The Role of Solar Energy in our Future Energy System

Eicke R. Weber,

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and

Albert-Ludwigs University, Freiburg, Germany

General Lecture, University of Stellenbosch

Stellenbosch, SA, January 24, 2014

Fraunhofer-Institute for Solar Energy Systems ISE

Largest European Solar Energy Research Institute

Topic: Technologies for the Energy Transformation

More than 1300 members of staff (incl. students)

15% basic financing
85% contract research
30% industry, 55% public
€ 84 M budget (‘13)

Business Areas:

- Energy - Efficient Buildings
- Silicon Photovoltaics (PV)
- III/V & Concentrator PV
- Dye-, OPV & other novel PV
- PV Modules & Power Plants
- Solar Thermal Technologies
- Hydrogen, FC Technologies
- System Integration, Grid
- Efficient Power Electronics
- Emission-free Mobility
- Storage Systems
- Energy System Analysis

- ISE Freiburg
- CSP Halle (with IWM)
- THM Freiberg (with IISB)
- LSC Gelsenkirchen
- CSE Boston (Fh-USA)

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A radical transformation of our energy system is needed –
Jeremy Rifkin: We are starting the 3rd Industrial Revolution!

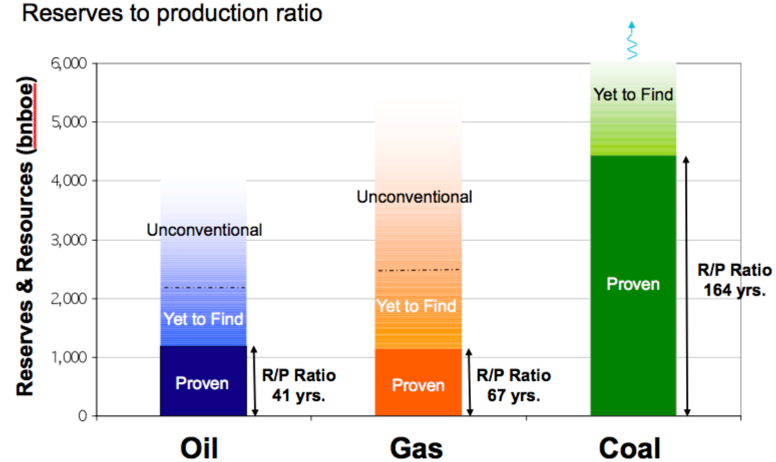
- The world has to transform to living in a sustainable way!
- Limited availability of fossil fuels
- Danger of catastrophic climate change
- Risk of nuclear disasters
- Growing dependency on imports from politically unstable regions
- **Economic advantages get noticable**

Important aspects to take into account:

- The transformation needs time and money
  - Technological development
  - Capacity building
  - Investments in infrastructure
- Industrialized countries and countries with high consumption per capita must lead!

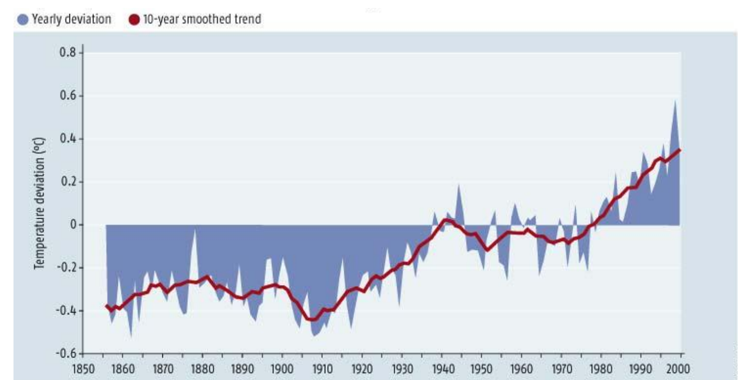
Availability of fossil resources

Reserves to production ratio



Source: World Energy Assessment 2001, HIS, WoodMackenzie, BP Stat Review 2005, BP estimates, Graph: Koonin, BP

The world is getting warmer



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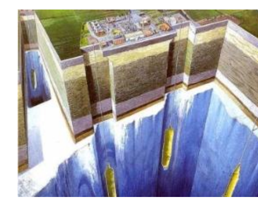
Cornerstones for the transformation of our energy system

- **Energy Efficiency:**
  Buildings, Production, Transport

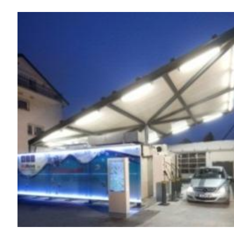
- **Massive increase renewable energies**
  Photovoltaics, Solar and geo thermal, wind, hydro, biomass.....

