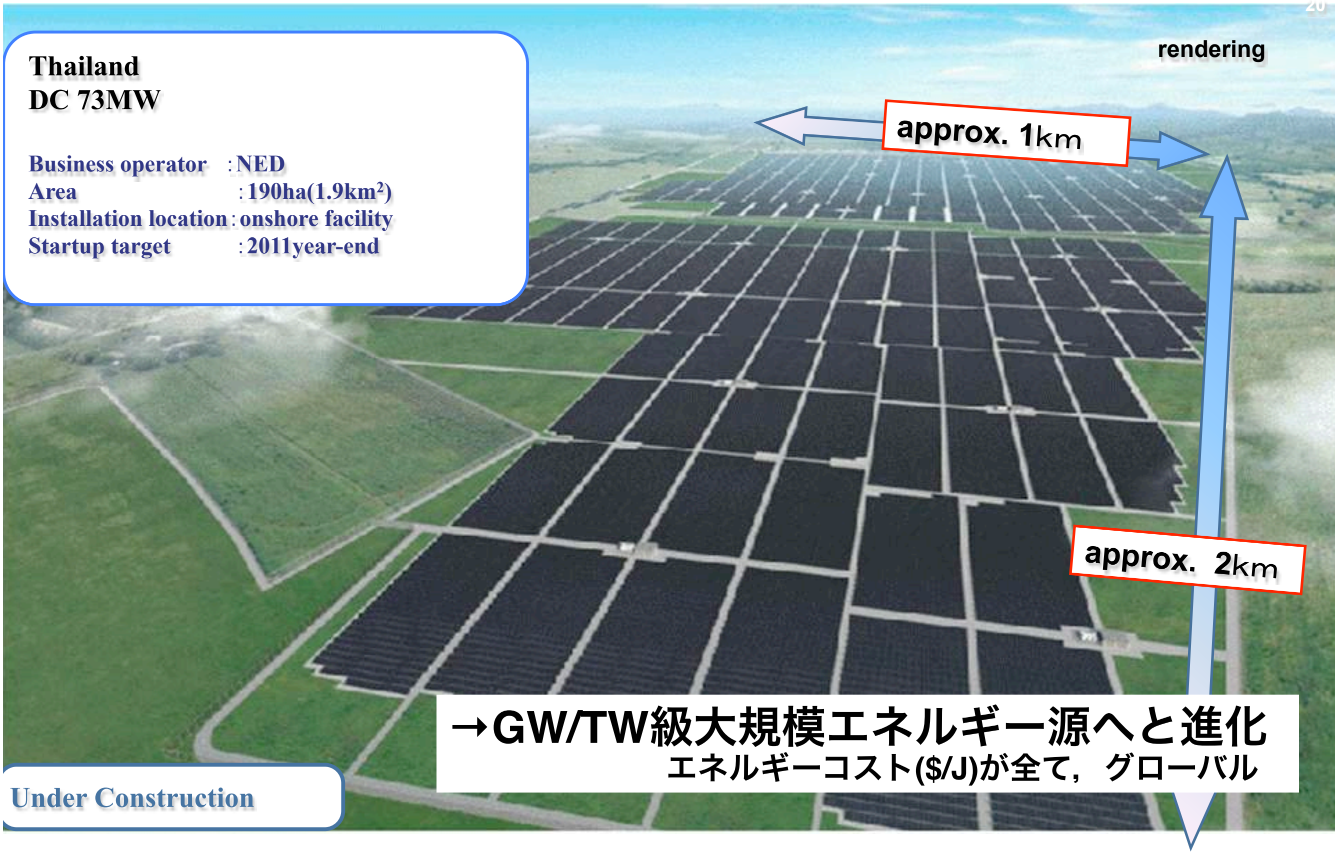
Individual Household

Mega Solar (PV Power Plant)



Sunlight Concentrator (lens)

GS+I

Puertollano and Seville (Spain)

www.concentrix-solar.de

Sunlight Concentrator (mirror)

Sunlight Concentrator (tower)

JFE Engineering

GS+I

Merits of CPV

- PV conversion efficiency is the highest
- Cell cost reduced by factor of concentration
- Rare material usage reduced by a factor of concentration
- Copper wire usage very much reduced
- Energy Profit Ratio increased with concentration
- Easy to upgrade (optics and converter separated)
- Easy to maintain (optics and converter separated)

All are very advantageous for ***mega/giga solar plants***

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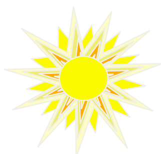
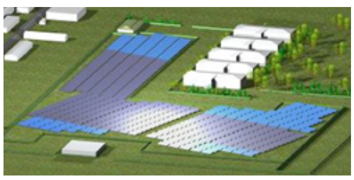
Area Needed for 1GW Power Gen



Power of Sunlight
1kW/m²

Nuclear Power Plant



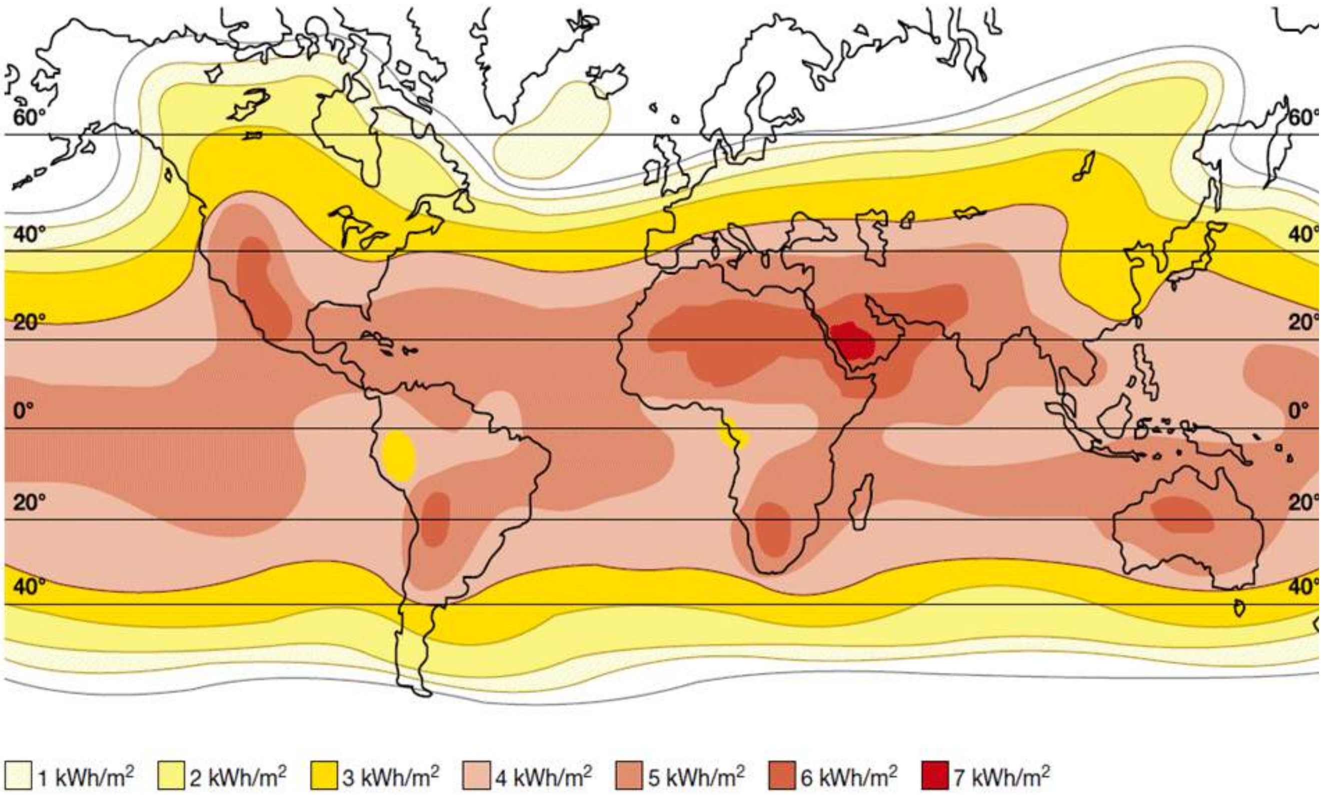
Thin Film
Efficiency ~10%

CPV
Efficiency ~40%

0.8 km sq. | 3.2 km sq. | 1.6 km sq.

※Utility area is not included

Global Insolation



Source : ABB Technical Application Papers No.10
Photovoltaik plants
unit:kWh/m2/day

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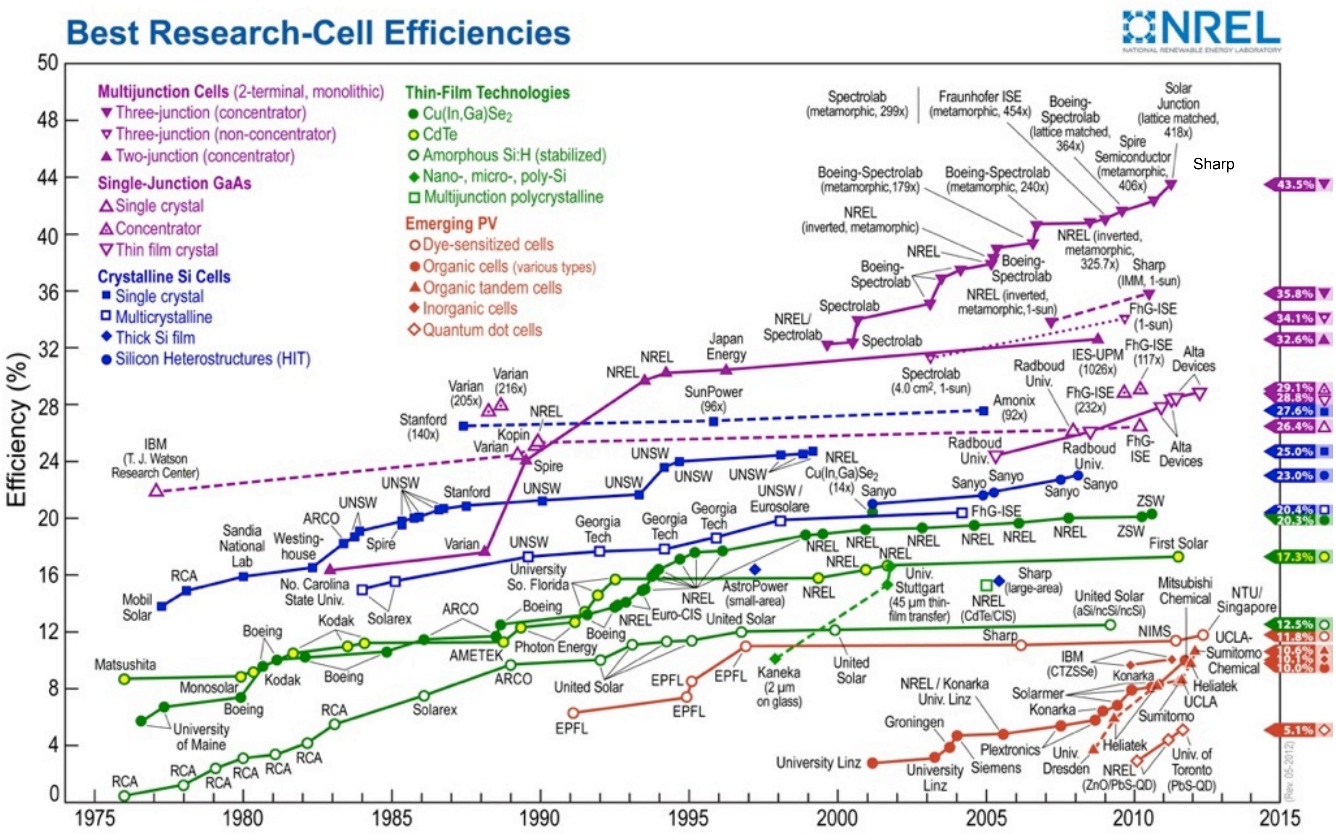
Conversion Efficiency of Solar Cells



