A Comparative LCA study on Potential of very-large scale PV Systems

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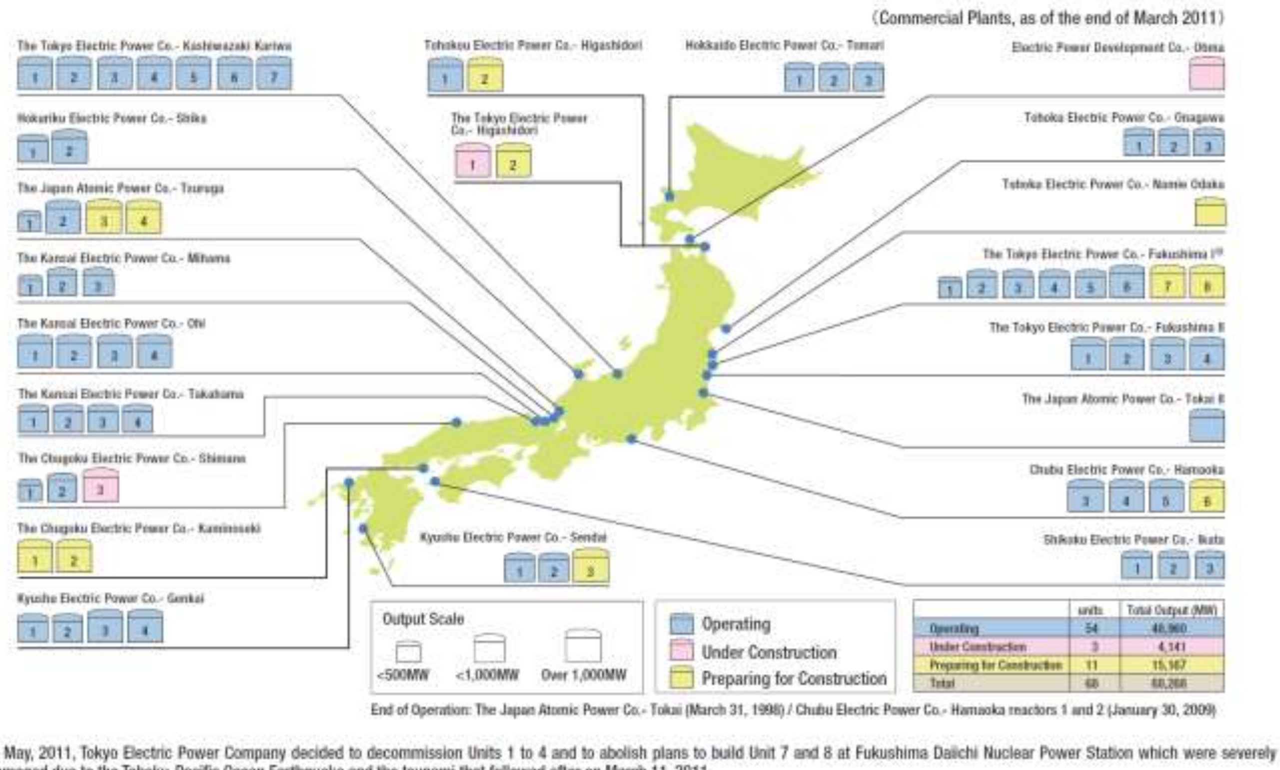
   - Energy from the Desert: Very Large Scale PV Power-State of the Art and Into the Future, Routledge, USA and Canada, 2012.

Nuclear power plants in Japan

- All nuclear power plant were stopped after the Great East Japan Earthquake, 11 March 2011.
- 3rd and 4th power plant in Ohi by Kansai Elec. was restarted in 5th and 21st of July 2012, and now in scheduled maintenance from 2nd and 15th of Sep 2013.



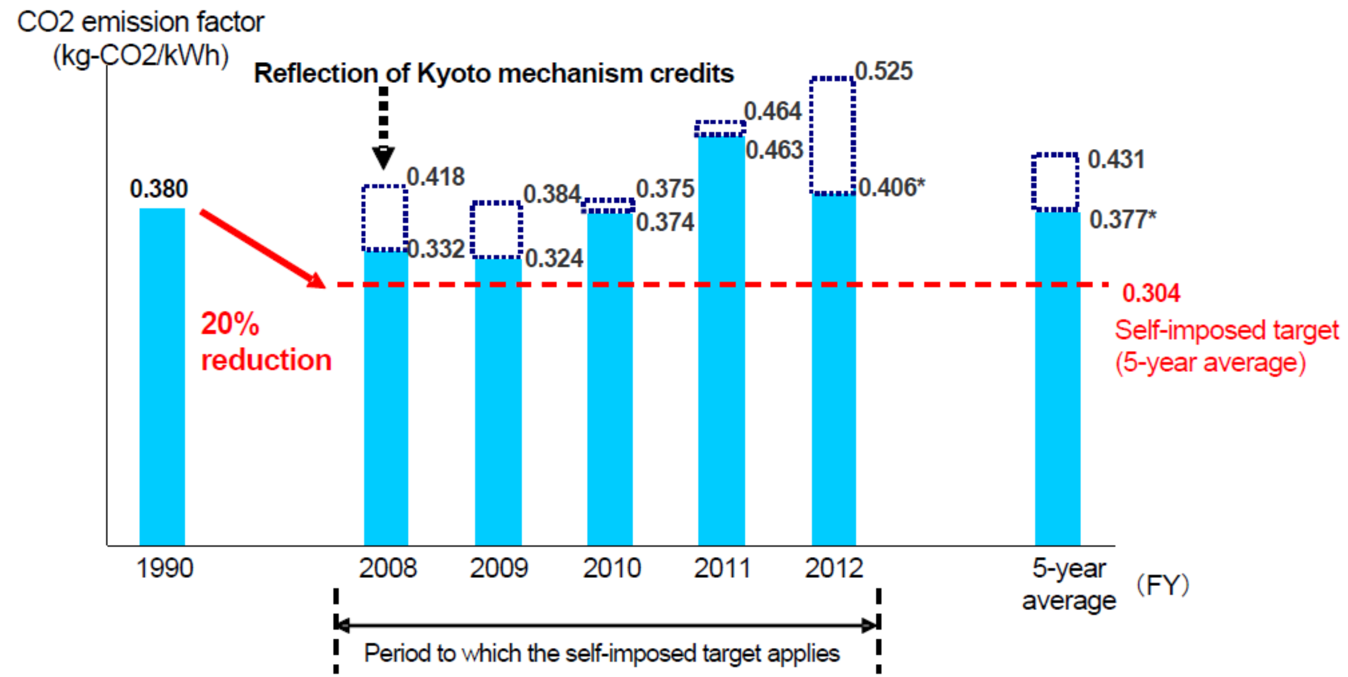
Statistics:
50 reactors
46GW
29% of elec.

Source: Graphical Flip-chart of Nuclear & Energy Related Topics, **The federation of electric Power Companies of Japan**, 2011

CO2 emissions rate of TEPCO in 2012

- **0,375 in 2010 -> 0,525 in 2012: 40% increase**
  - 0,374 -> 0,406 with Kyoto protocol

2. Our target CO2 emission factor and achievement



* Our FY 2012 CO2 emission factor related to our self-imposed target will be adjusted by reflecting a credit to be issued later for FY 2012, and is expected to be 0.396kg-CO2/kWh, which is lower than the value reported based on the "Act on Promotion of Global Warming Countermeasures" (0.406kg-CO2/kWh). 0.377kg-CO2/kWh shown as the 5-year average over the period to which the self-imposed target applies was calculated by reflecting a credit that will be issued later.

Press Release
(Jul 30,2013)

Stern Review

- Nicholas Stern
  - Chair of the Grantham Research Institute on Climate Change and the Environment at the London School of Economics
    Review on “The Economics of Climate Change”

- Stern Review on The Economics of Climate Change (2006)
  - Without action: 5% of GDP
    - or 20% including wider range of risks and impacts
  - With action: 1% of GDP

2. Basics and points for comparing LCA results

Energy payback time (EPBT)

$$EPBT = \frac{E_{mat} + E_{manf} + E_{trans} + E_{inst} + E_{EOL}}{(E_{agen} / n_G) - EO_{\&M}}$$

EPBT expresses the number of years the system takes to recover the initial energy consumption involved in its creation throughout its life cycle via its own energy production.

- E_{mat} : Primary energy demand to produce materials comprising PV system
- E_{manuf} : Primary energy demand to manufacture PV system
- E_{trans} : Primary energy demand to transport materials used during the life cycle
- E_{inst} : Primary energy demand to install the system
- E_{EOL} : Primary energy demand for end-of-life management
- E_{agen} : Annual electricity generation
- $E_{O\&M}$: Annual primary energy demand for operation and maintenance
- n_G : Grid efficiency, the average primary energy to electricity conversion efficiency at the demand side

Guideline by IEA/PVPS Task12, Report by Task8

CO2 emissions rate

Report by Task8

$$g_{co2} = \frac{G_{input}}{E_{gen} \cdot L_{PV}} = \frac{G_{man} + G_{trans} + G_{inst} + G_{use} + G_{decomm}}{E_{gen} \cdot L_{PV}}$$

- g_{co2} : life-cycle CO_2 emission intensity [**g-CO2eq/kWh**]
- G_{input} : CO_2 emissions during system life-cycle [g-CO2eq]
- G_{man} : CO_2 emissions due to manufacture of each system component [g-CO2eq]
- G_{trans} : CO_2 emissions for transportation of the system components [g-CO2eq]
- G_{inst} : CO_2 emissions for installation of the system components [g-CO2eq]
- G_{use} : CO_2 emissions during system operation and maintenance [g-CO2eq]
- G_{decomm}: CO_2 emissions during system decommissioning
- E_{gen} *:* Annual AC power generation [kWh]
- L_{PV} : lifetime of the PV system [years]

Calculation of LCA

Background data: From database (steel, electricity…)
Foreground data: Collecting from actual system and estimation

- **Software**
  - SimaPro

  - MiLCA

Database

- Ecoinvent
- LCA Society of Japan

For comparison of LCA

- **Condition/assumptions should be clear**
  - Lifetime
  - Irradiation data
  - Performance ratio
  - Degradation

- **Manufacturing location**
  - Efficiency of electricity generation
  - CO_2 emissions of electricity

- **g-CO_2, g-C, g-CO_2eq, or g-Ceq**

Lifetime

- **There is a guideline.**
- **But they are different between papers.**

PV modules	30 years for mature module technologies
Inverters	15 years for small plants or residential PV systems; 30 years with 10% part replacement every 10 years for large plants
Structure	30 years for rooftop- and facade-mounted units, and between 30 to 60 years for ground-mounted installations on metal supports. Sensitivity analysis should be performed.
Cabling	30 years

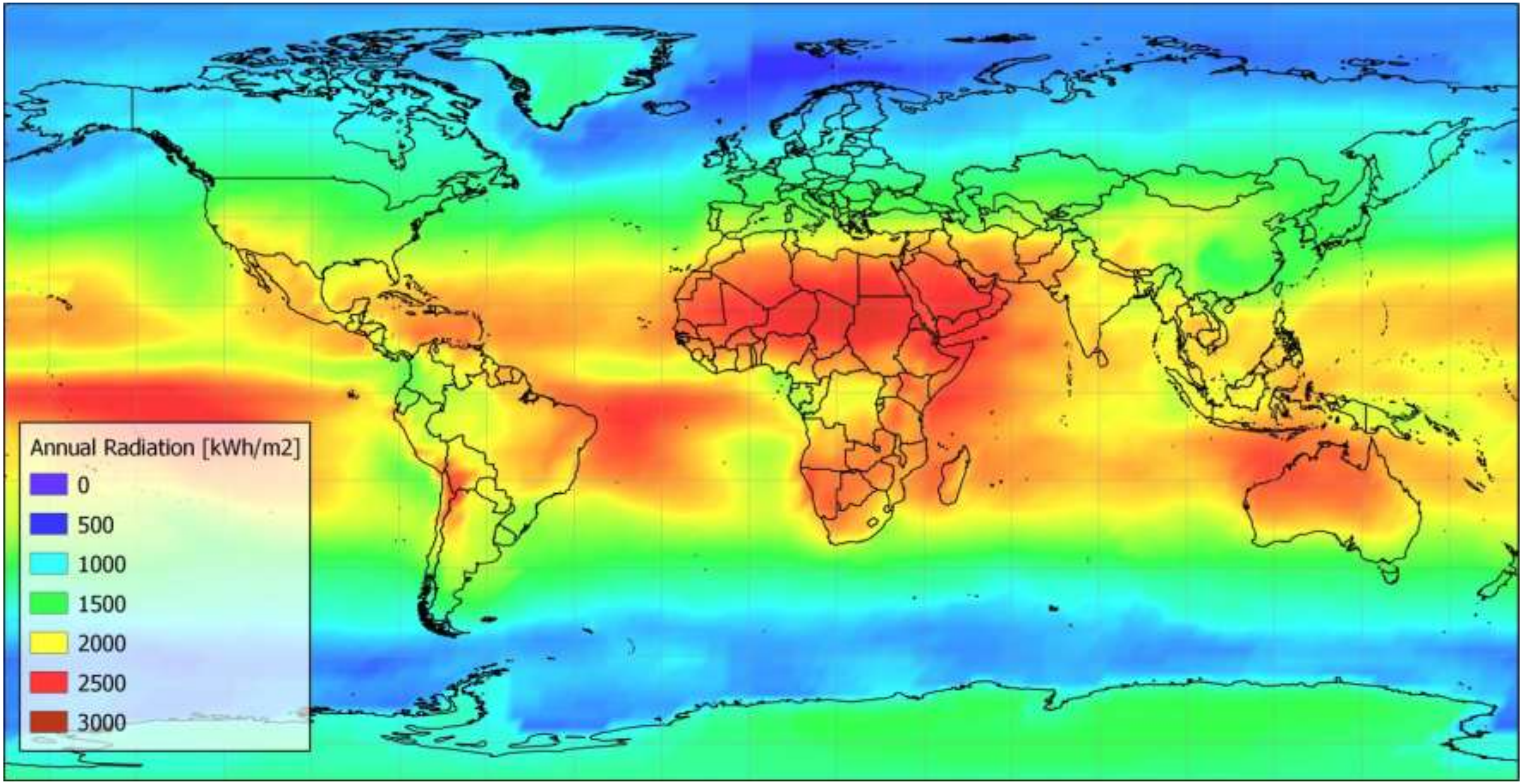
PV LCA guideline by IEA/PVPS Task12

Conditions/assumptions

- **Irradiation**
  - Local data at tilted angle
  - or 1700kWh/m2/year
- **Performance ratio (PR)**
  - 0,75 for rooftop-mounted
  - 0,80 for ground-mounted
- **Degradation**
  - 0,80 at the end of life-time
  - Crystalline-Si: 0,5%/year
  - Thin-film: 0,5%/year (or higher)