- **Fast development of the electric grid**
  Transmission and distribution grid, bidirectional

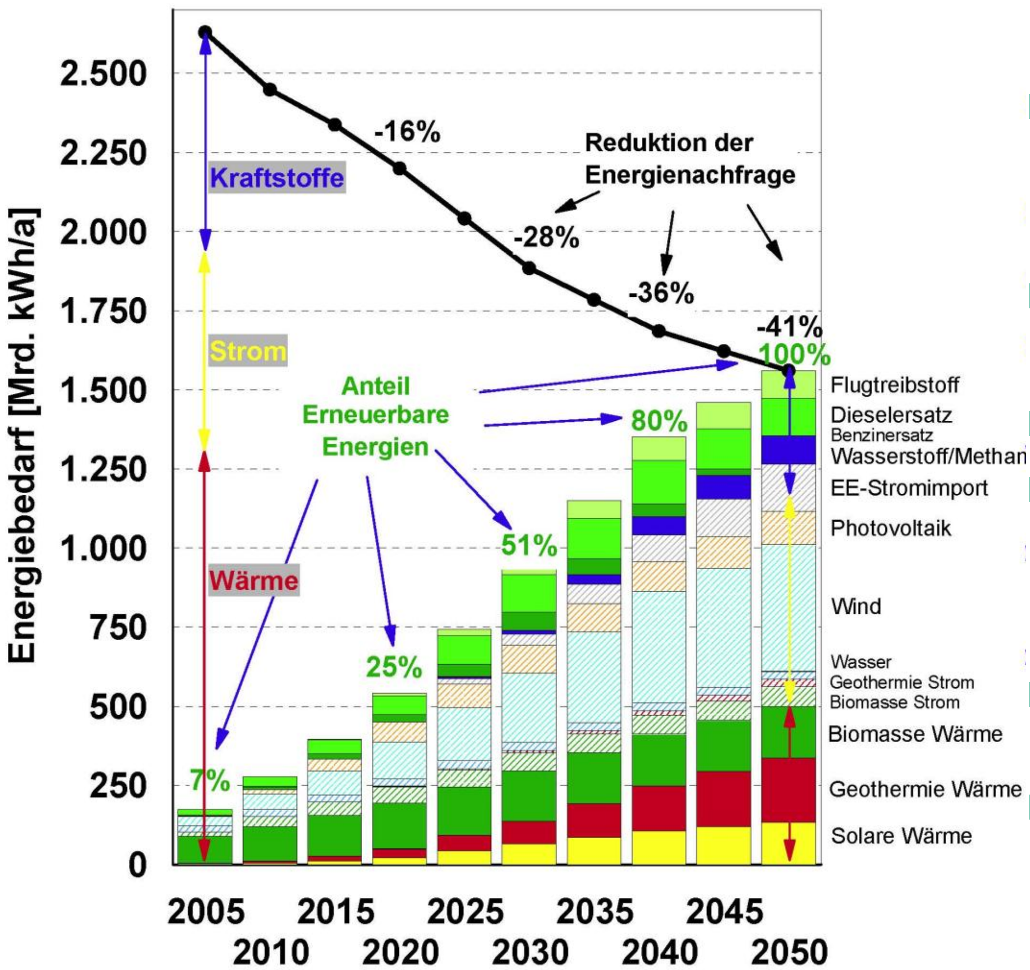
- **Small and large scale energy storage systems**
  Electricity, Hydrogen, Methane, Biogas, Solar Heat



- **Mobility as integral part of the energy system**
  Electric mobility by means of batteries and hydrogen/fuel cells