The Solar Spectrum

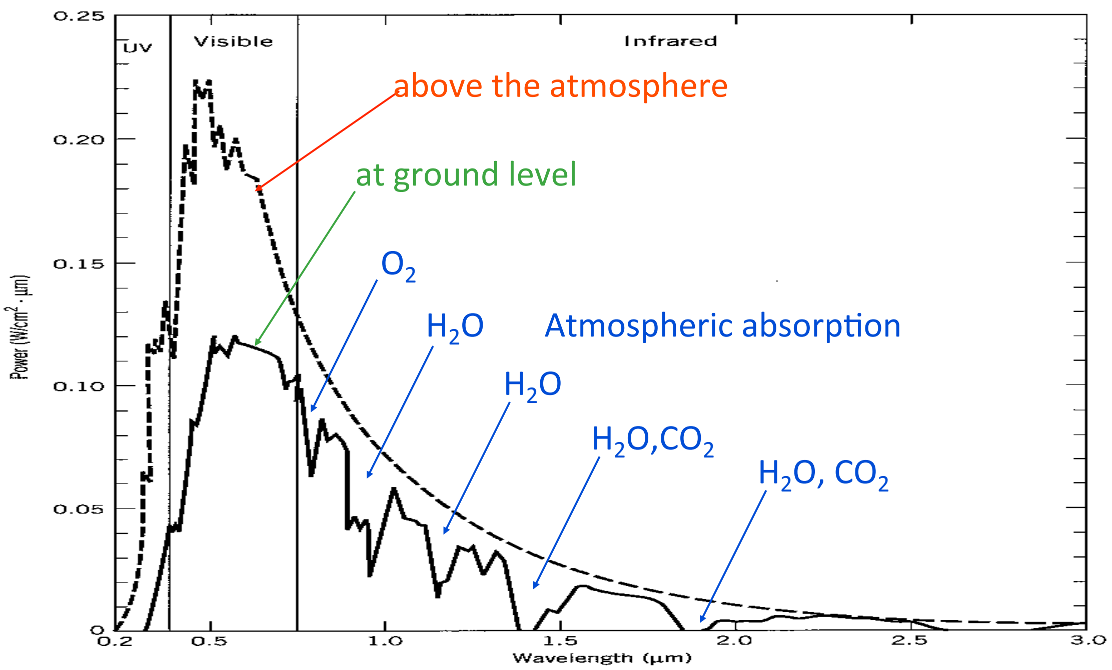
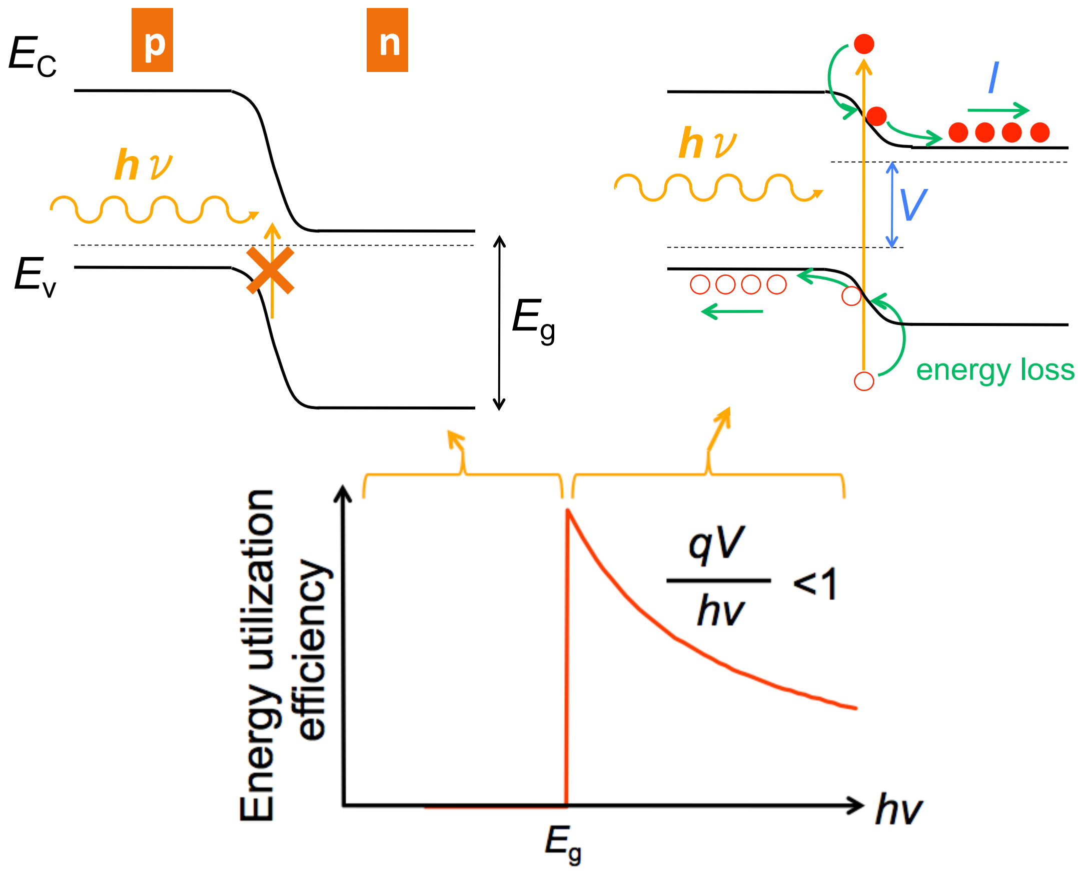


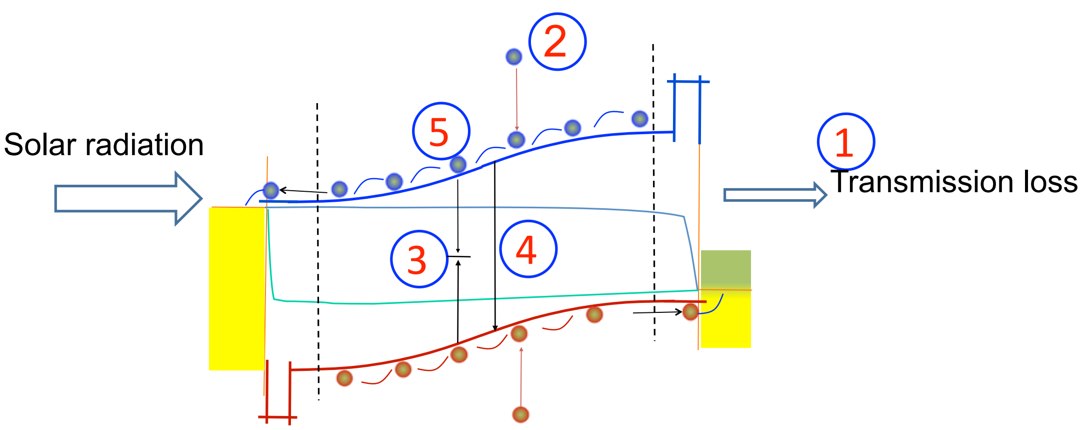
Figure 4.1 The wavelength distribution of solar radiation above the atmosphere (dashed line) and at the earth's surface (solid line). The Solar Constant is given by the area under the dashed curve. The sharp dips in the solid line are due to absorption of certain wavelengths by various atmospheric gases, including water vapor and carbon dioxide. (Adapted from *On the Nature and Distribution of Solar Radiation*, Watt Engineering, Washington, D.C.: U.S. Government Printing Office, Department of Energy HCP/T2552-01, 1978).