PV LCA guideline by IEA/PVPS Task12

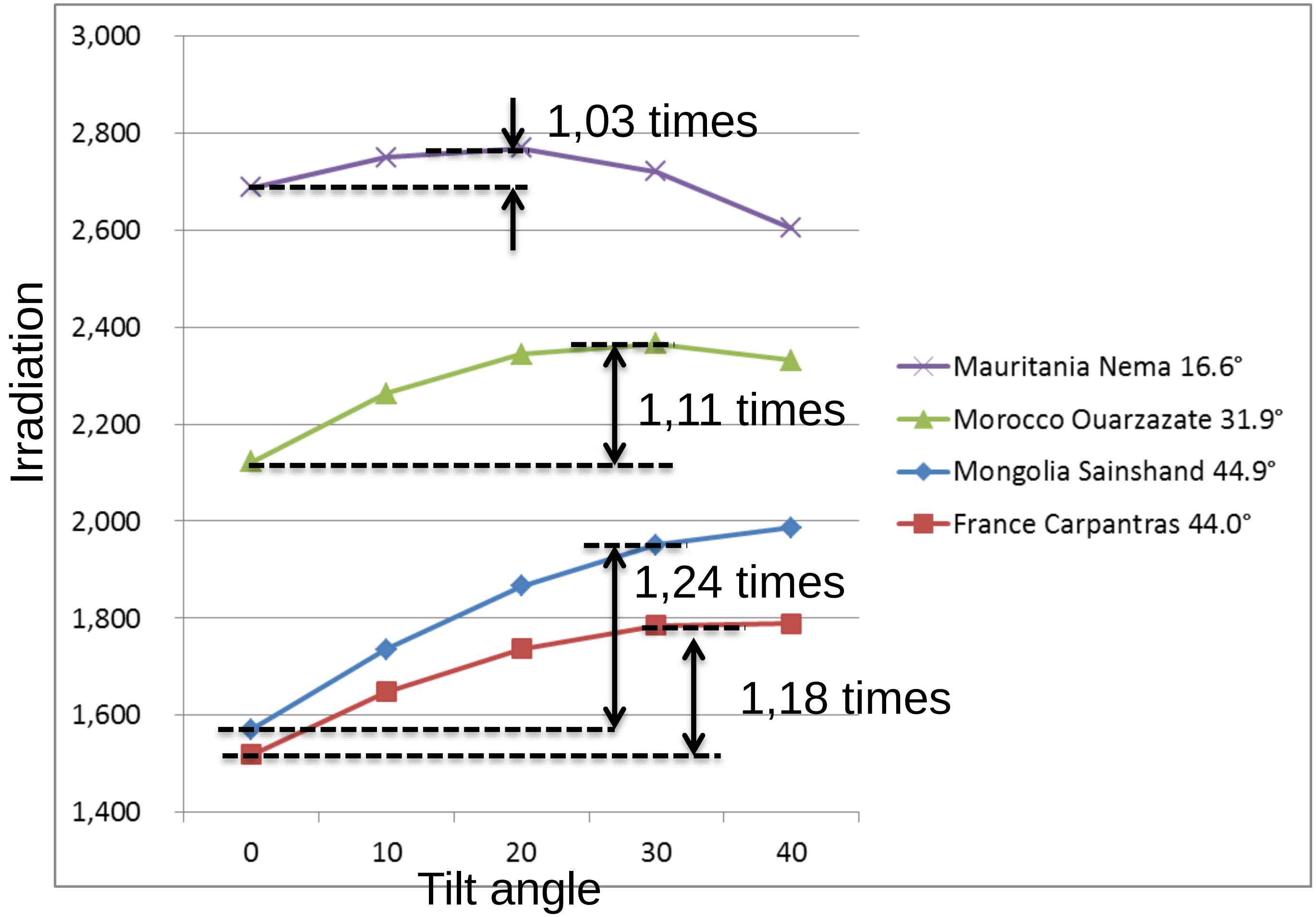
Differences of Irradiation



Data: NASA, SeaWiFS

Horizon vs tilted angle

- **Don't look only horizontal data**



Energy payback time (EPBT)

$$EPBT = \frac{E_{mat} + E_{manf} + E_{trans} + E_{inst} + E_{EOL}}{(E_{agen} / n_G) - EO_{\&M}}$$

- η_G : Grid efficiency, the average primary energy to electricity conversion efficiency at the demand side

- All data will be calculated in primary energy base.
- Electricity output of PV system will be calculated in primary energy too.
- However, electricity conversion efficiency is depends on location.

Guideline by IEA/PVPS Task12, Report by Task8

Power generation efficiency by countries

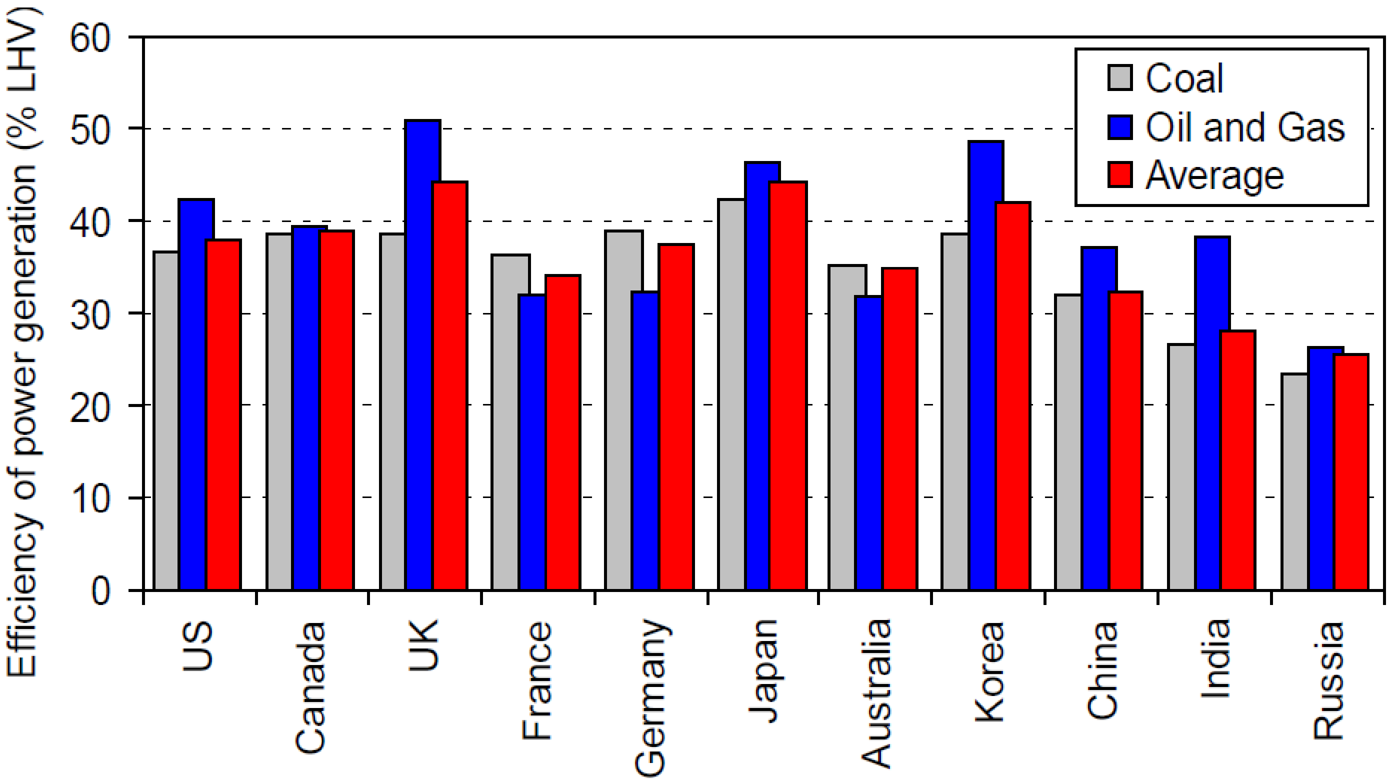
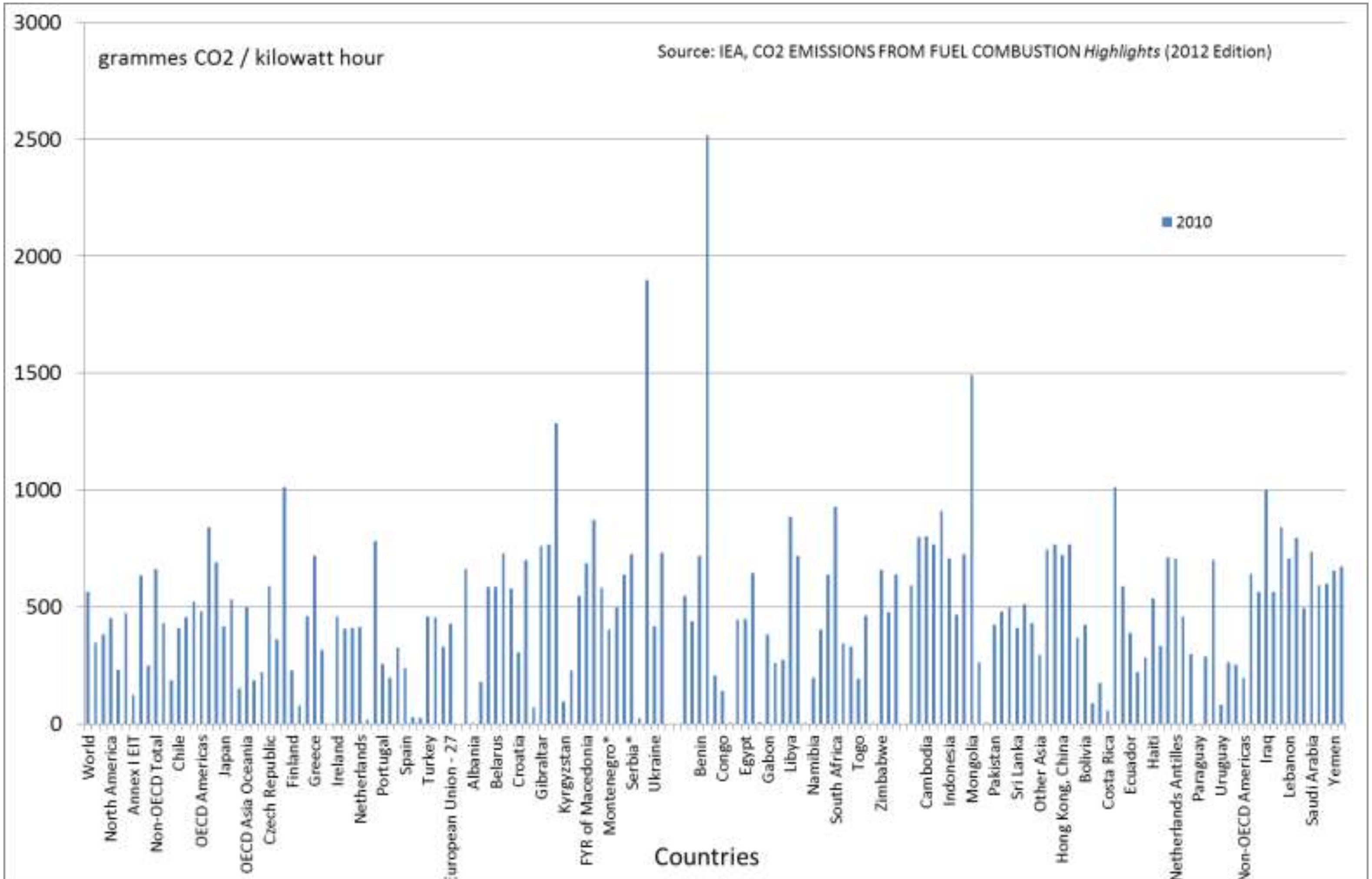