Example: Scenario for 100% Renewable Energy Supply till 2050 in Germany

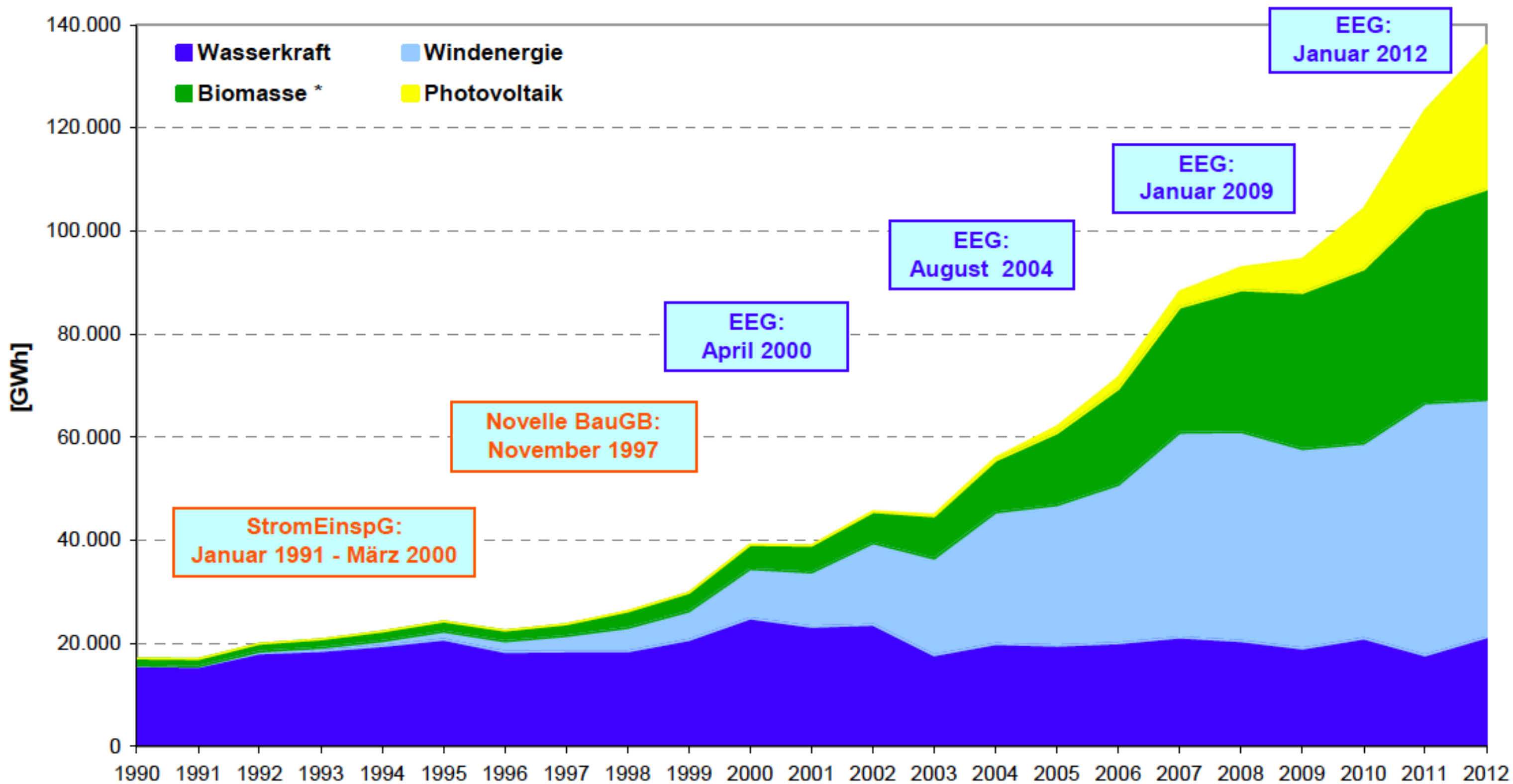


Key Features:

- Strong decrease of heat demand from buildings (energy renovations, ‘zero-energy’ houses
- Increase of combined-cycle heat/power plants
- Thermal storage for heating and cooling
- Coupling of electricity grid and gas pipelines through production of regenerative hydrogen and methan
- Introduction of e-mobility with battery- and fuel cell powered cars
- Use of liquid biofuels, especially for heavy trucks and air traffic

Electricity generation from renewable energy sources

Development in Germany 1990 – 2012



* Feste und flüssige Biomasse, Biogas, Klär- und Deponiegas, biogener Anteil des Abfalls; 1 GWh = 1 Mio. kWh;
Aufgrund geringer Strommengen ist die Tiefengeothermie nicht dargestellt; StromEinspG: Stromeinspeisungsgesetz; BauGB: Baugesetzbuch; EEG: Erneuerbare-Energien-Gesetz;
Quelle: BMU - E I 1 nach Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat); Stand: Februar 2013; Angaben vorläufig