Fundamental energy losses in solar cells



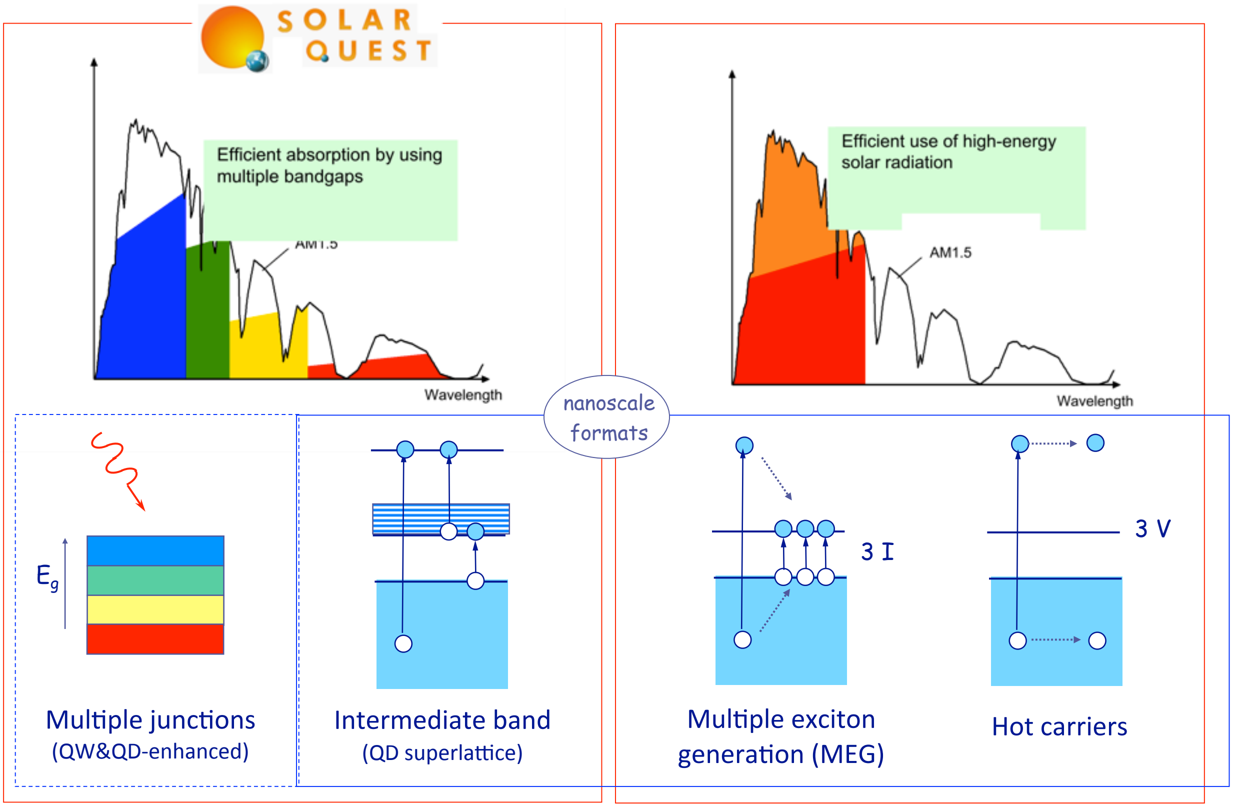
Major Loss Mechanisms

1. Transmission loss
2. Thermalization loss ($h\nu_{average} \rightarrow E_g$+kT)
3. Nonradiative recombination loss (SRH, Auger)
4. Radiative recombination loss (Photon recycling and coupling)
5. Spatial relaxation loss (E_g+kT → qV_m)

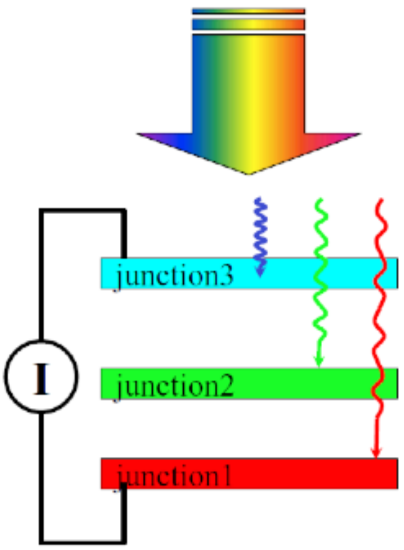


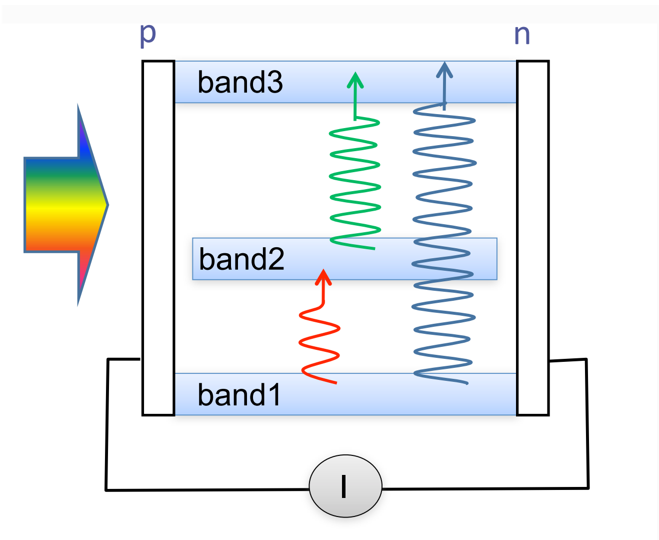
GS+I

Innovative PV : > 50% Efficient Solar Cells



High Efficiency Structures





Tunnel junctions not necessary

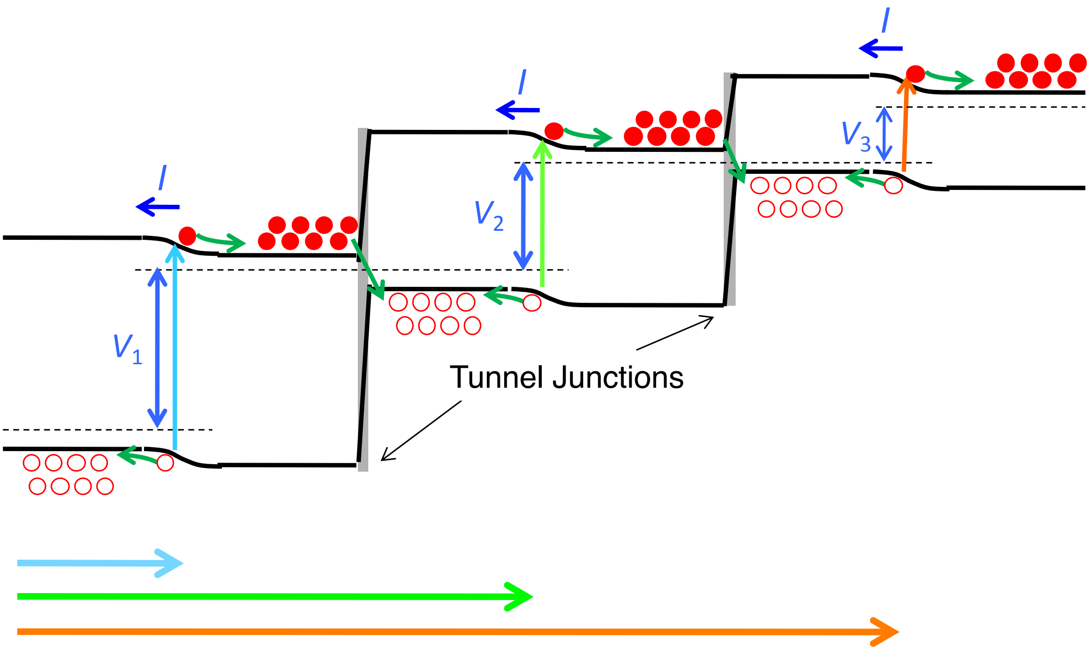
Multi-junction

- Single gap (two bands) each junction
- N junctions ⇒ N absorptions
- Efficiency~30-40%

Multi-band

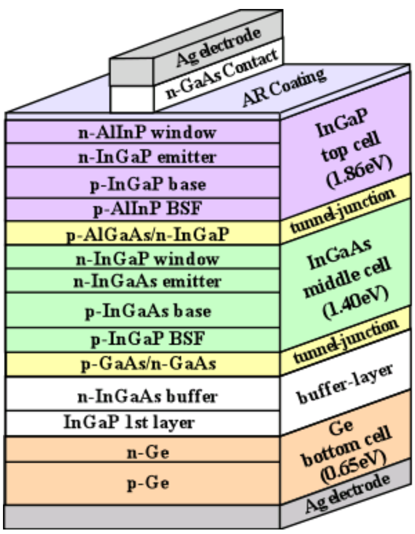
- Single junction (no lattice-mismatch)
- N bands ⇒ N·(N-1)/2 gaps
  ⇒ N·(N-1)/2 absorptions
- Add one band ⇒ add N absorptions

Band Diagram of Multijunction Cell

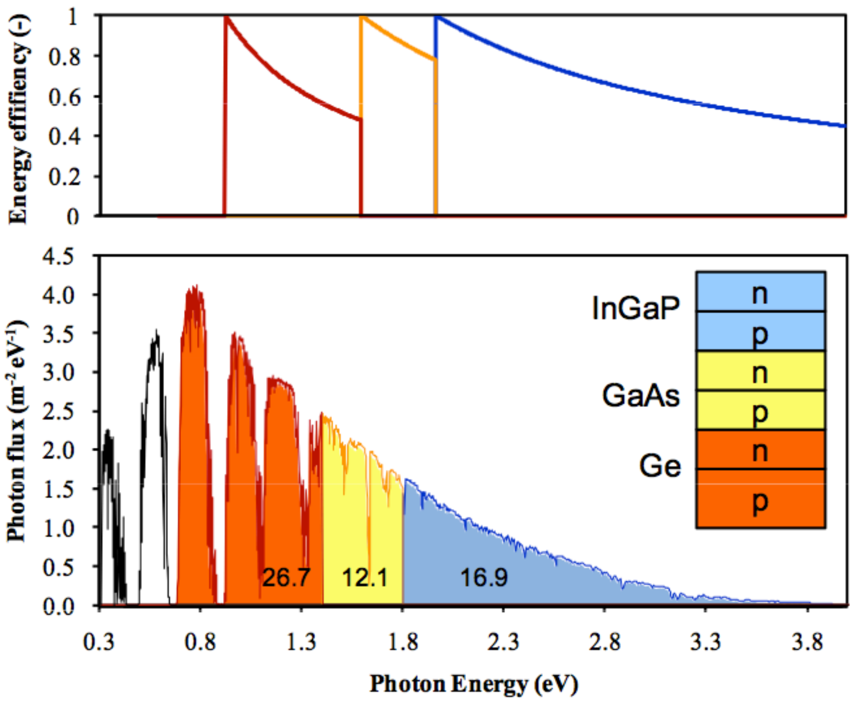


High energy (and thus short wavelength) photons are absorbed first

Multi-junction solar cells for high efficiency



M. Yamaguchi et al.,
Solar Energy 79 (2005) 78-85

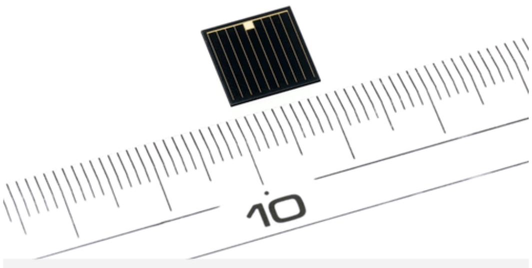


- Photon collection up to lower energies
- Smaller photon energy loss by multi-step bandgaps
  - Current from the middle cell limits the total current output.