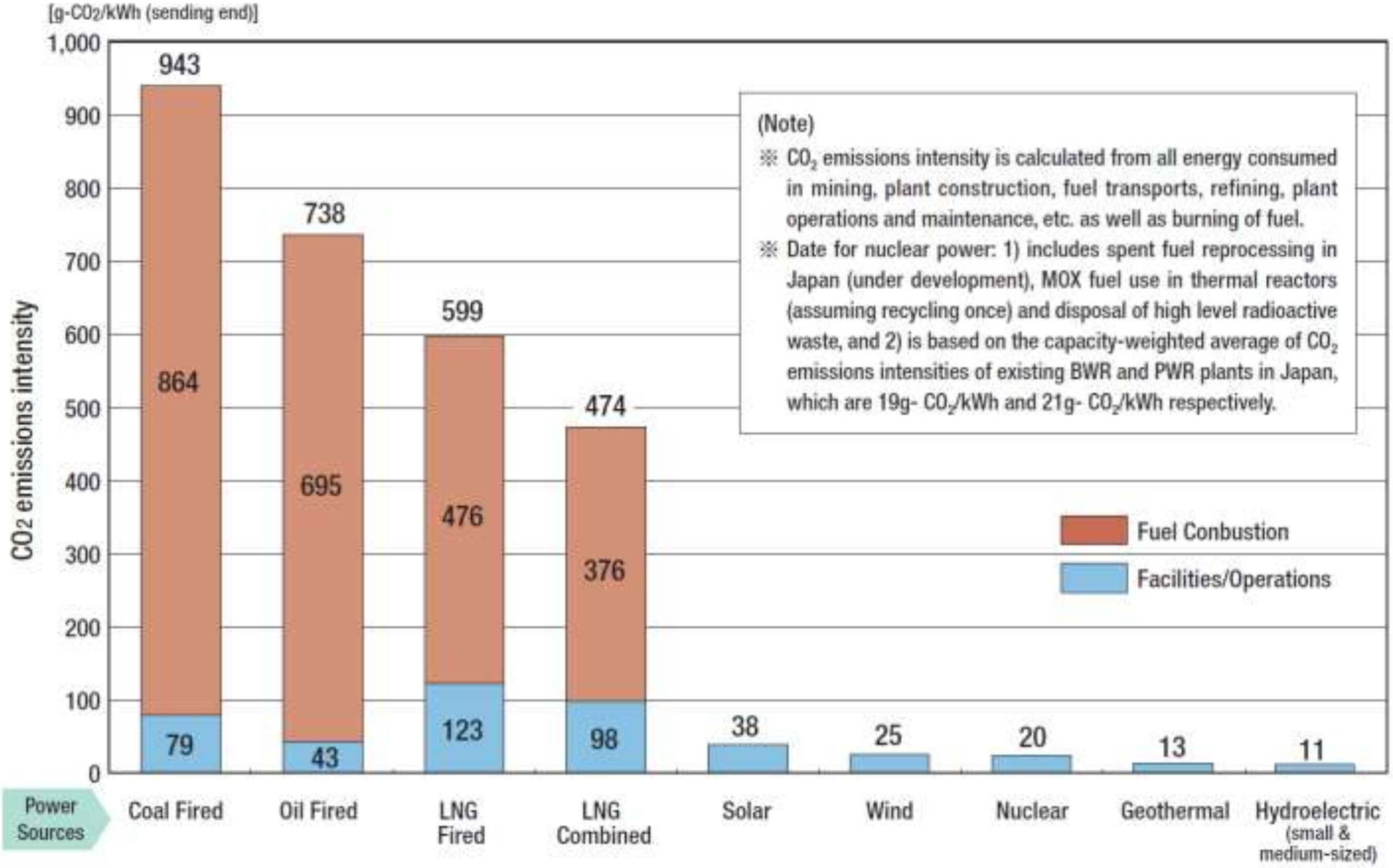
図 1-1　2005 年における各国の発電効率の比較（CHP を含む）

Source: Research Institute of Innovative Technology for the Earth

CO2 emissions per electricity generation



CO2 emissions per kWh by fuel



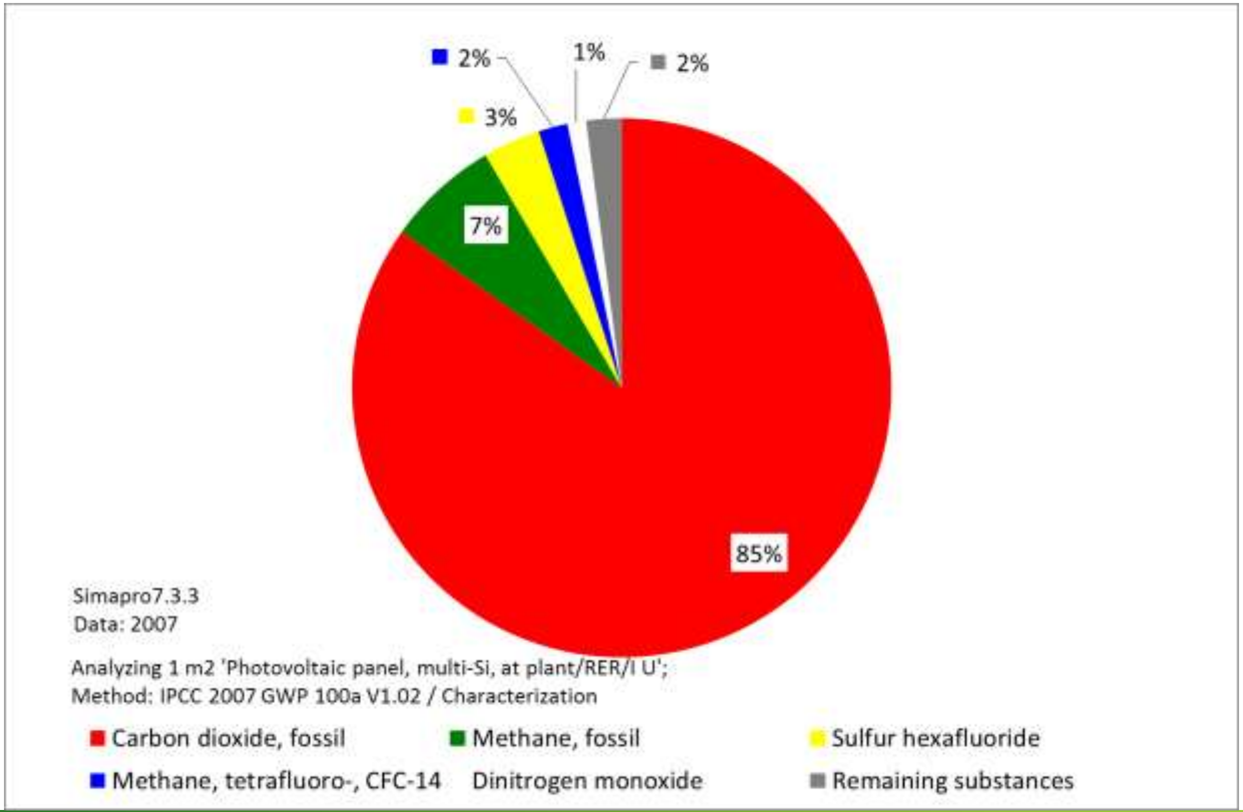
Source: Graphical Flip-chart of Nuclear & Energy Related Topics, The federation of electric Power Companies of Japan, 2011
Data: CRIEPI: Central Research Institute of Electric Power Industry, Evaluation of Life Cycle CO2 Emissions of Power Generation Technologies – Update for State-fo-the art plants – , Eiichi Imamura and Koji Nagano, 2010

ceatech FROM RESEARCH TO INDUSTRY

ines NATIONAL INSTITUTE OF SOLAR ENERGY

Unit of green house gases

- **CO2 or C?**
  - CO2 = 44/12 x C = 3,7 x C “Calculation of Molecule”
- **CO2 or CO2eq?**
  - CO2 only or including other GHGs.



Points to read LCA results

- **Condition of assumptions should be clear**
  - Lifetime
  - Irradiation data
  - Performance ratio
  - Degradation

- **Manufacturing location**
  - CO_2 emissions of Electricity

- **g-CO_2, g-C, g-CO_2eq, or g-Ceq**

Masakazu Ito, Mitsuru Kudo, Masashi Nagura, Kosuke Kurokawa, A comparative study on life cycle analysis of 20 different PV modules installed at the Hokuto mega-solar plant, Progress in Photovoltaics: Research and Application, 19 (2011) 878-886.

3. Example of research result

A comparative study on life cycle analysis of 20 different PV modules installed at the Hokuto mega-solar plant

Background – About the Project –

- **NEDO started a 5 year MW system project in 2006**
  - Focusing on generating high-quality electricity which does not affect grid voltage, frequency and waveform mainly.
- **Hokuto site (Our team)**
  - 2 MW system
  - Development of large capacity inverter
  - To find suitable PV module for LSPV
  - Environmental study
- **Wakkanai site**
  - 5 MW system
  - Research on electricity stability with battery
  - and so on

NEDO: New Energy and Industrial Technology Development Organization

About – the Hokuto city–

- The Hokuto city has the longest duration of sunshine in Japan
- Close to Tokyo and easy access from highway

An aerial photo of the mega-solar system

撮影：北杜市

Purposes – Environmental Study on PV –

- **Purposes**
  1. To find environmental-friendly design (PVSEC-17)
  2. To evaluate environmental effect of Large PV systems by LCA to know if it can resolve environment issues and how much potential it have.
  3. To apply real energy yield.
     This is important to calculate Energy payback time and CO_2 emissions rate.
- **Approach**
  - Summarize 'Real' input and output data of the PV systems
  - Calculate CO_2 emission and Energy input and output by using real system data

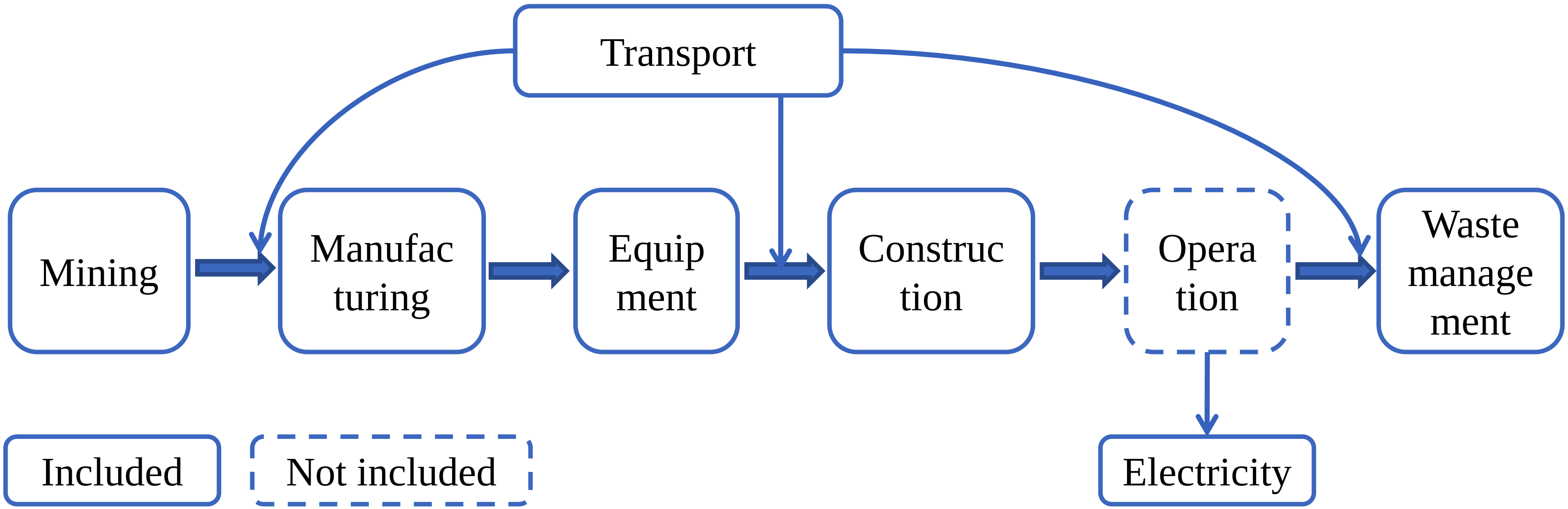
PV modules installed at the site

Type	Nominal power [W]	Module efficiency [%]	Capacity [kW]
A1: sc-Si	84	13.2	30
A2: a-Si/sc-Si	186	15.9	30
A3: sc-Si	160	12.6	10
A4: sc-Si	160	12.6	10
A5: sc-Si	150	11.8	10
A6: sc-Si	200	12.0	30
A7: sc-Si	173	12.0	30
B1: mc-Si	167	12.6	30
B2: mc-Si	179	14.0	100
B4: mc-Si	167	13.2	30
B5: mc-Si	180	12.3	10
B6: mc-Si	190	13.0	10
B7: mc-Si	240	12.4	30
B8: mc-Si	170	13.5	10
C1:a-Si	60	6.1	30
C2: μc-Si/a-Si	110	8.8	10
C3: μc-Si/a-Si	130	8.3	10
D1: CIS	70	8.8	30
D2: CIS	125	11.2	3