Year 2012

Total* **22.9%**
136.1 TWh

PV **4.7%**
28.0 TWh
32.6 GW

Bio **6.9%**
40.9 TWh

Wind **7.7%**
46.0 TWh
31.3 GW

Hydro **3.6%**
21.2 TWh

* Brutto electricity demand

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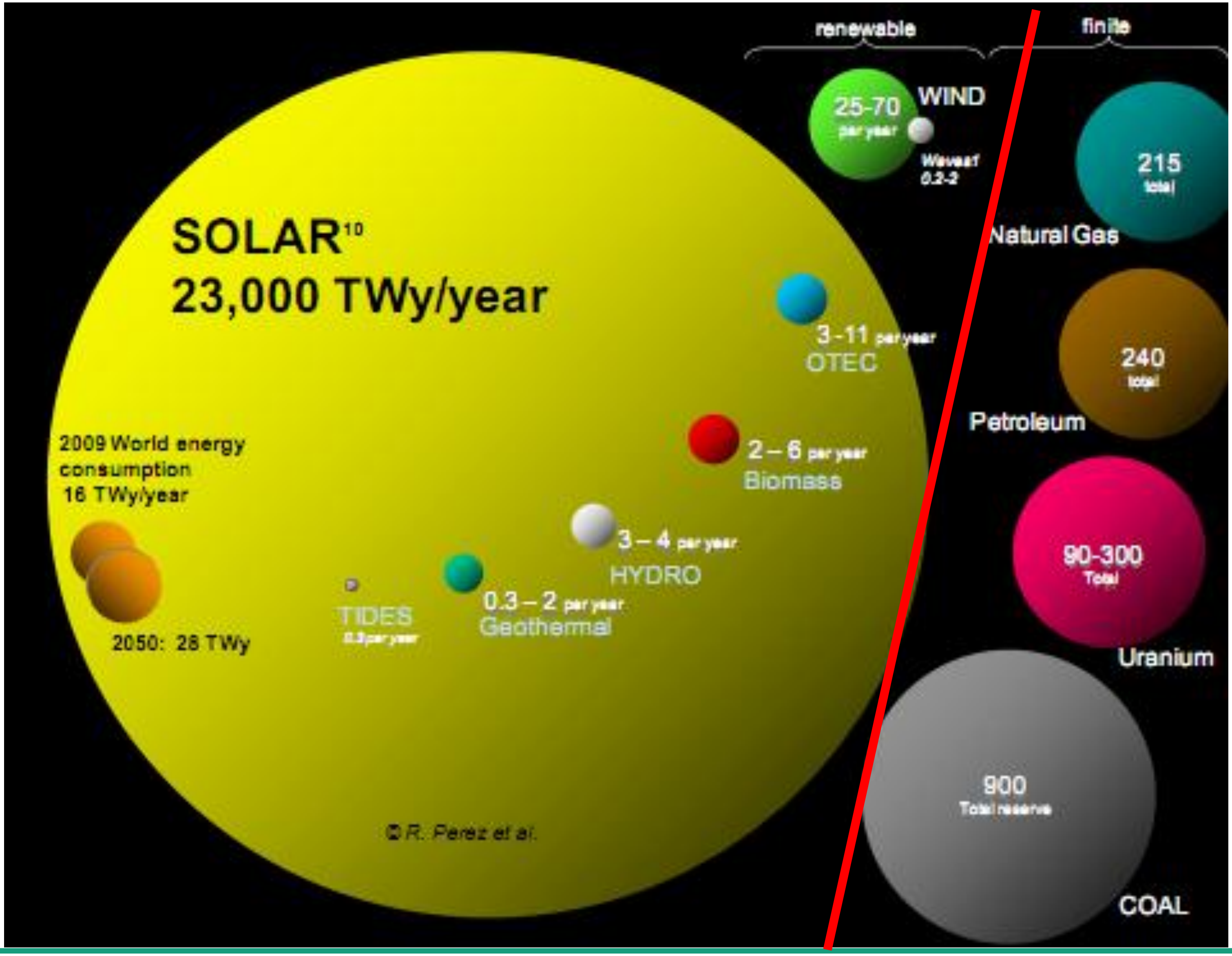
World Energy Resources *(1Twy = 8760 TWhr)*



Source: R. Perez et al.