News Release 2009年10月22日

化合物3接合型太陽電池で実現

太陽電池セルで世界最高変換効率35.8%を達成



世界最高変換効率35.8%を達成した化合物3接合型太陽電池セル

Press Release by

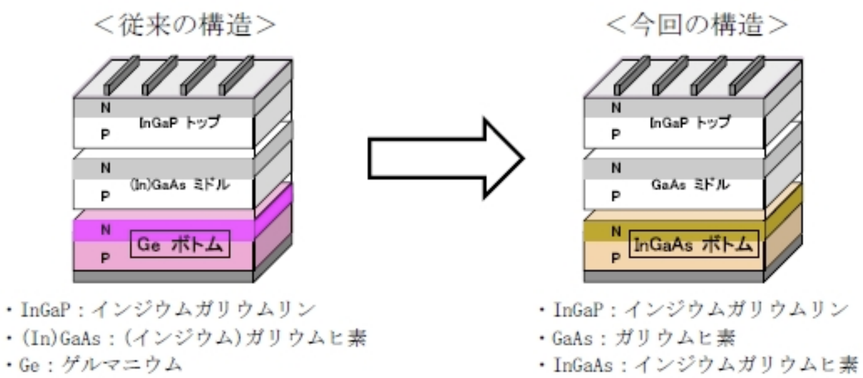
SHARP

SHARP Corp.

on October 22, 2009

New World Record of
Conv. Efficiency : 35.8%
(w/o concentration)

42.1%@280x (IEEE PVSC 2010)



Achieving 1 sun conversion efficiency world record

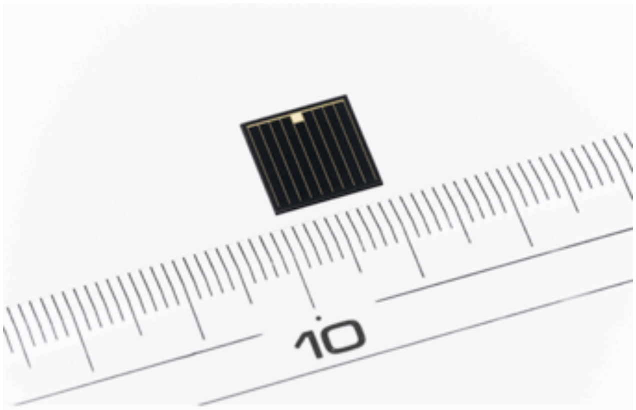
▶ニュースリリースの検索はこちら

News Release 2011年11月4日

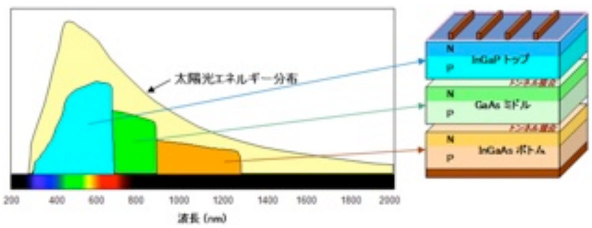
SHARP

化合物3接合型太陽電池で実現

太陽電池セルで世界最高変換効率36.9%を達成

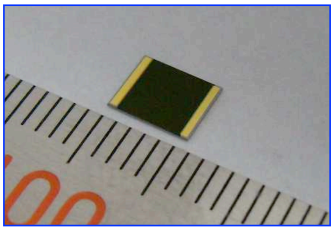


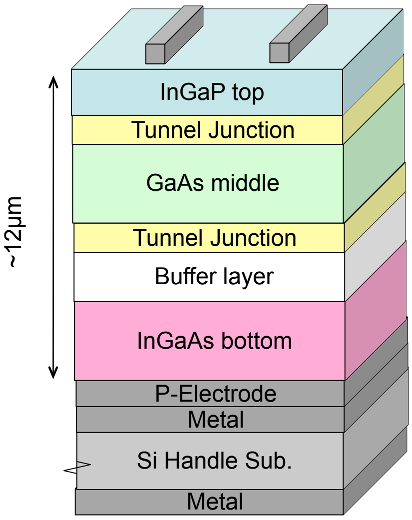
世界最高変換効率36.9%を達成した化合物3接合型太陽電池セル

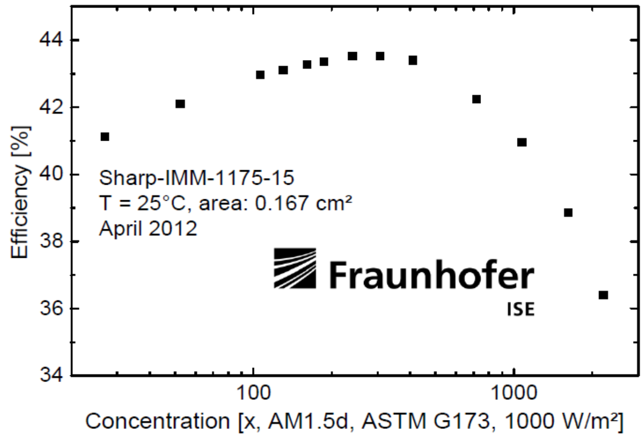


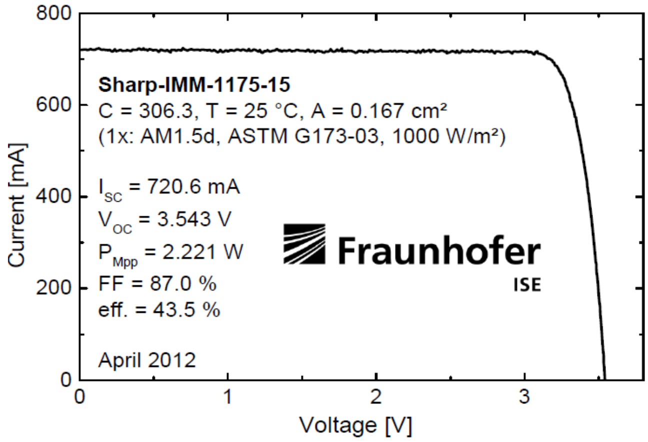
Achievement of World Highest Efficiency of 43.5% @306 Sun

Cell Chip (4mm x 4mm)

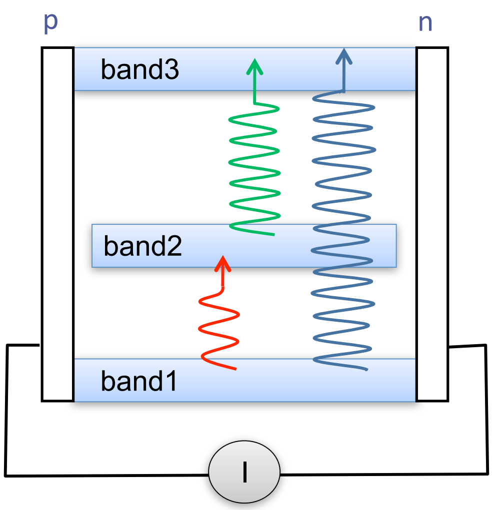


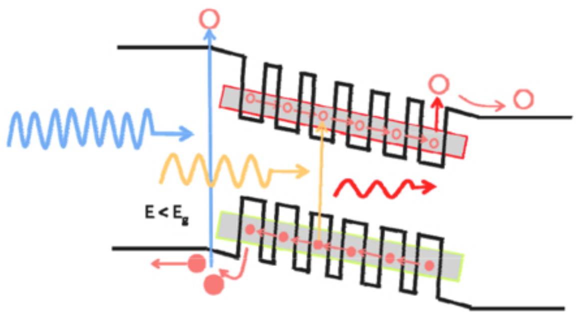


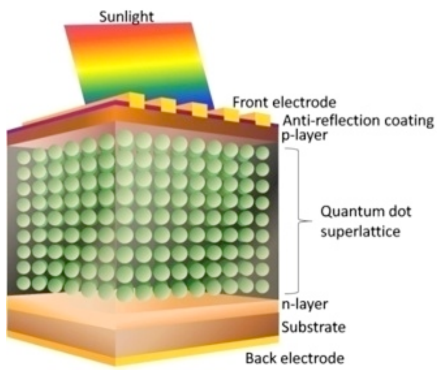




Intermediate-band solar cell





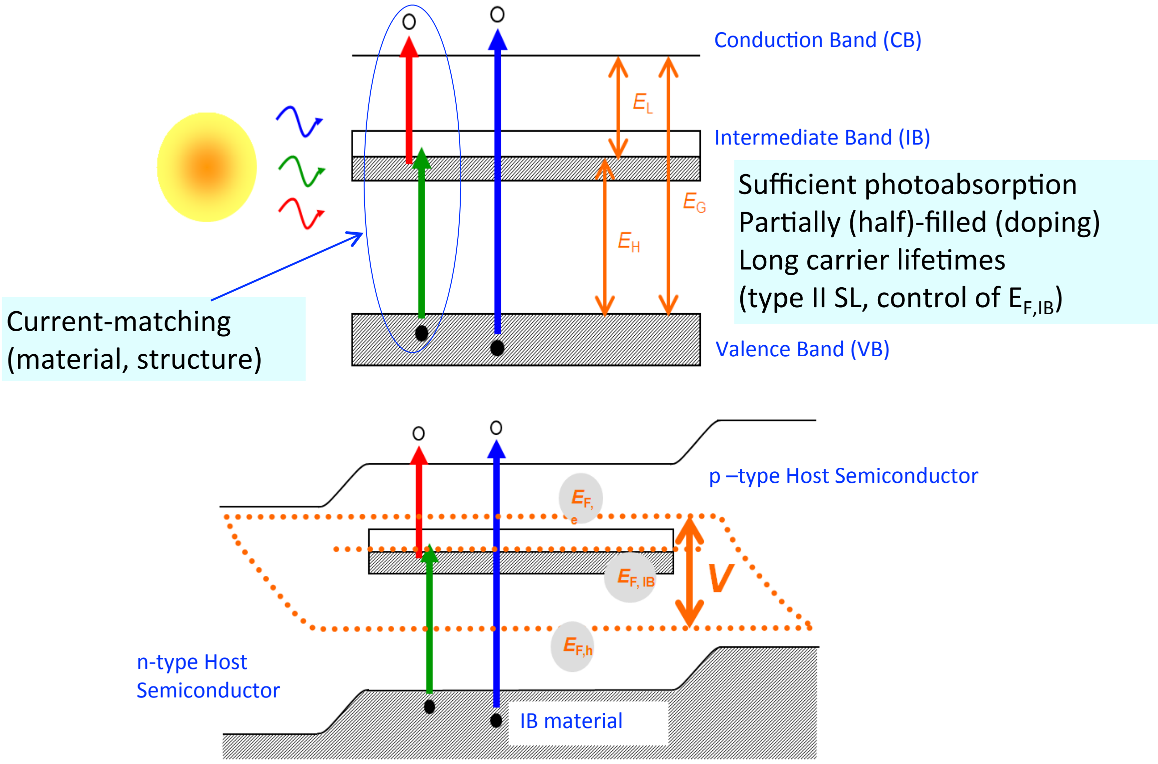


- Single-junction
- Multiple-wavelength absorption
- Energy up-conversion by multi-step excitation