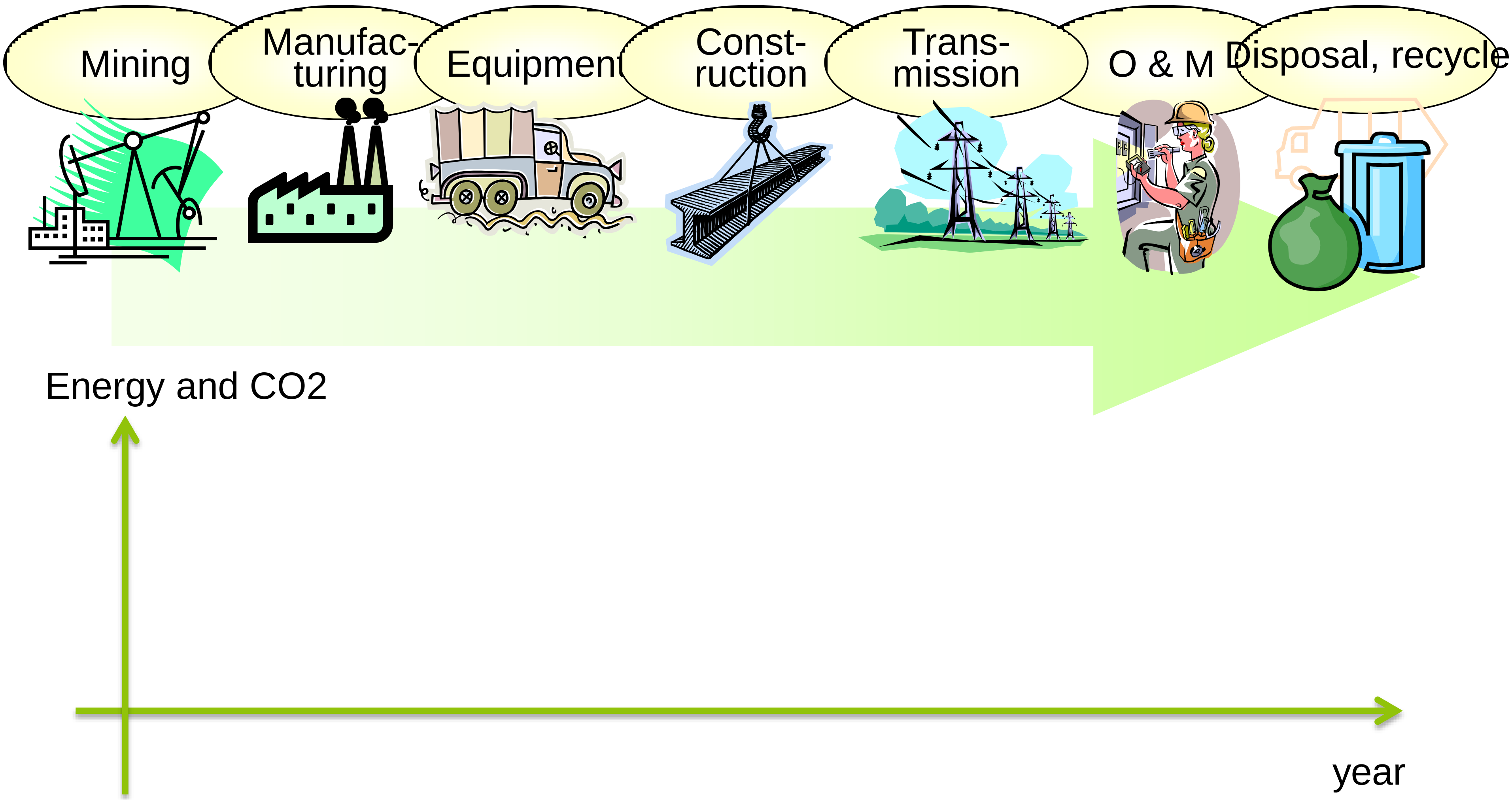
Balance of System for LCA

- **Inverter: 10 kW for each 10kW array unit**
- **Array: Galvanized steel, 30° tilt angle,**
  30 m/s wind speed
- **Foundation: Pile**
- **Cable**
- **Junction box**
- **Transformer**
- **etc…**

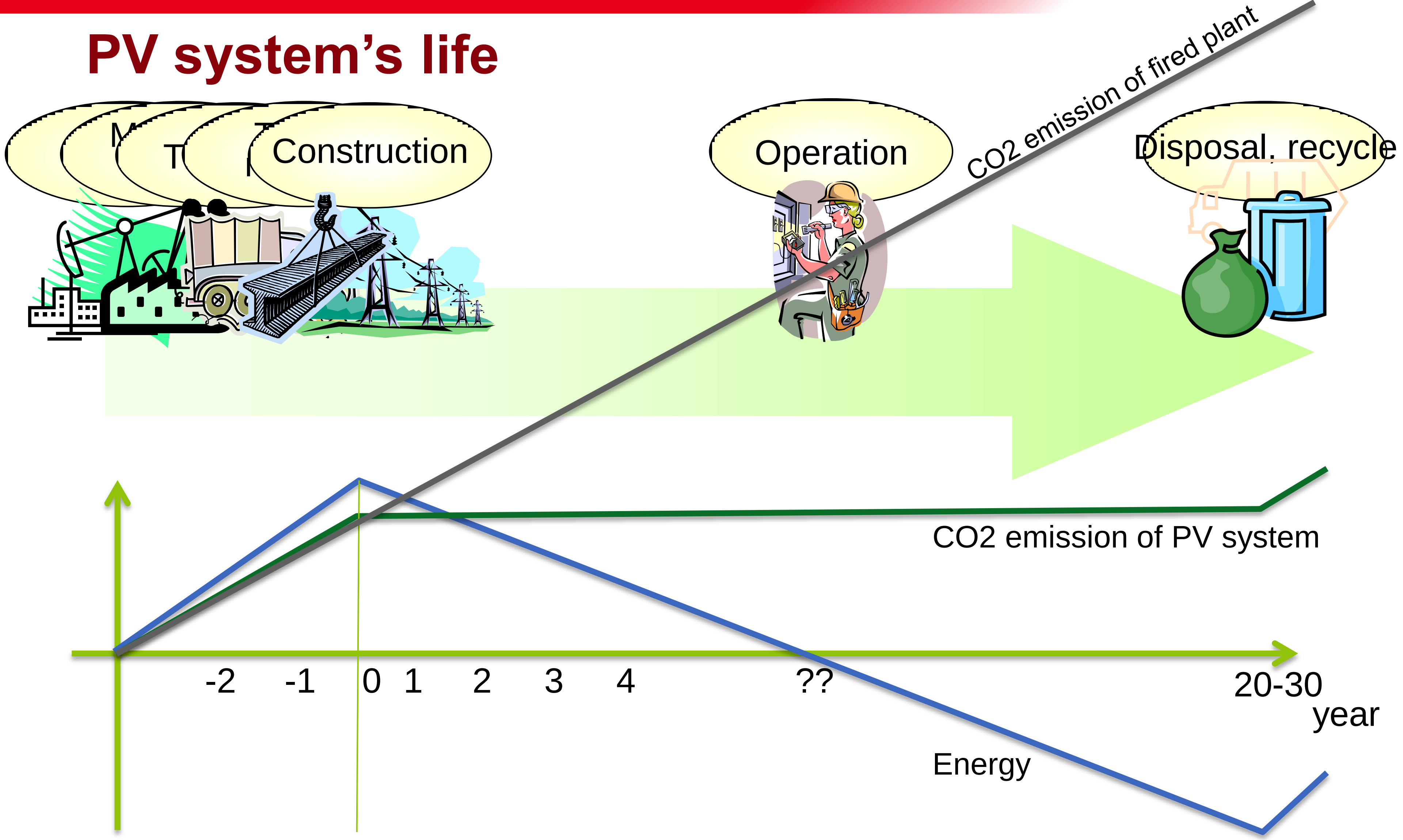
Boundary of LCA



PV system’s life



PV system's life



Assumptions of this study

- **PV module**
  - Put 6 types of PV LCA data by MJ/m2 or kg-CO2/m2 from reference
  - One PV technology per one data
  - Each PV modules are assumed that capacity is 600 kW
- **Inverter**
  - From database
- **Other BOS**
  - Actual amount of kg
  - LCA data is from database
- **Annual power generation**
  - Actual output (one year)
  - Considering fixed degradation rate

References for LCA of the 20 PV systems

	PV module, Inverter	Other components
Mining	NEDO database	LCA database
Manufacturing	NEDO database	LCA database
Transport	Actual km data	LCA database
Construction	Actual data	
Waste management	LCA database	LCA database

PV modules of NEDO database is assumed to be produced in Japan

LCA database: JLCA-LCA database 2009 Fy 1st Edition, JEMAI LCA Pro, Japan Environmental Management Association for Industry

Annual yield of each PV systems

Type	Yeild [kWh/kW]
A1: sc-Si	1412
A2: a-Si/sc-Si	1397
A3: sc-Si	1487
A4: sc-Si	1319
A5: sc-Si	1420
A6: sc-Si	1428
A7: sc-Si	1383
B1: mc-Si	1338
B2: mc-Si	1426
B4: mc-Si	1419
B5: mc-Si	1500
B6: mc-Si	1451
B7: mc-Si	1404
B8: mc-Si	1440
C1:a-Si	1295
C2:c-Si/a-Si	1337
C3:a-Si	1333
D1:CIS	1538
D2:CIS	1494

(Before considering degradation)

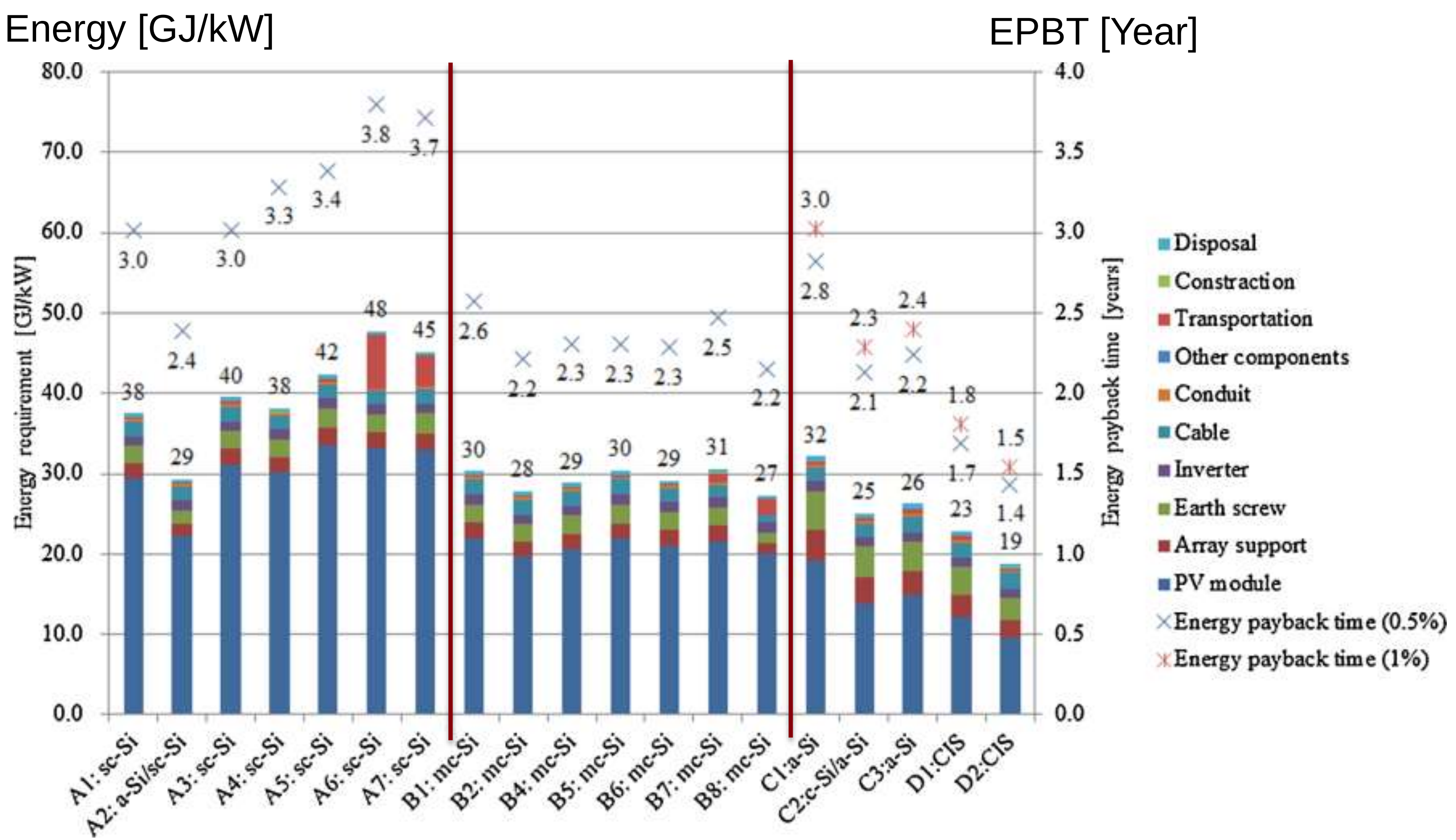
- **kW is not from label but by flash test of each PV modules**
- **0.5 % degradation is also considered. (It maybe small for thin-film)**
- **Life-time : 30 years for all component**
  Life-time of inverter (10 kW) is 15 years