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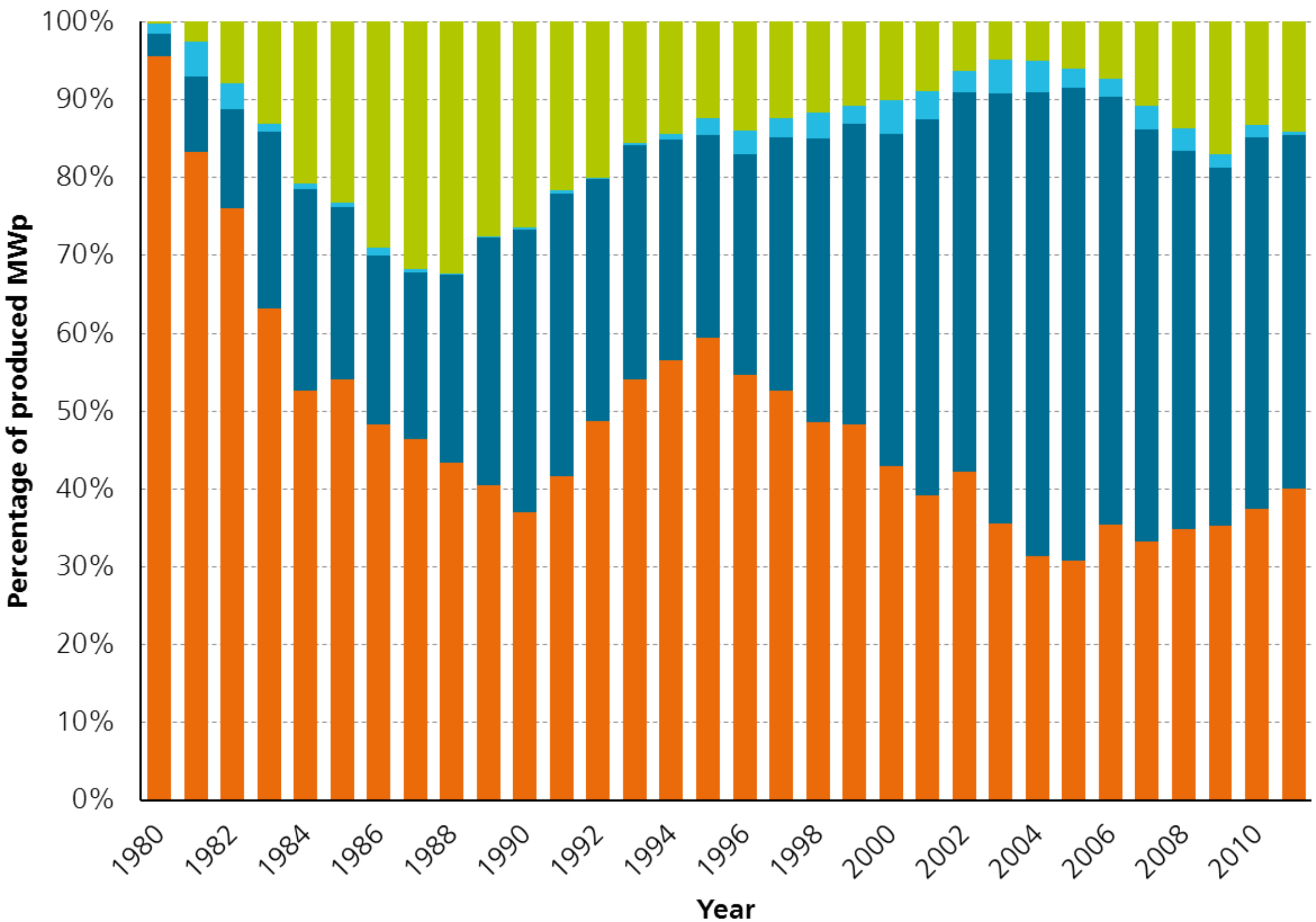
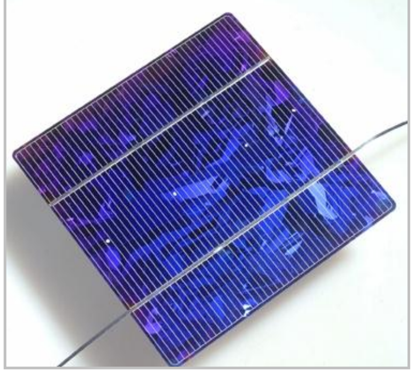
PV Production Development by Technology