Theoretical efficiency >60%

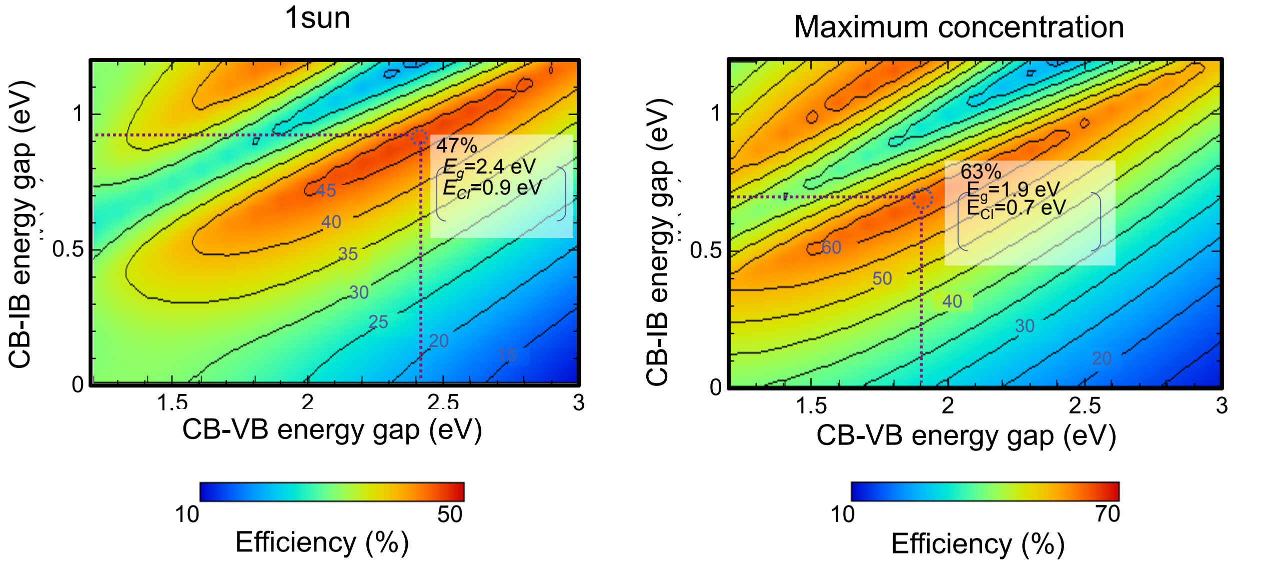
- Multi-band implementation
  ➔Mini-bands
  by quantum-dots superlattice

Intermediate Band Solar Cell：Operation Principle



A. Luque and A. Martí, Phys. Rev. Lett. **78,** 5014 (1997)

Intermediate Band Solar Cell：Theoretical Efficiencies



η = 47% (1sun)

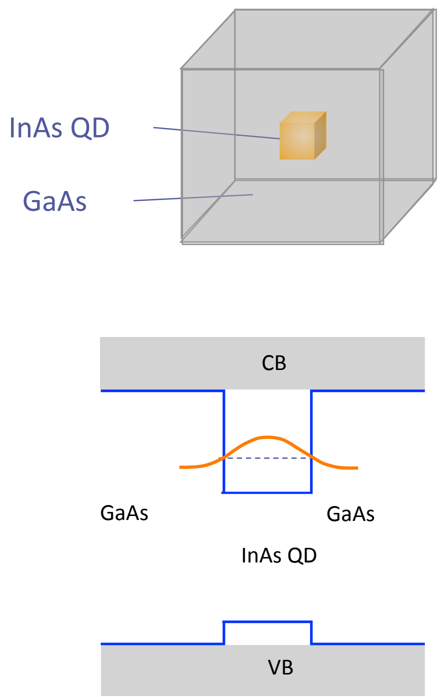
η = 63% (Maximum concentration)

THE UNIVERSITY OF TOKYO

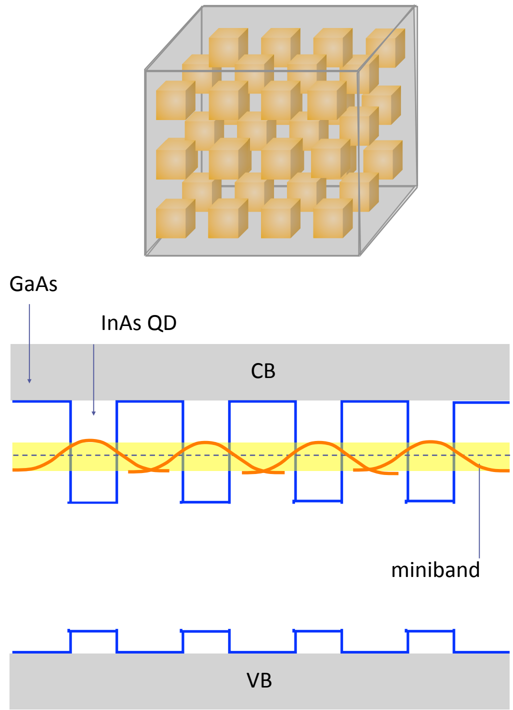
S. Yagi and Y. Okada, 2nd Innovative PV (Tsukuba, 2009)

Intermediate Band Realized with Quantum dot Superlattice

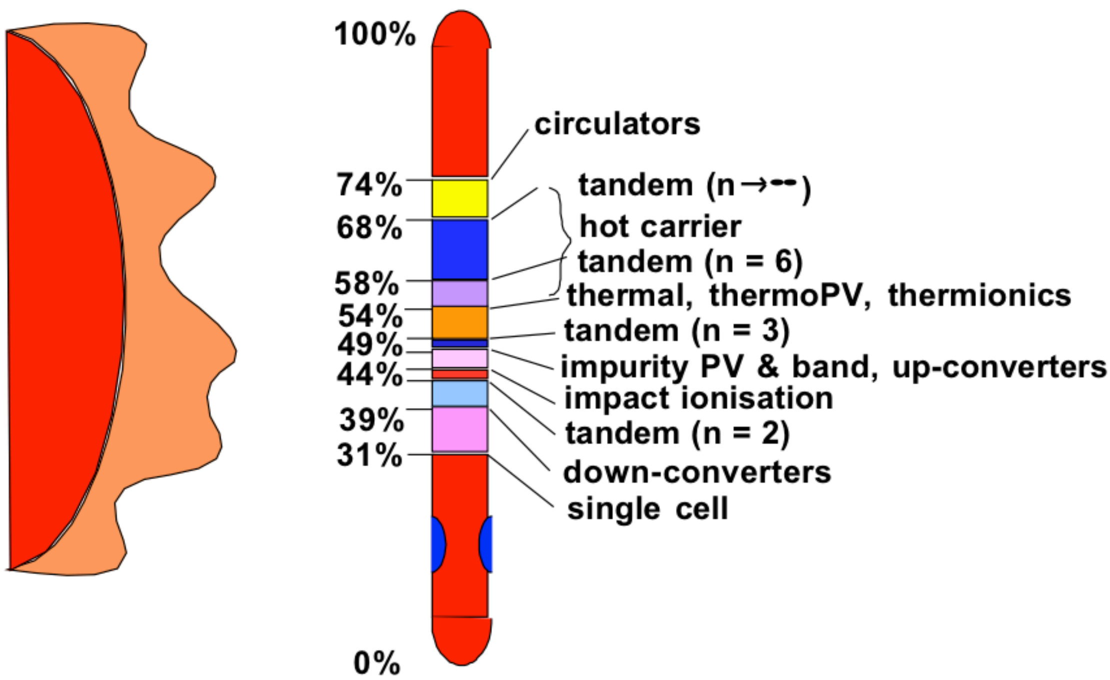
Single QD



QD Superlattice



Theoretical Conversion Efficiency Limits



by courtesy of M. Green (UNSW)

Post-Silicon Ultra-High Efficiency Solar Cell Development Project

Leader: Prof. Yoshiaki Nakano, The University of Tokyo, RCAST
Vice leaders: Prof. Masafumi Yamaguchi, Toyota Technological Institute
Prof. Takashi Tomita, The University of Tokyo, RCAST

NEDO

Team 1: Super high efficiency concentrator multi-junction solar cells
Leader: *Prof. Masafumi Yamaguchi, Toyota Technological Institute*
Toyota Technological Institute · Miyazaki Univ. · SHARP Corp.

Team 2: Novel materials and structures for multi-junction solar cells
Leader: Prof. Yoshiaki Nakano, The University of Tokyo, RCAST
The Univ. of Tokyo · SHARP Corp. · Toyota Technological Institute · Nagoya Univ. · Meijo Univ. · Kyushu Univ. · University of Hyogo

Team 3: Quantum-dot multi-band solar cells
Leader: Prof. Yoshitaka Okada, The University of Tokyo, RCAST
The Univ. of Tokyo · The Univ. of Electro-Communications

Team 4: Advanced photon management and nano/micro fabrication technology
Leader: Prof. Kenjiro Miyano The University of Tokyo, RCAST
The Univ. of Tokyo · SHARP Corp. · JX

7

Targets

2014 → 2030

III-V semiconductor ultra-high efficiency cell (η=48%) under high concentration

Multi-junction

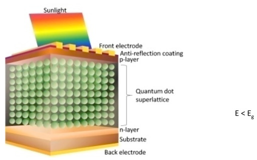
Lattice mismatch (inverse-metamorphic + epitaxial lift-off)

- sub. / InGaP / GaAs / InGaAs — 45% (x1000)
- sub. / AlInGaP / GaAs / InGaAs / InGaAs — 48% (x1000)
- Hybrid-material bottom cell: sub. / InGaP / GaAs / HB (mechanical stack) — 45% (x1000)

Lattice-matched

- Quantum structures: AlGaAs / QW/QD / Ge — 45% (x1000); AlInGaP / (In)GaAs / QW/QD / Ge — 48% (x1000)
- GaInNAs bulk: AlGaAs / GaInNAs / Ge — 45% (x1000); AlInGaP / (In)GaAs / GaInNAs / Ge — 48% (x1000)
- Nitride multi-junction: InGaN / InGaN / InGaN / InGaN — 3J 42%, 4J 45%