Assumptions of LCA data of the system equipment

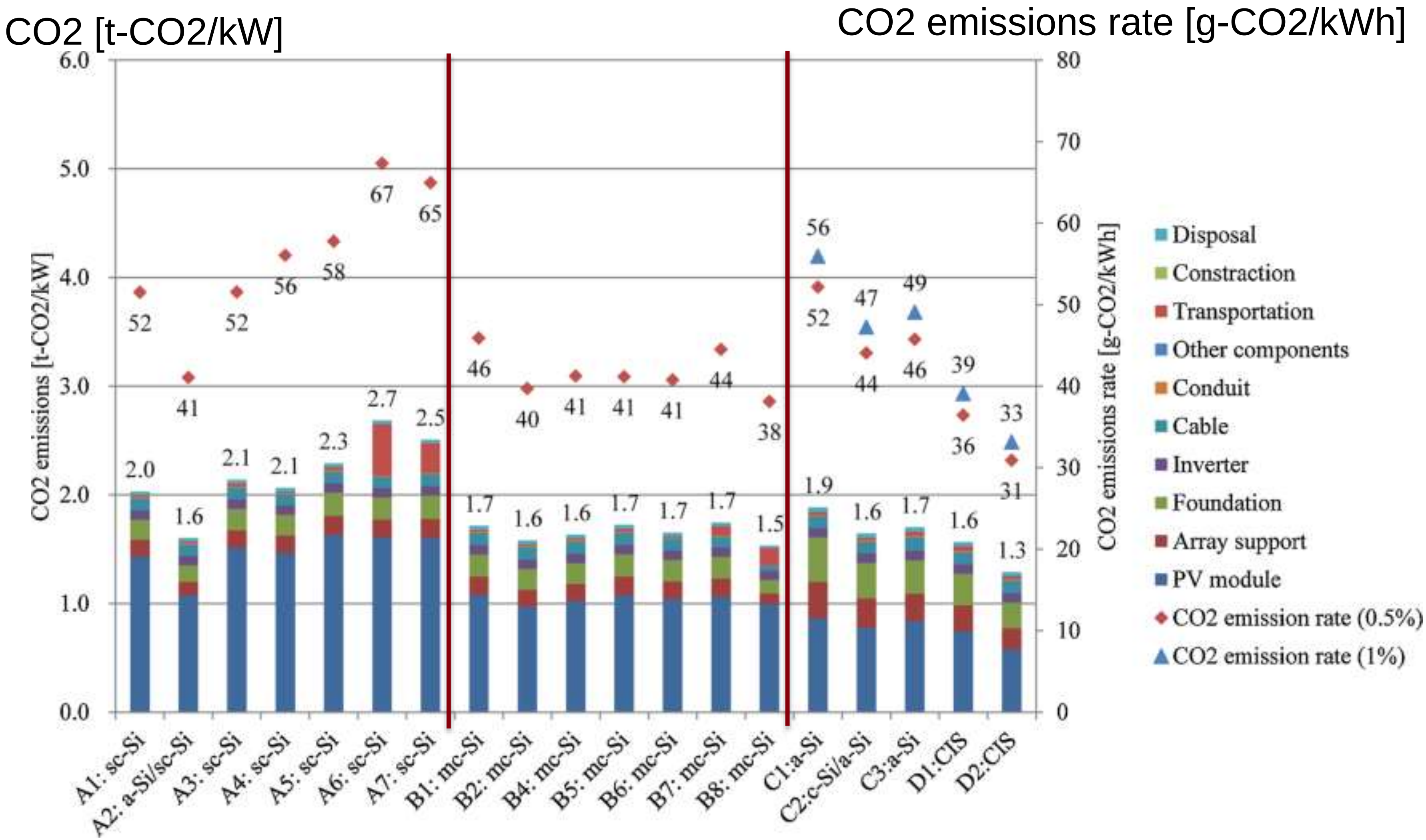
	Module efficiency in reference	Energy requirement	CO_2 emissions
PV module (in 2008)			
sc-Si	14.3 %	3986 MJ/m^2	193.5 $kg\text{-}CO_2/m^2$
a-Si/sc-Si	16.6 %	3679 MJ/m^2	178.0 $kg\text{-}CO_2/m^2$
mc-Si	13.9 %	2737 MJ/m^2	135.2 $kg\text{-}CO_2/m^2$
a-Si (in 2000)	-	1202 MJ/m^2	54.3 $kg\text{-}CO_2/m^2$
a-Si/μc-Si	8.6 %	1210 MJ/m^2	67.8 $kg\text{-}CO_2/m^2$
CIS	10.1%	1105 MJ/m^2	67.5 $kg\text{-}CO_2/m^2$
10 kW inverter		0.57 GJ/kW	43 $kg\text{-}CO_2/kW$
Cable and conduit		1068 GJ/600kW	62.0 $t\text{-}CO_2/600kW$
Array (Galvanized steel)		22.5 GJ/t	1.91 $t\text{-}CO_2/t$

Other small components, junction box, transformer, etc. are also included.

Energy requirement and EPBT

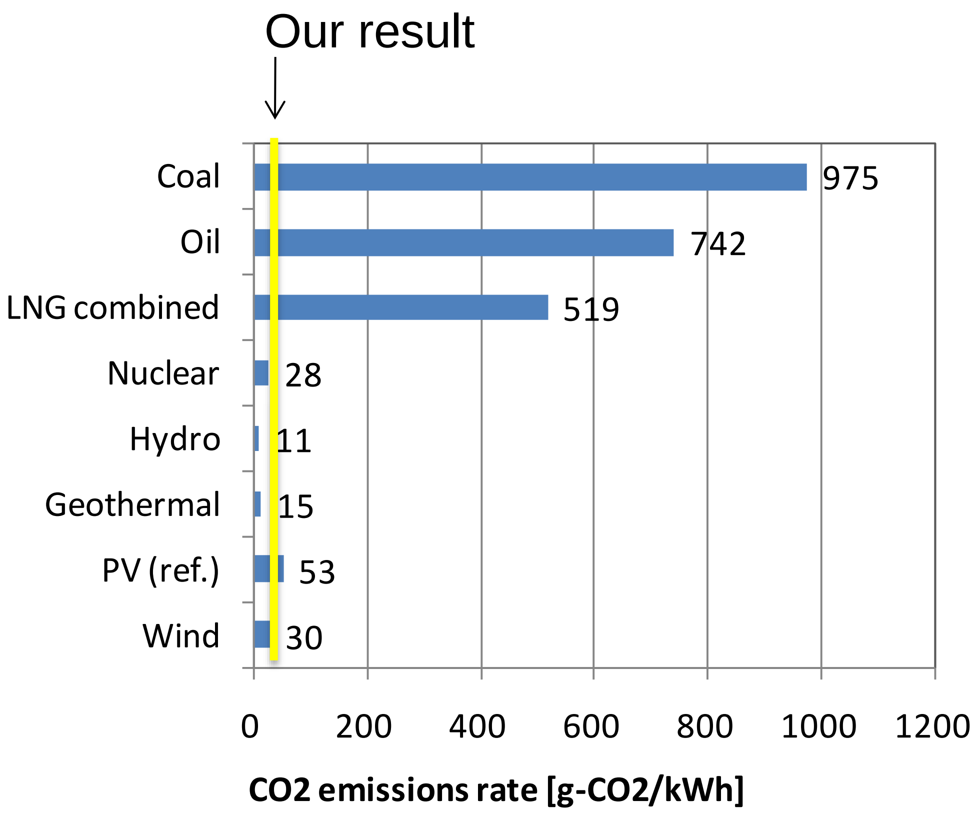


CO2 emissions and CO2 emissions rate



Comparison of CO2 emissions

- CO_2 emission rate of the PV systems are much smaller than conventional fossil fuel energies.



Reference: CRIEPI, Evaluation of power source by LC-CO_2 (Japanese)

Conclusions

- **In this study, the authors evaluated the Mega-solar system with 20 different PV modules by LCA approach.**
- **The mc-Si and CIS got good result.**
  - mc-Si and CIS PV module have high efficiency and lower energy requirement.
- **Installed sc-Si did not get good result at now**
  - Efficiency is lower than usual. (11.8~13.2%)
- **However, the CO_2 emission rate is much lower than fossil power plant. Therefore, they have potentials to mitigate global warming.**

Keiichi Komoto, Christian Breyer, Edwin Cunow, Karim Megherbi, David Faiman, Peter van der Vleuten, Energy from the Desert: Very Large Scale PV Power-State of the Art and Into the Future, Routledge, USA and Canada, 2012.

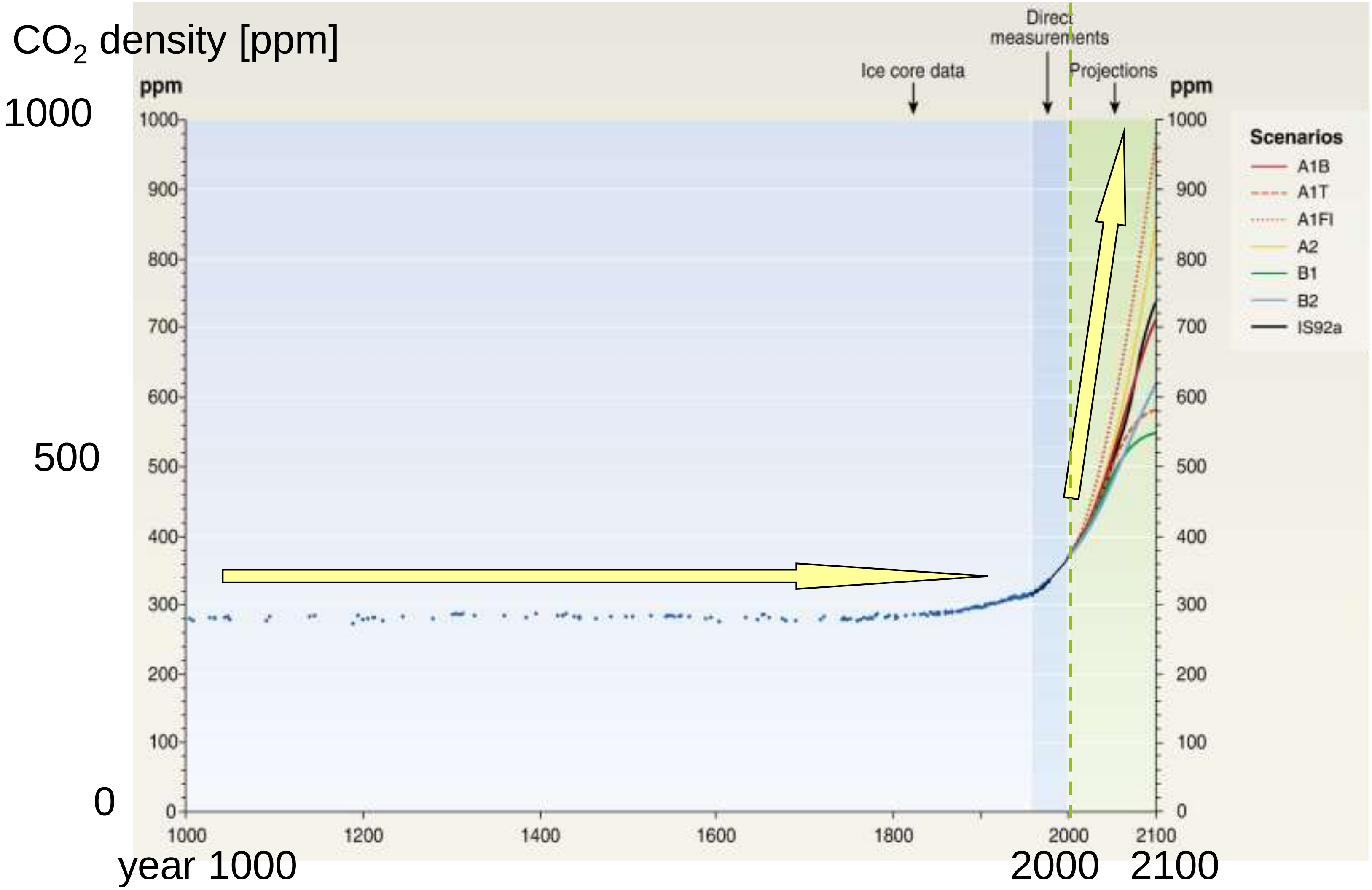
4. Example of research result

Life-Cycle Analyses of Very-Large Scale PV Systems using five Types of PV Modules


10 years ago:
OUR FUTURE DREAM !
Nowadays:
More Realistic !
VLS-PV

Transition and Perspective of CO_2 (IPCC)

CO_2 density [ppm]