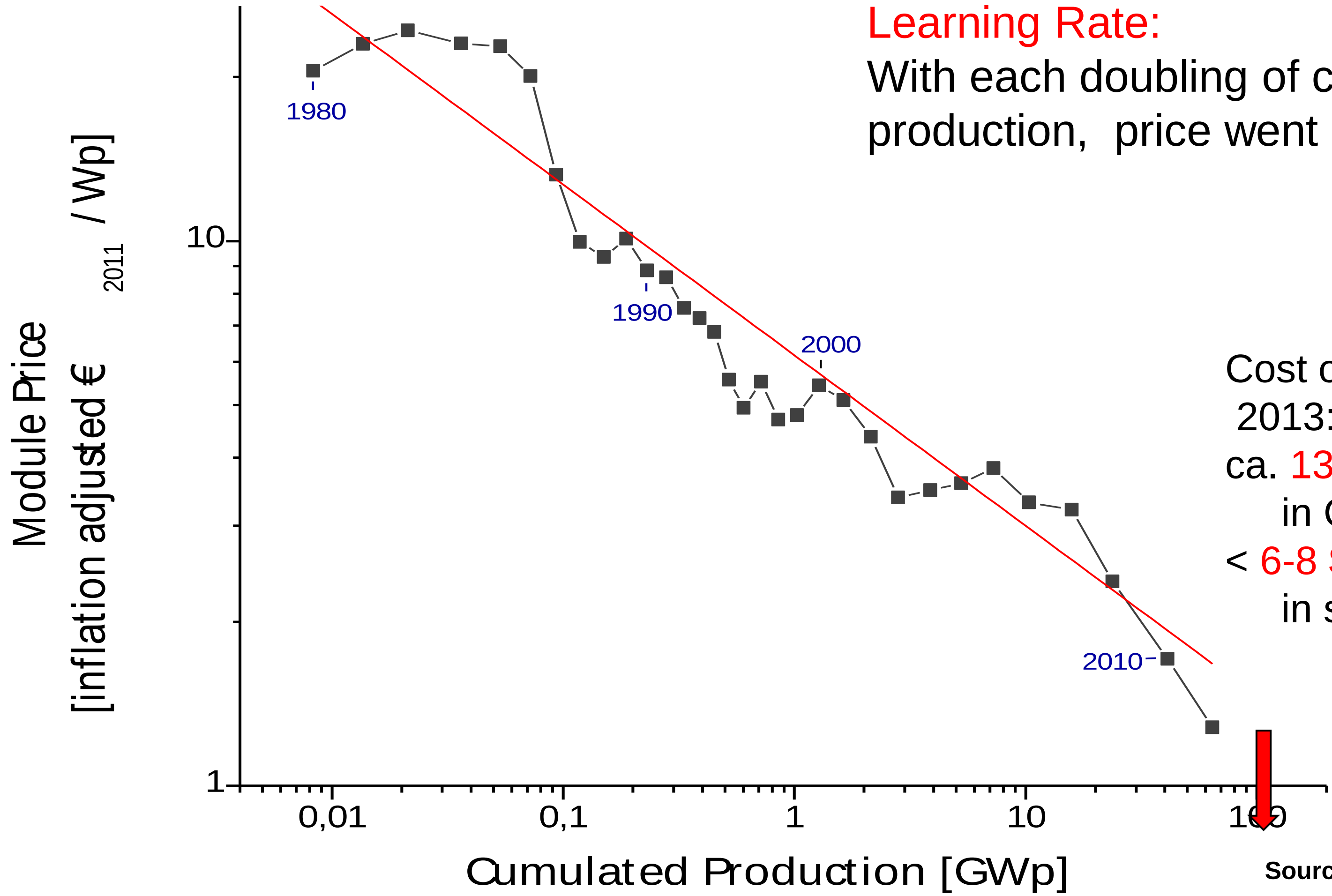
Production 2011 (MWp)

Thin film	3,204
Ribbon-Si	120
Multi-Si	10,336
Mono-Si	9,114

Source: Navigant Consulting

Design: PSE AG 2012

Price Learning Curve (all c-Si PV Technologies)