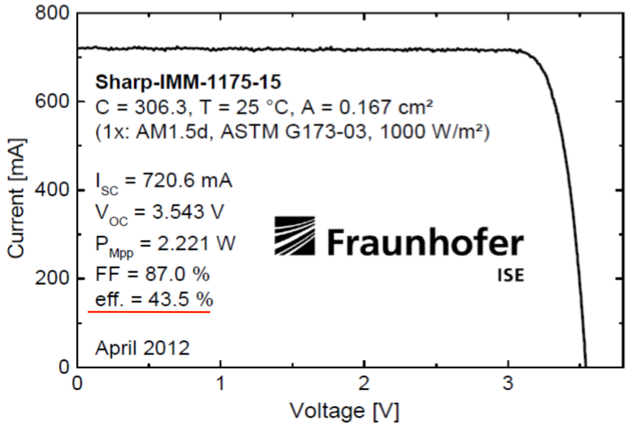
Quantum dot Multi-band

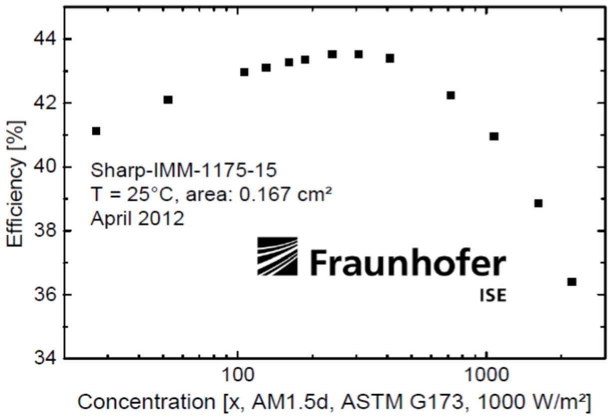


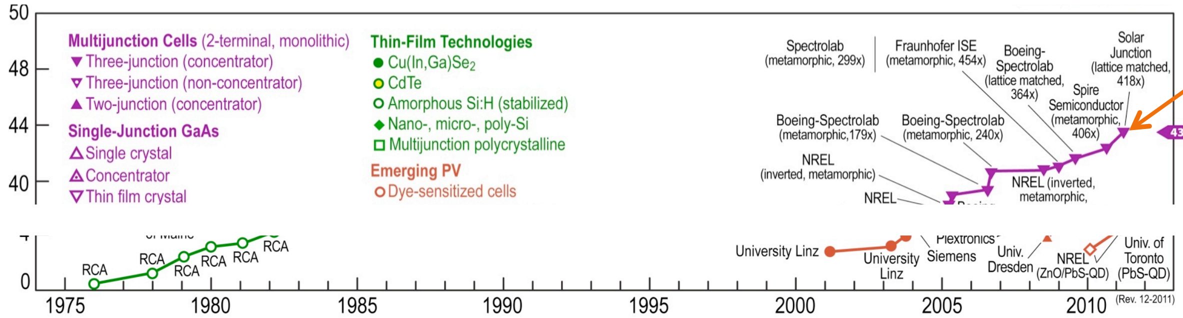
40% (x1000)

>50% (x1000)

43.5% Cell @304 suns







Roadmap of concentrator photovoltaics

2012 **2015** **2030**

Conversion efficiency (cell)

Multi-junctions

43% (x400) — 45% (x1000) — 48% (x1000)

Improvement

sub.
InGaP
GaAs
InGaAs

Inverted mismatch growth

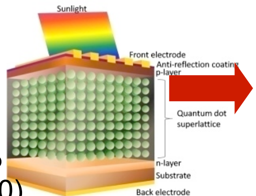
InGaP
Ge

GaInNAs or Quantum structure

AlInGaP
(In)GaAs
Ge

Improvement

Intermediate-band



40% (x1000)

Quantum dot

>50% (>x1000)

World-wide energy network

Dissemination

Low-cost module R&D

GW-scale installation

7₡/kWh — 4₡/kWh — 2₡/kWh

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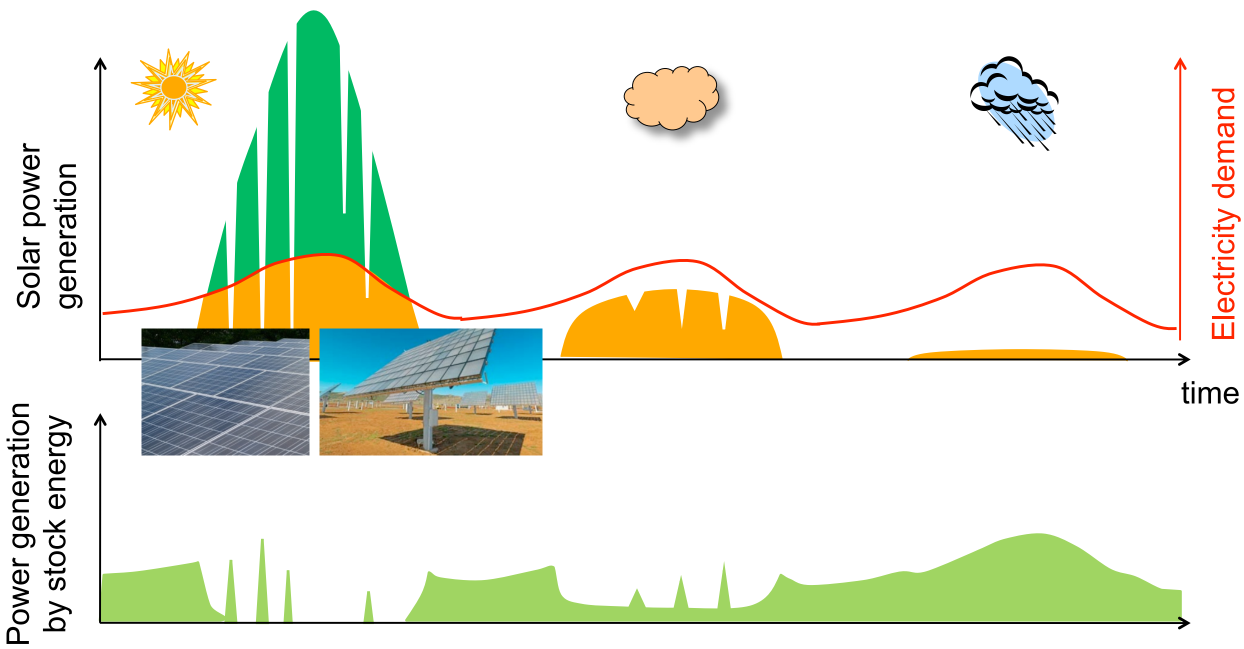
Necessity of "energy storage"

GS+I University of Tokyo



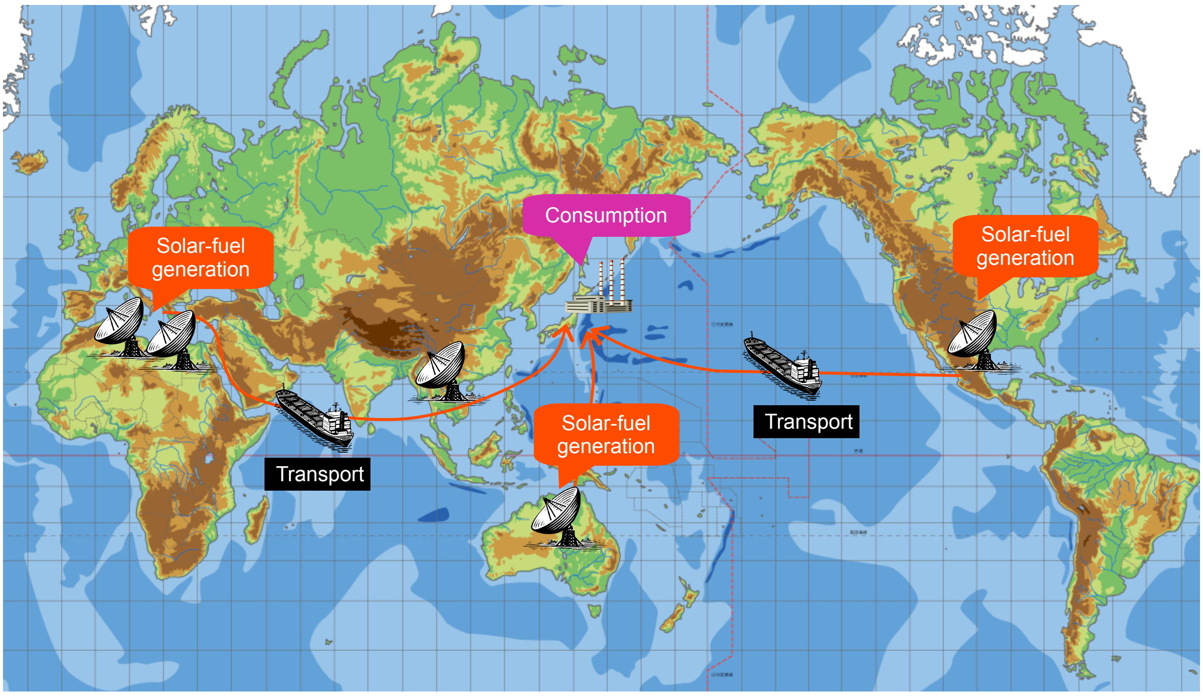
Strategy 1: Word-wide grid connection

GS+I
University of Tokyo

- Overcoming fluctuation in renewable power generation by a large-area grid and multiple methodology.