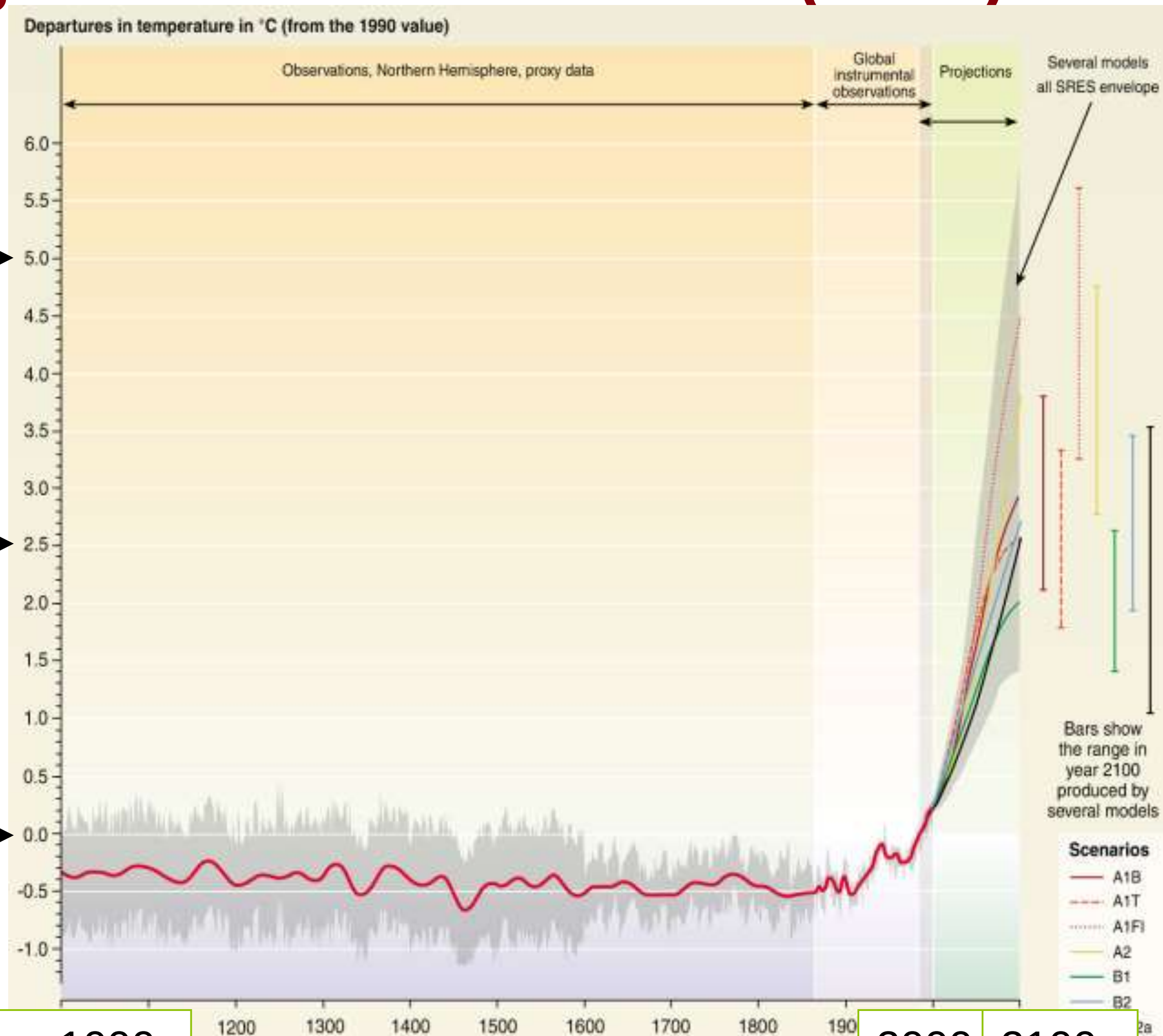


Warming on Surface of the Earth (IPCC)

+5°C

+2.5°C

1990 Average



year 1000

2000

2100

Evaluation scheme of LCA

1
- Designing of array and foundation

2
- Estimation of in-plain irradiation

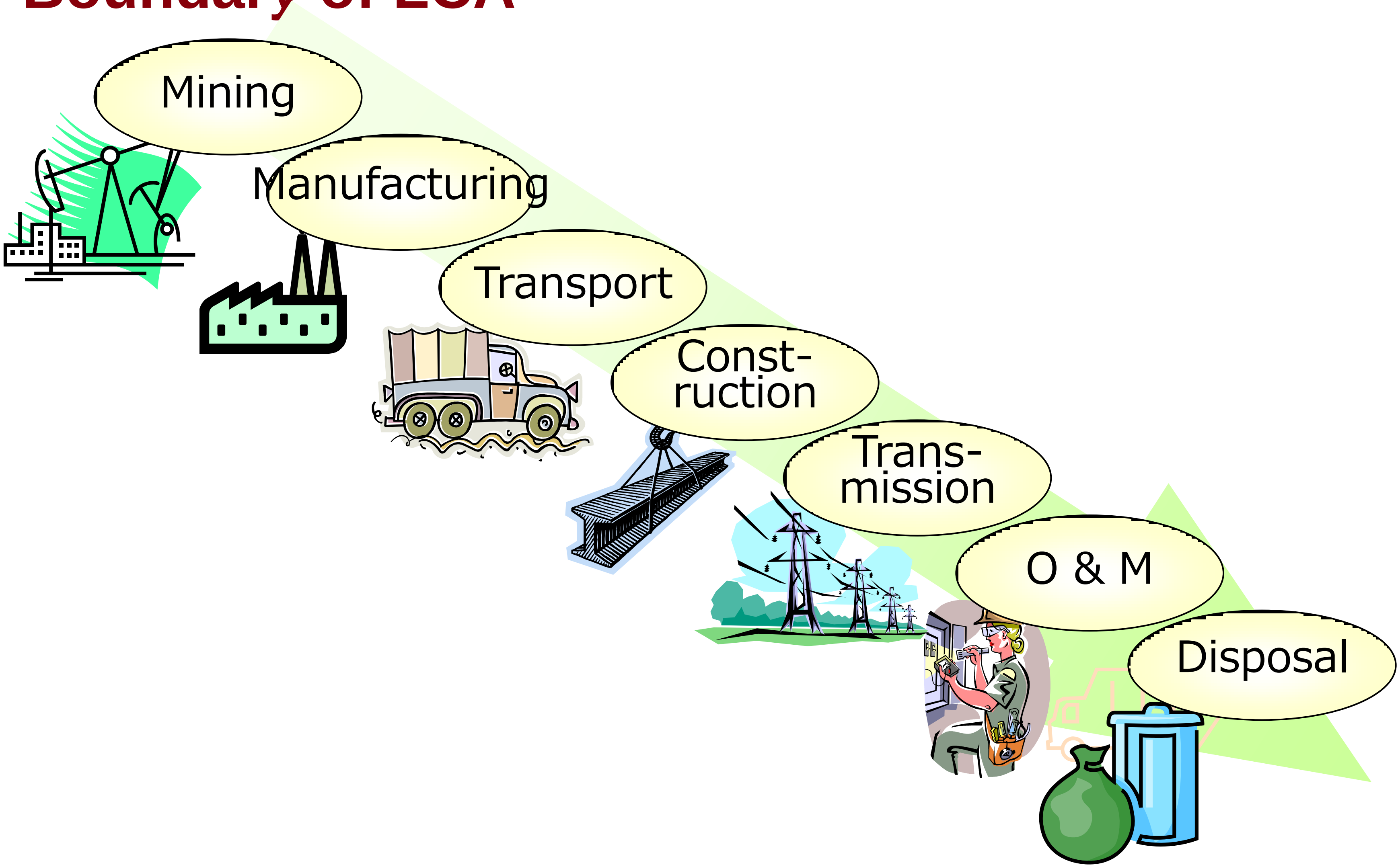
3
- Calculation of output

4
- Transmission loss

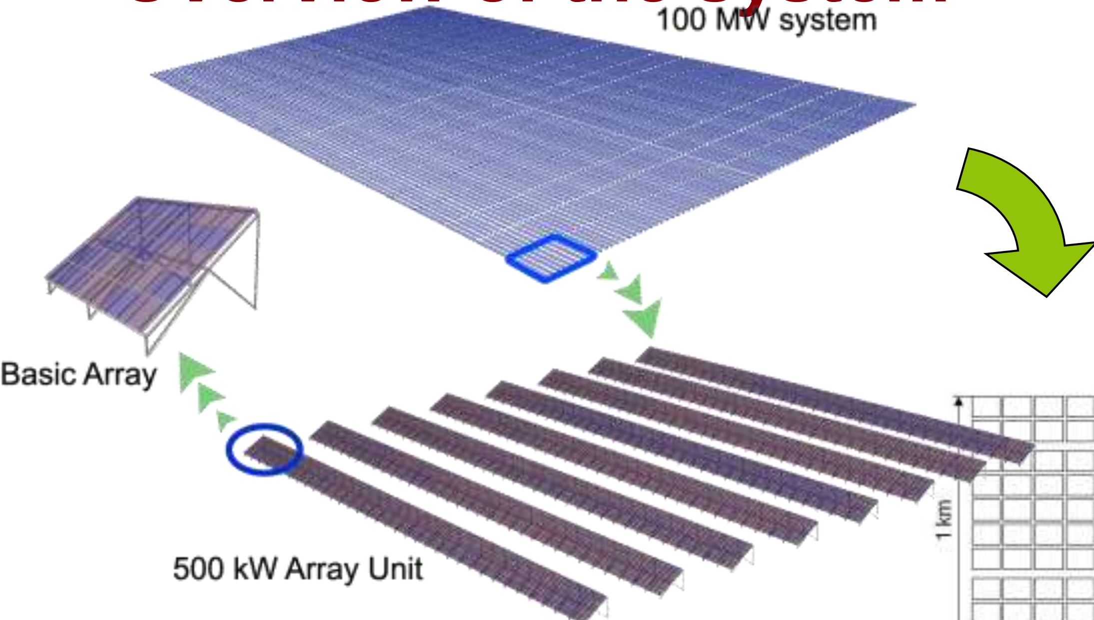
5
- Life-Cycle Analysis

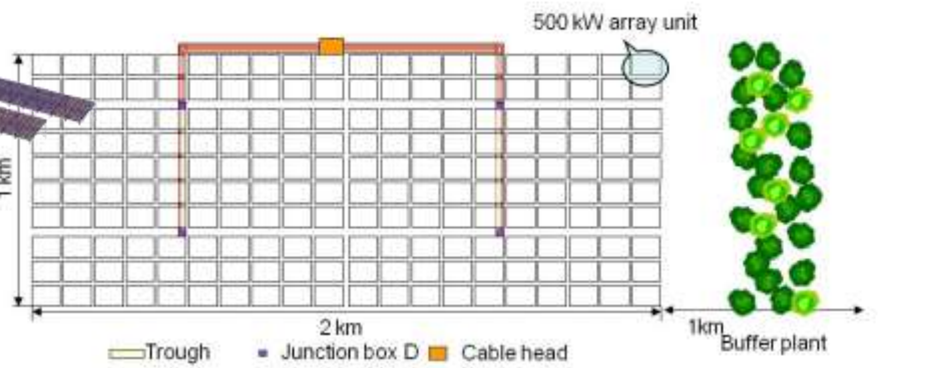
6
- Sensitivity analysis

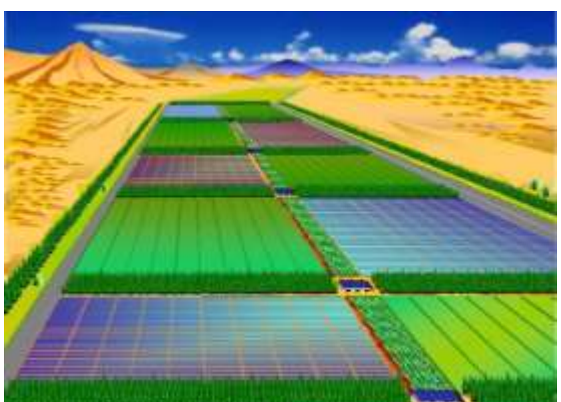
Boundary of LCA

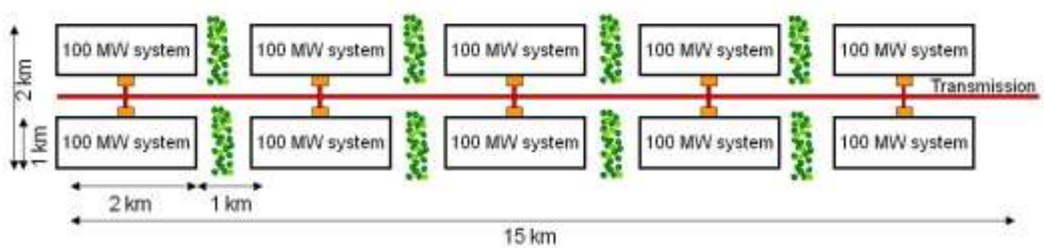


Overview of the system

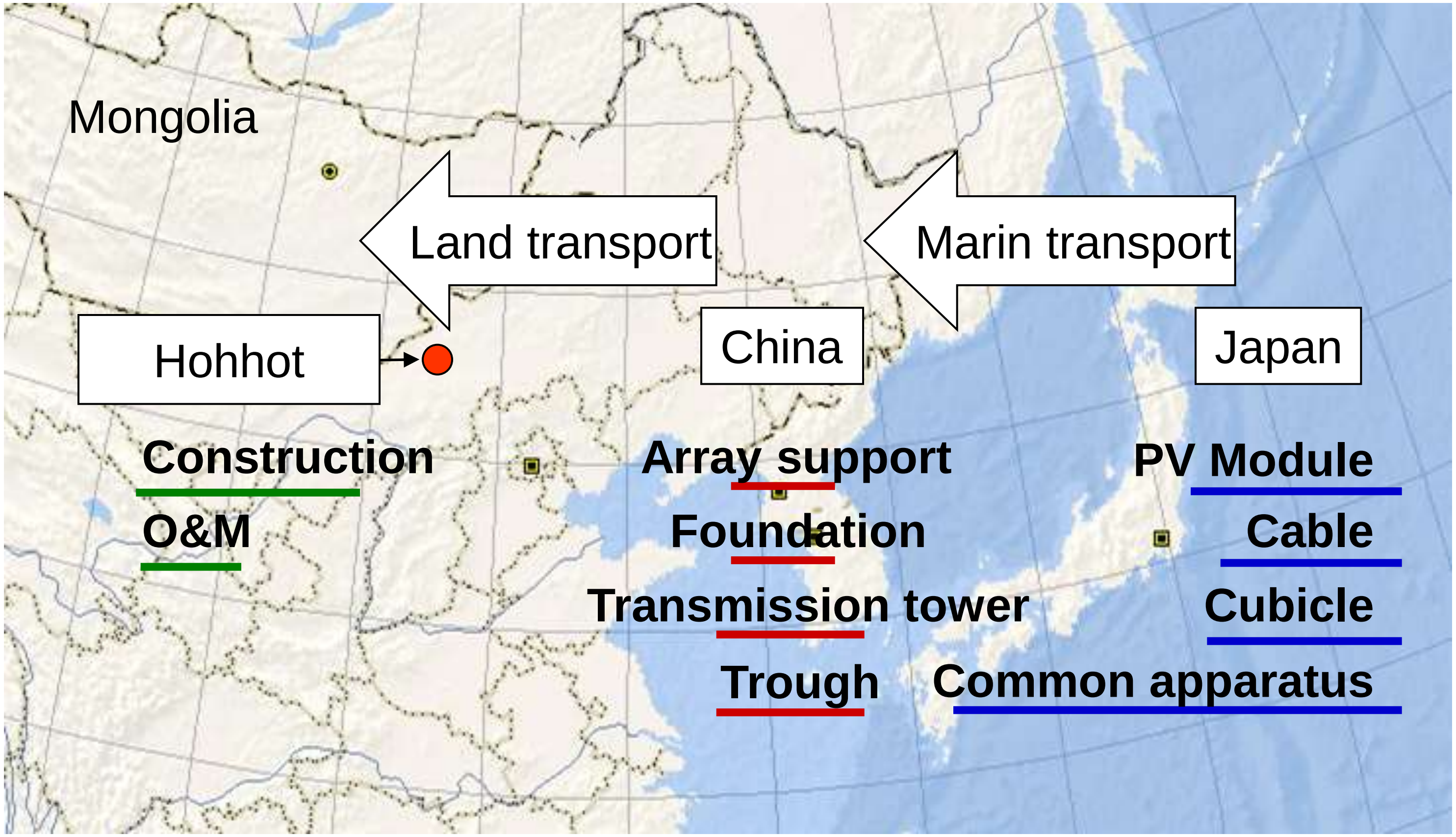








Assumptions of transport



Assumption: PV module

- **mc-Si (multi crystalline silicon)**
  - 186 W, 13.9 %
- **sc-Si (single crystalline silicon**
  - 165 W, 14.3 %
- **a-Si/sc-Si (amorphous silicon/sc-Si)**
  - 195 W, 16.6 %
- **Thin-film Si (a-Si/micro crystalline silicon)**
  - 37.5 W, 8.6 %
- **CIS (cupper indium di-selenide)**
  - 80 W, 10.1 %,

Assumptions

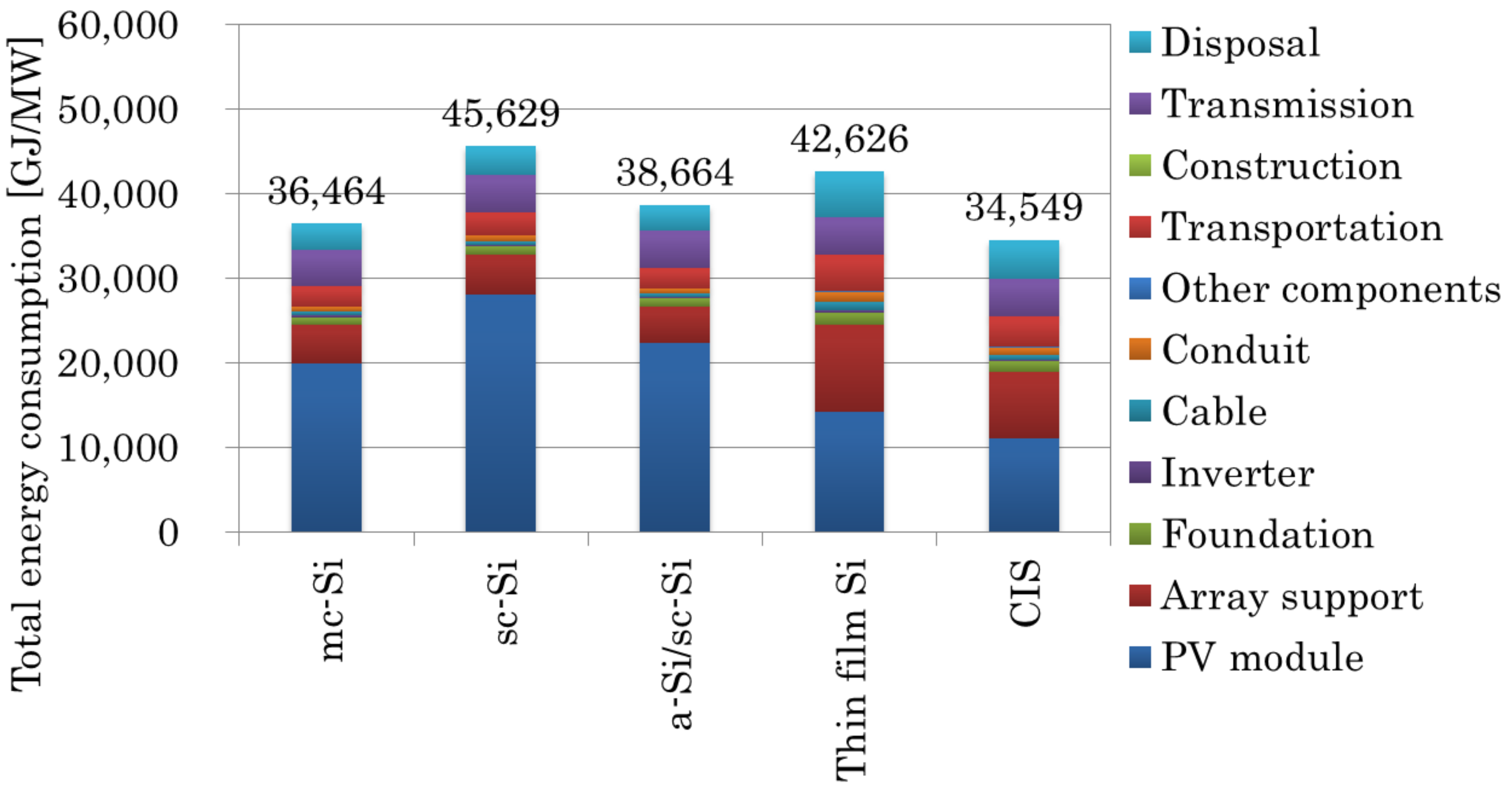
1. Capacity : 1 GW
2. Installation site : Gobi desert
3. Array : South facing, Fixed flat plate
4. PV module : mc-Si, sc-Si, a-Si/s-Si, a-Si/μc-Si, CIS
5. PR : 78% (depends on coefficiency of temp.)
6. Life-time : 30 years (15 years for Inverter)
7. O&M : 9 persons make 3 team for 3 shifts
8. Degradation : 0.5%/year

Equipment

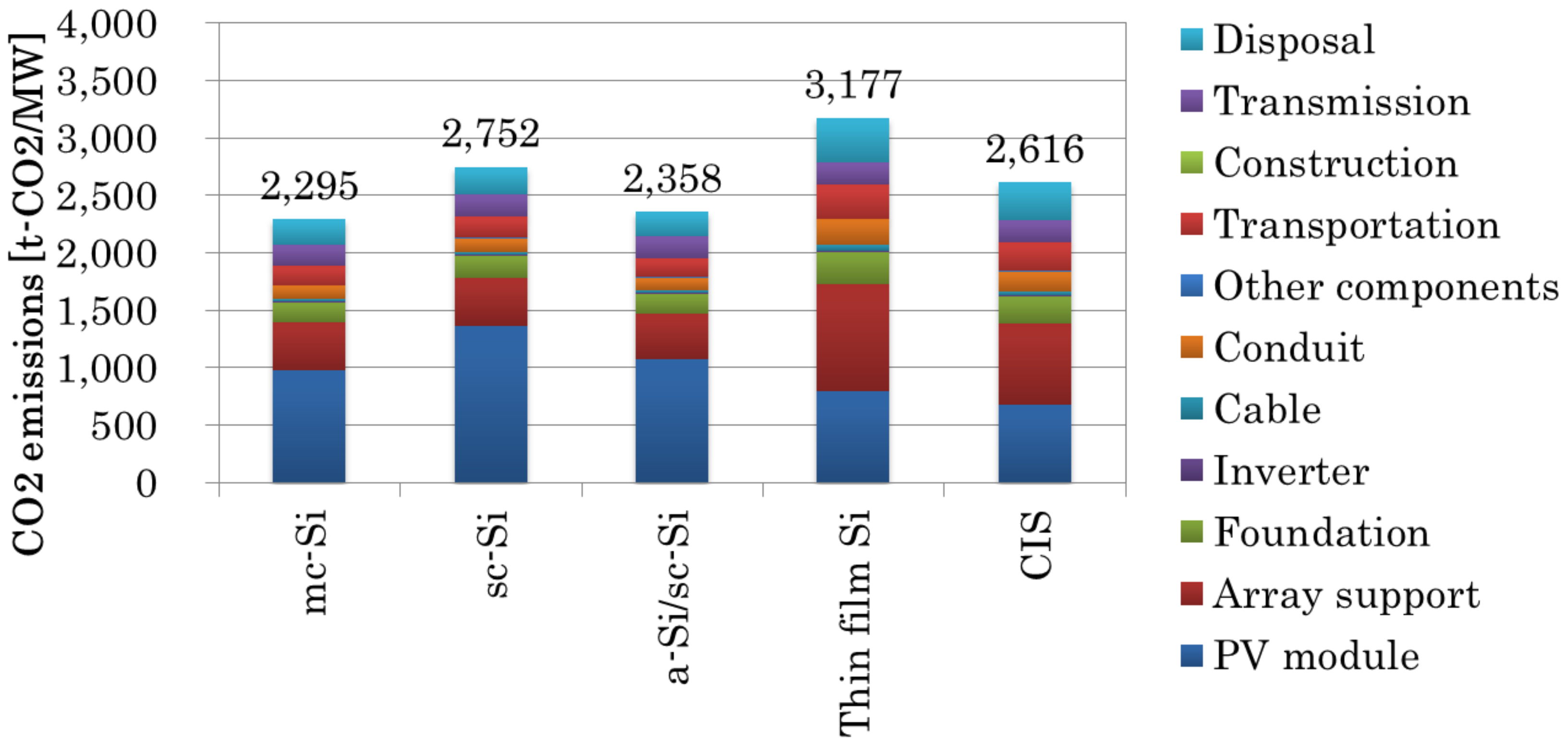
Energy from the desert 2012

PV module	**mc-Si**	**sc-Si**	**a-Si/sc-Si**	**Thin-film Si**	**CIS**
Capacity (MW)	1 071	1 024	1 021	1 036	1 034
Annual power generation [GWh]	1 687	1 596	1 592	1 615	1 604
Land requirement (km^2/GW)	21,3	20,7	18,0	34,5	29,2
Array support structure (10^3 tonne)	93	88	83	199	152
Foundation (10^3 m^3)	513	546	463	798	683
600 V CV 2 mm^2 (km)	10 692	10 469	11 941	129 397	37 812
600 V CV 5,5-8 mm^2 double core (km)	1 717	1 838	1 734	4 095	2 183
600 V CV 60-150 mm^2 (km)	1 060	941	1 146	2 100	1 555
6,6 kV CV-T 22 mm^2 (km)	262	233	283	343	302
6,6 kV CV 200 mm^2 (km)	306	320	229	356	344
110 kV CV 150 mm^2 (km)	255	245	236	319	292
Trough (30-degree) (m^3)	346 307	345 816	316 393	669 445	529 150
Inverter with transformer (set)	4 040 (include replacement and maintenance)				
6,6 kV circuit breaker (set)	2 080				
110 kV/6,6kV transformer (set)	50				
110 kV disconnecting SW (set)	180				
110 kV GIS (set)	100				
SVC (set)	20				
Common power board (set)	10				
110 kV TACSR 410 mm^2 (km)	1 202				
AC 70 mm^2 (km)	100				
Tower (steel) (tonne)	22 044				
Foundation (tonne)	50 932				