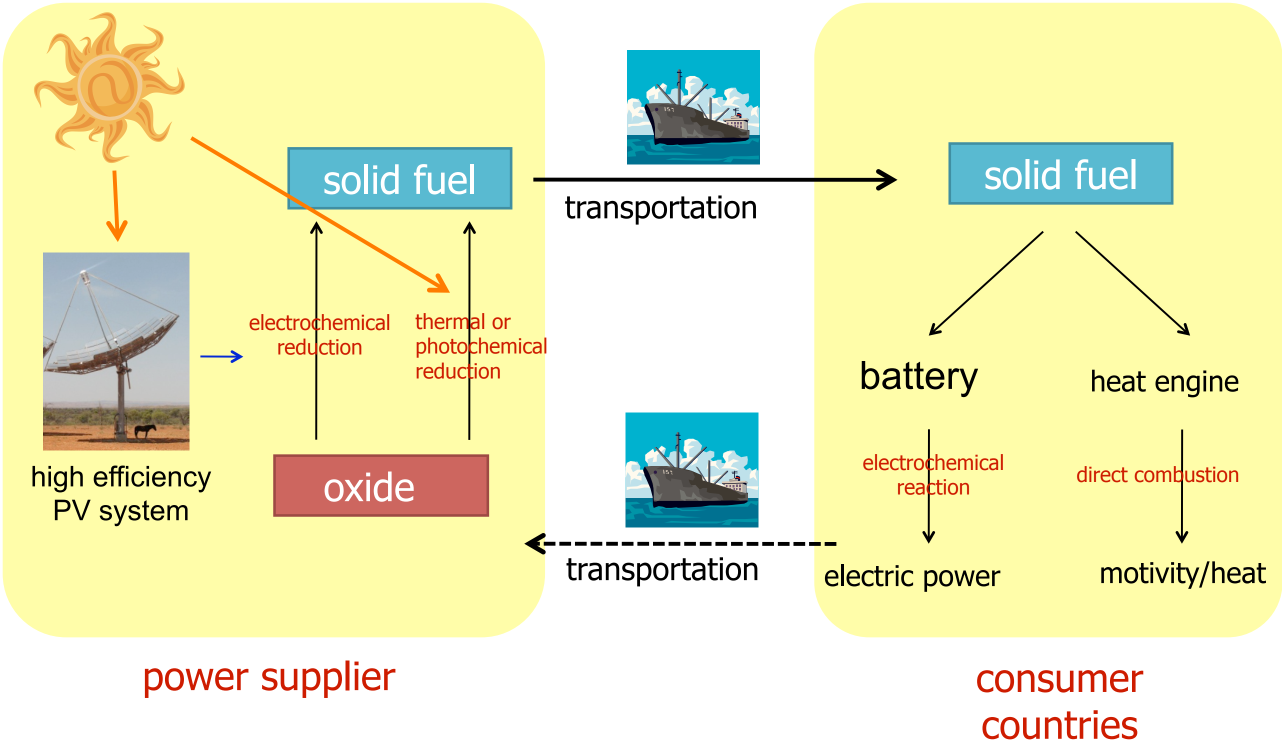
Strategy 1': Word-wide energy transport

GS+I
University of Tokyo



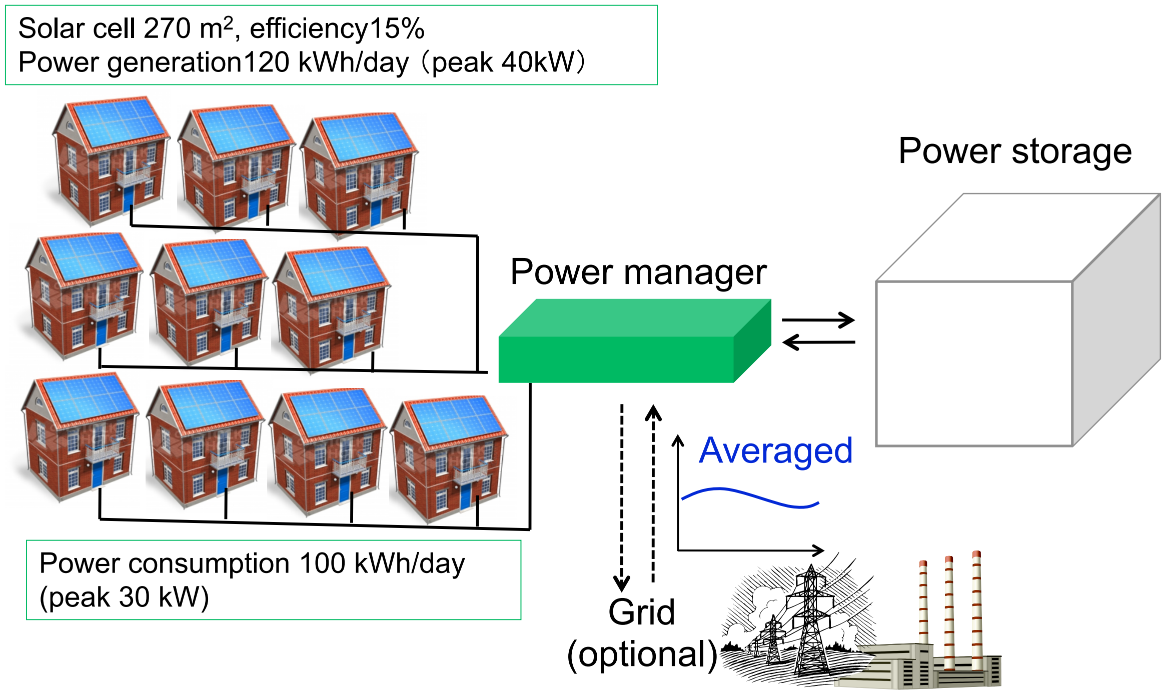
- Energy "delivery" to isolated countries.
- Storage media required: high energy density & stability

Energy transportation



Strategy 2: Autonomous distributed system

University of Tokyo



- Small-scale autonomous power grid
  - Minimized fluctuation in power in/out from/to larger grid.

Strategy 2': New infrastructure in developing countries

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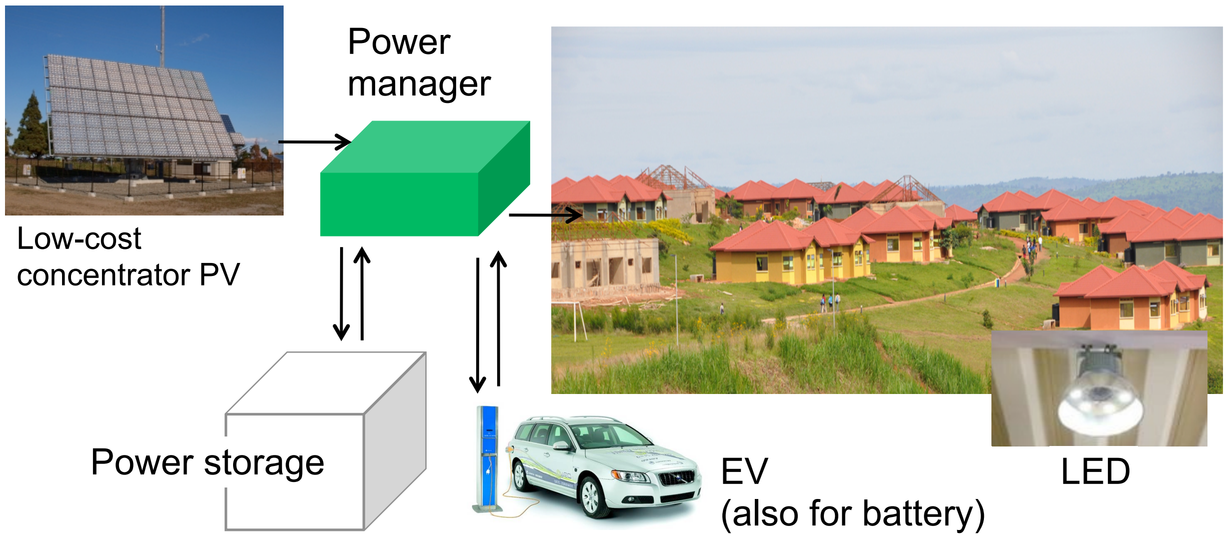

- New electricity infrastructure
  - PV + DC power storage + LED + EV: all DC system
  - Low-cost, autonomous system: no need for grid

Requirements to energy-storage media

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- Global scale
  - High-energy density
  - Easy to transport

- Miniature scale
  - Medium-high energy density
  - Safety in stockade
  - Easy to handle

Energy density in various storage media

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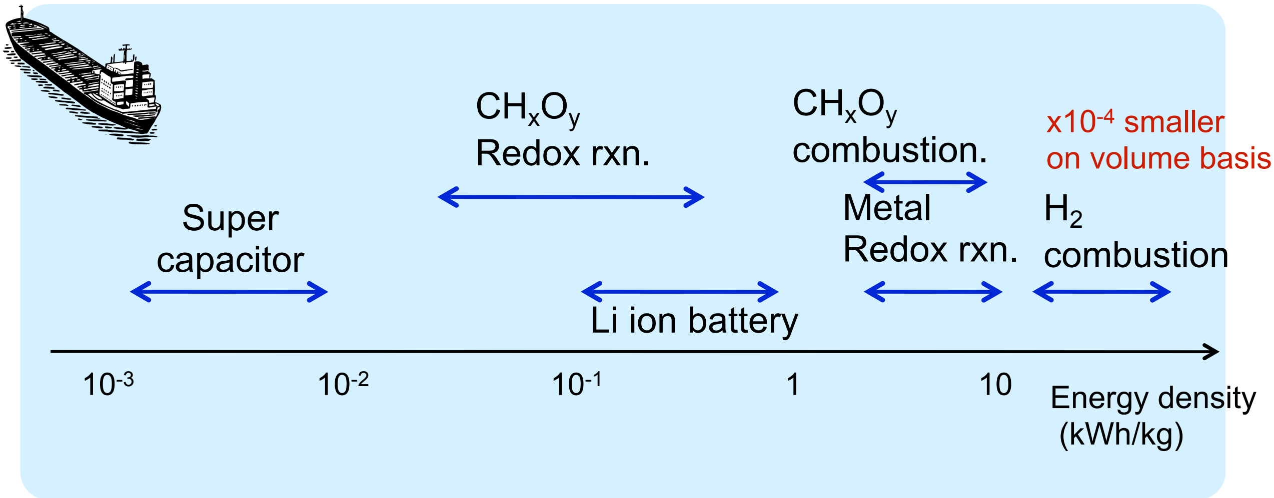

- Metal redox reaction
  - High energy density, ready for transport
- Hydrocarbon combustion
  - The same as existing fossil fuels
  - Solar synthesis of hydrocarbons is highly demanded.

Solar thermal reduction of metals

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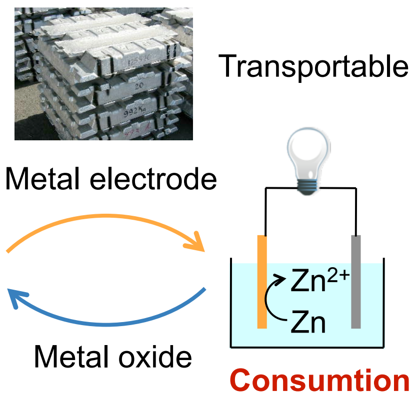
Energy storage system by metal reduction using direct heating



$$2ZnO \xrightarrow{heat} Zn + O_2$$

Direct transition by heating

Solar-electrochemical metal reduction

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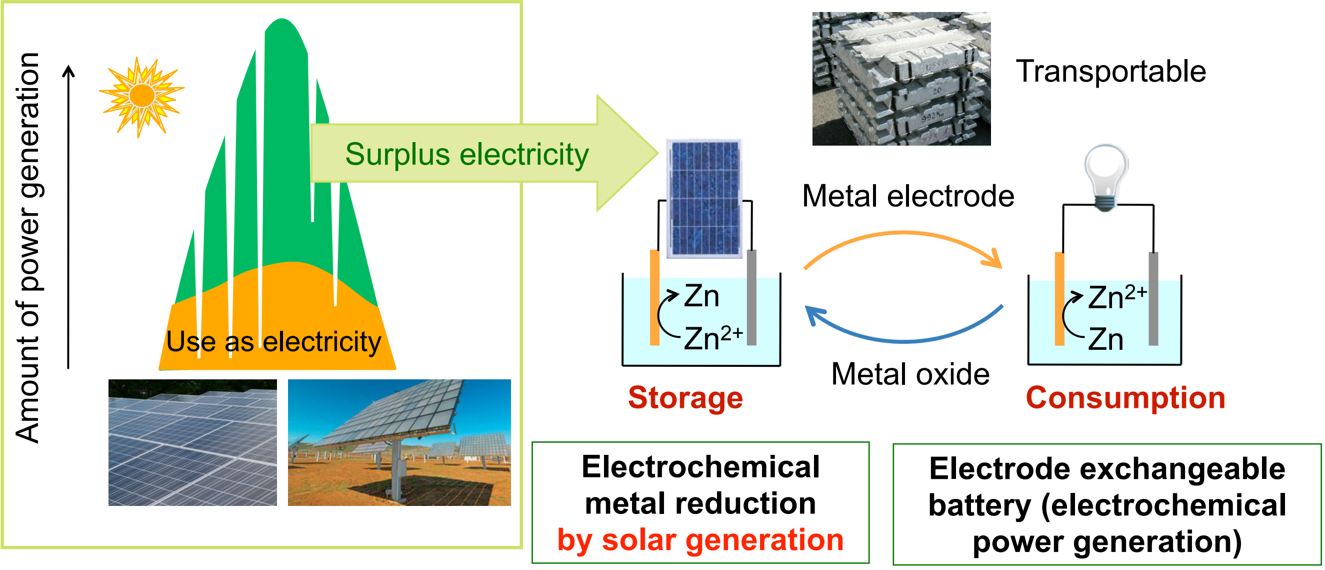
Energy storage system by metal oxidation and reduction using electricity



Photochemical hydrocarbon generation

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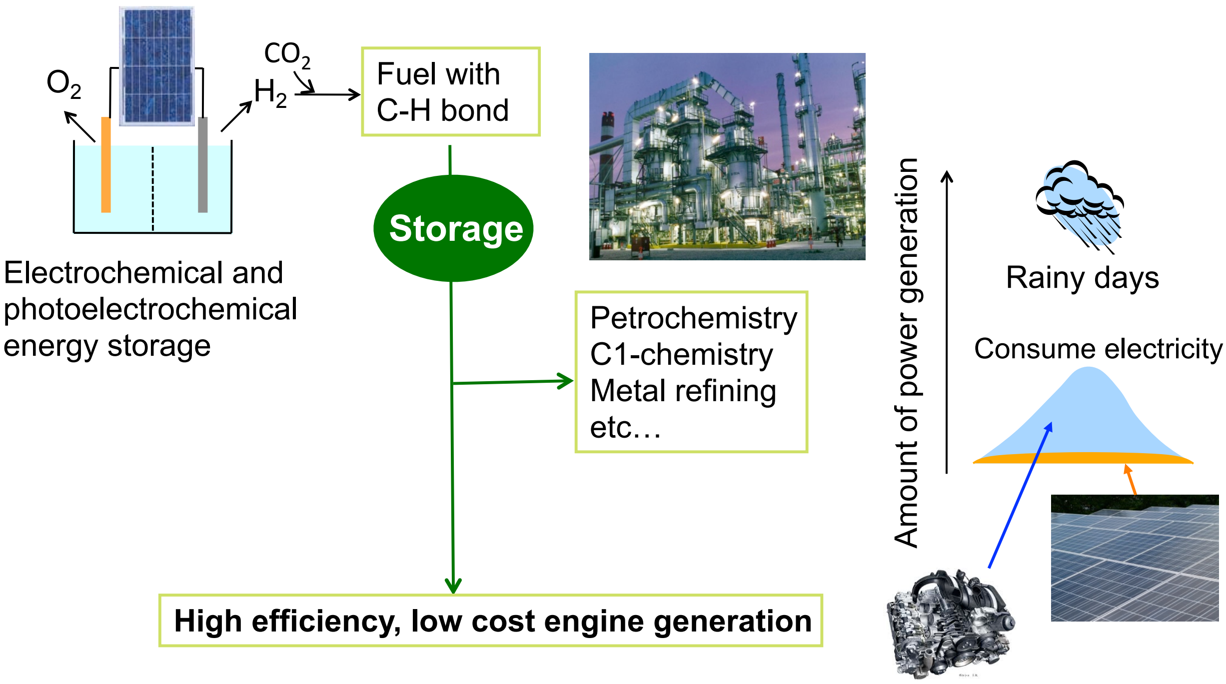
Energy storage system using direct conversion from sunlight to C-H chemicals



Out Future Vision

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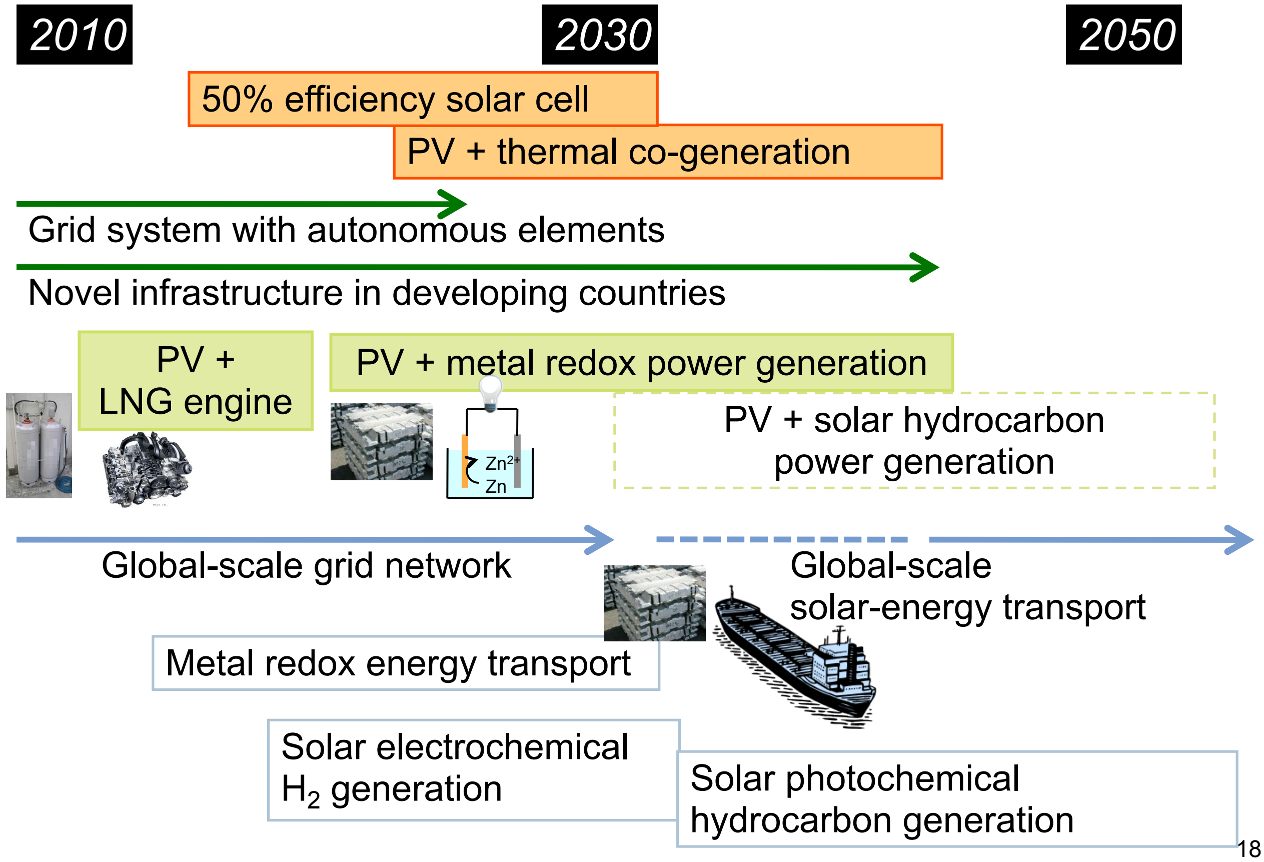
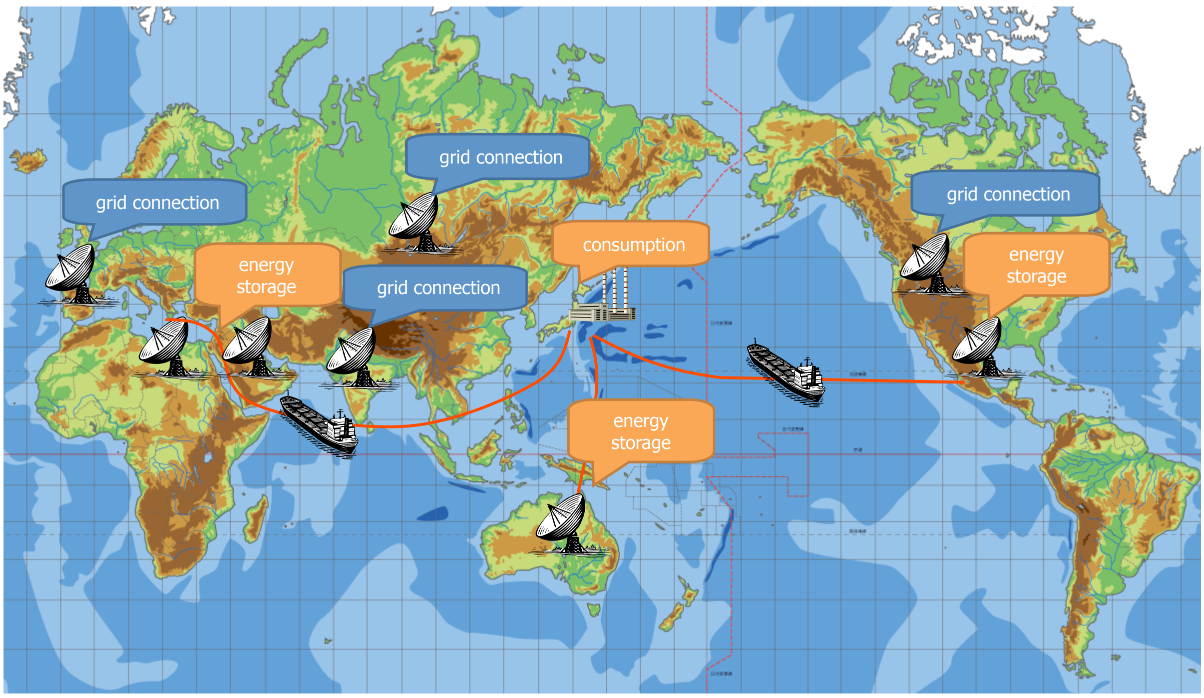


OUR GOAL: Carbon-free, clean, and fully-recyclable global energy system based on large-scale PV plants



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Thank you very much!

Research Center for Advanced Science and Technology (RCAST)
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