Energy consumption

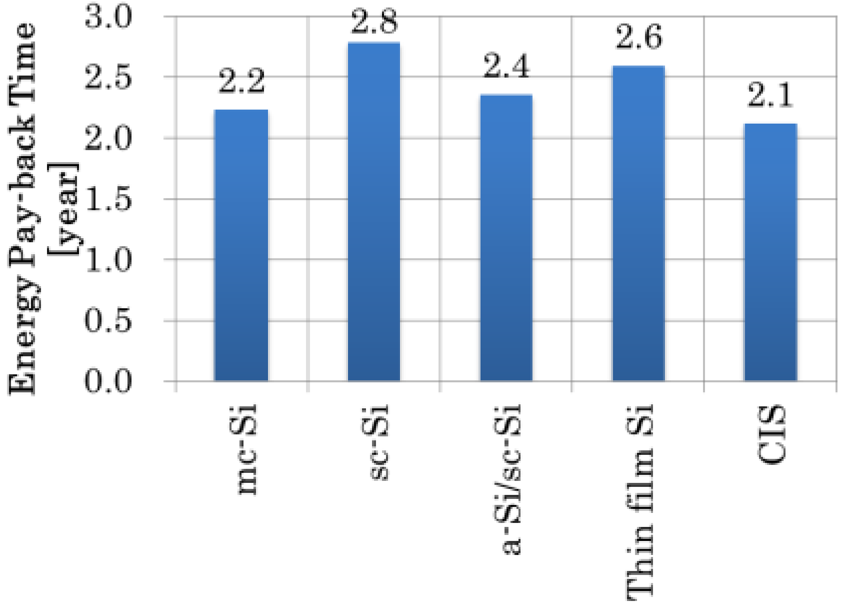


CO_2 emissions

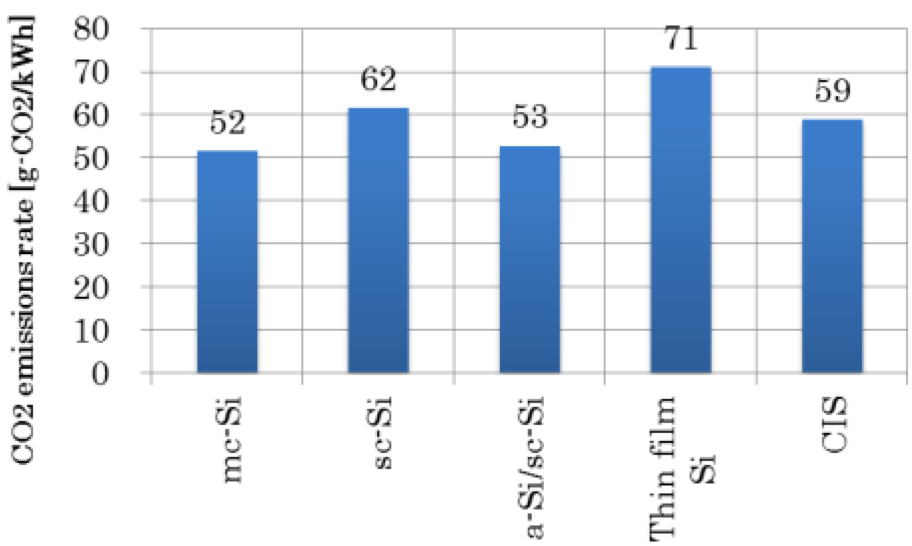


Energy pay-back time and CO2 emissions rate

Energy pay-back time



CO_2 emission rate



Summary

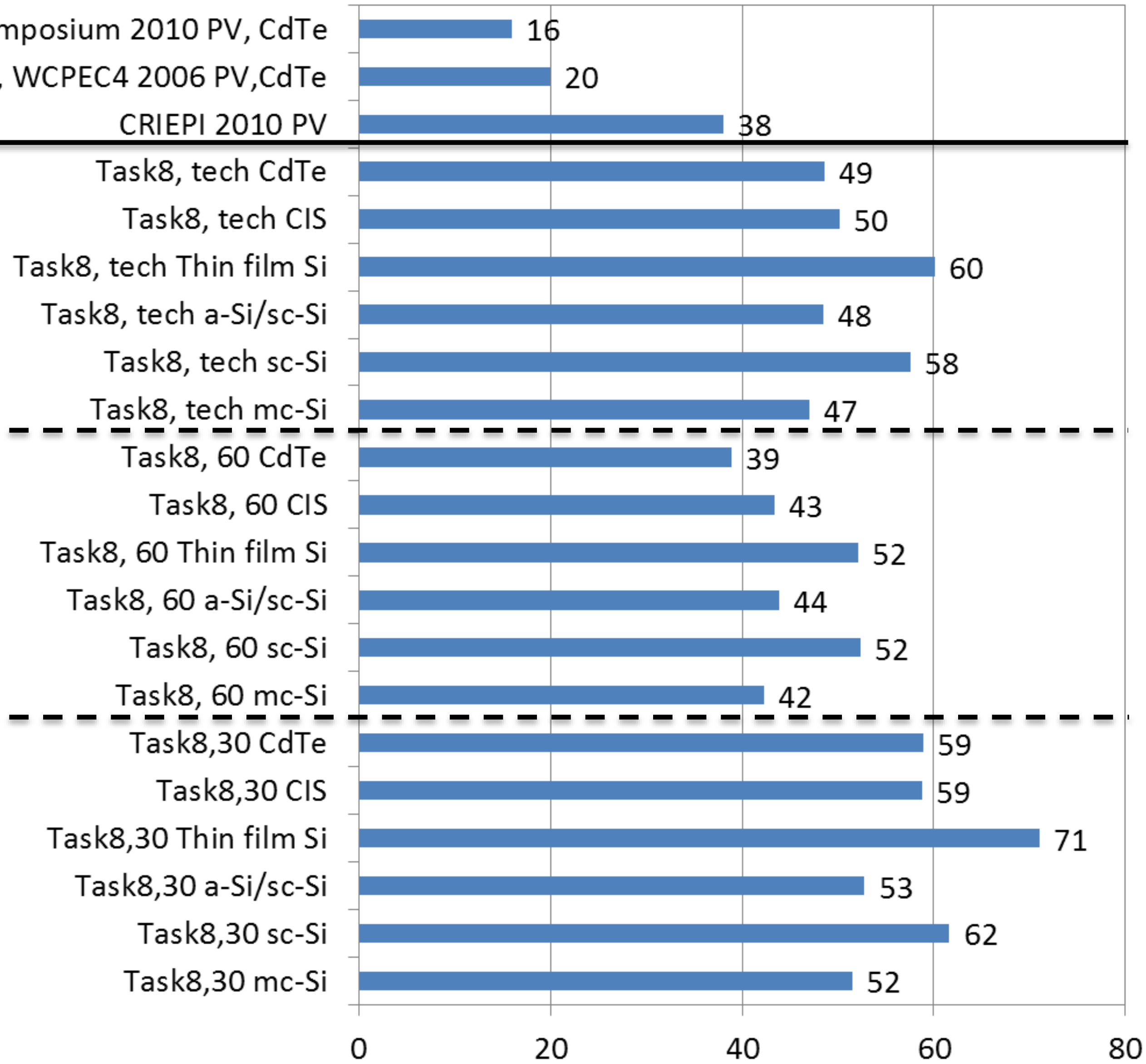
- **The authors studied environmental aspects**
  - Energy requirement, EPT, CO_2 emissions, and CO_2 emission rate
  - There are no big differences. But;

- **Energy**
  - CIS is the smallest and sc-Si is the largest
  - EPT of CIS is the smallest. It is 2.1 yeas. sc-Si is 2.8 yeas.

- **CO_2 emissions**
  - Thin-film Si is the largest: 71 g-CO_2/kWh
  - mc-Si, a-Si/sc-Si, CIS are the smallest: 52-53 g-CO_2/kWh

Results with Sensitivity analysis

Reference



Results assuming high level manufacturing of array and foundation

Results with 60 years life-time of array and foundation

Results (Original)

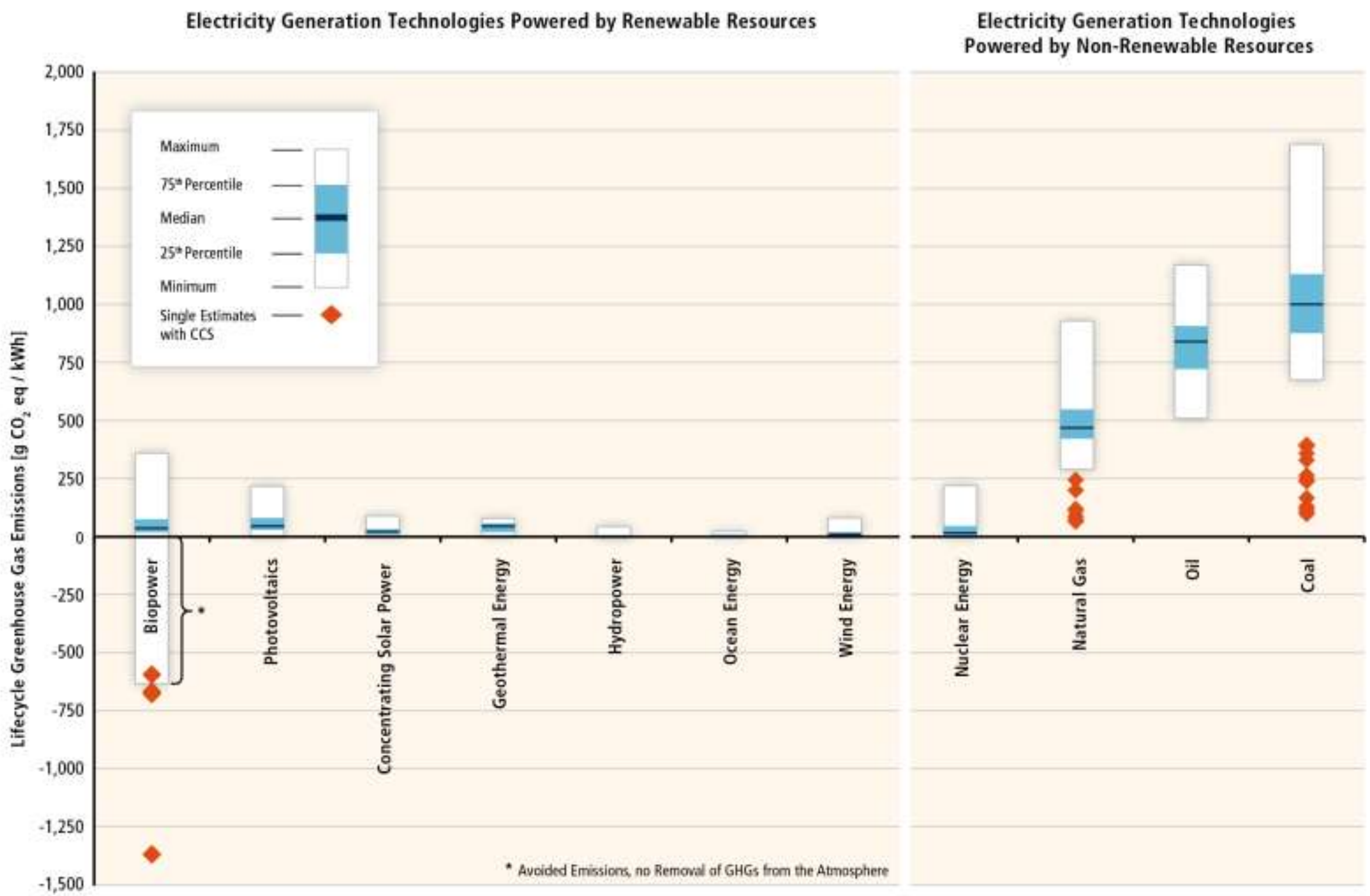
ipcc
INTERGOVERNMENTAL PANEL ON climate change

IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation

Summary for Policymakers

This Summary for Policymakers was formally approved at the 11th Session of Working Group III of the IPCC

Abu Dhabi, United Arab Emirates, 5-8 May 2011



	Biopower	Photovoltaics	Concentrating Solar Power	Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Nuclear Energy	Natural Gas	Oil	Coal
Count of Estimates	222(+4)	124	42	8	28	10	126	125	83(+7)	24	169(+12)
Count of References	52(+0)	26	13	6	11	5	49	32	36(+4)	10	50(+10)

IPCC, 2011: Summary for Policymakers. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press. Figure SPM.XX

Summary

1. **Background**

2. **Basics and points for comparing LCA results**
   - Which explained how to read LCA results.

3. **Example of research result**
   - A comparative study on life cycle analysis of 20 different PV modules installed at the Hokuto mega-solar plant

4. **Example of research result**
   - Very large scale PV systems assumed to be installed in Deserts were evaluated from environmental view points.

Thank you for your attention !

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