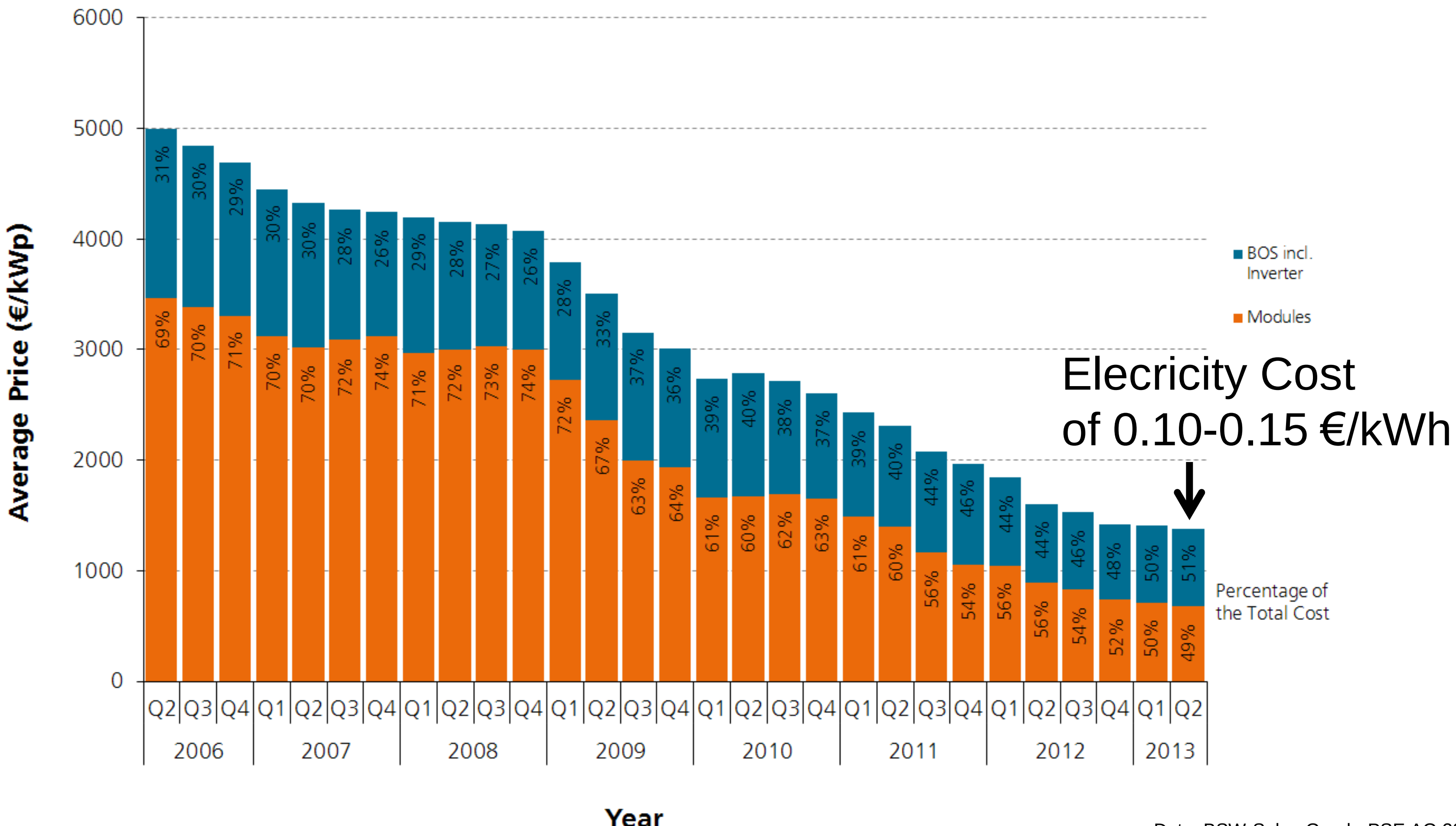
Learning Rate:
With each doubling of cumulative production, price went down by 20%!

Cost of PV electricity 2013:
ca. 13 €ct/kWh in Germany
< 6-8 $ct/kWh in sun-rich countries

Source: Navigant Consulting; EuPD Module price (since 2006)
Design: PSE AG 2012

2013: Ready-installed rooftop system in Germany: **down to € 1.20 /Watt!**

Average Price for Rooftop PV Installations in Germany (10kWp - 100kWp)



Data: BSW-Solar, Graph: PSE AG 2013

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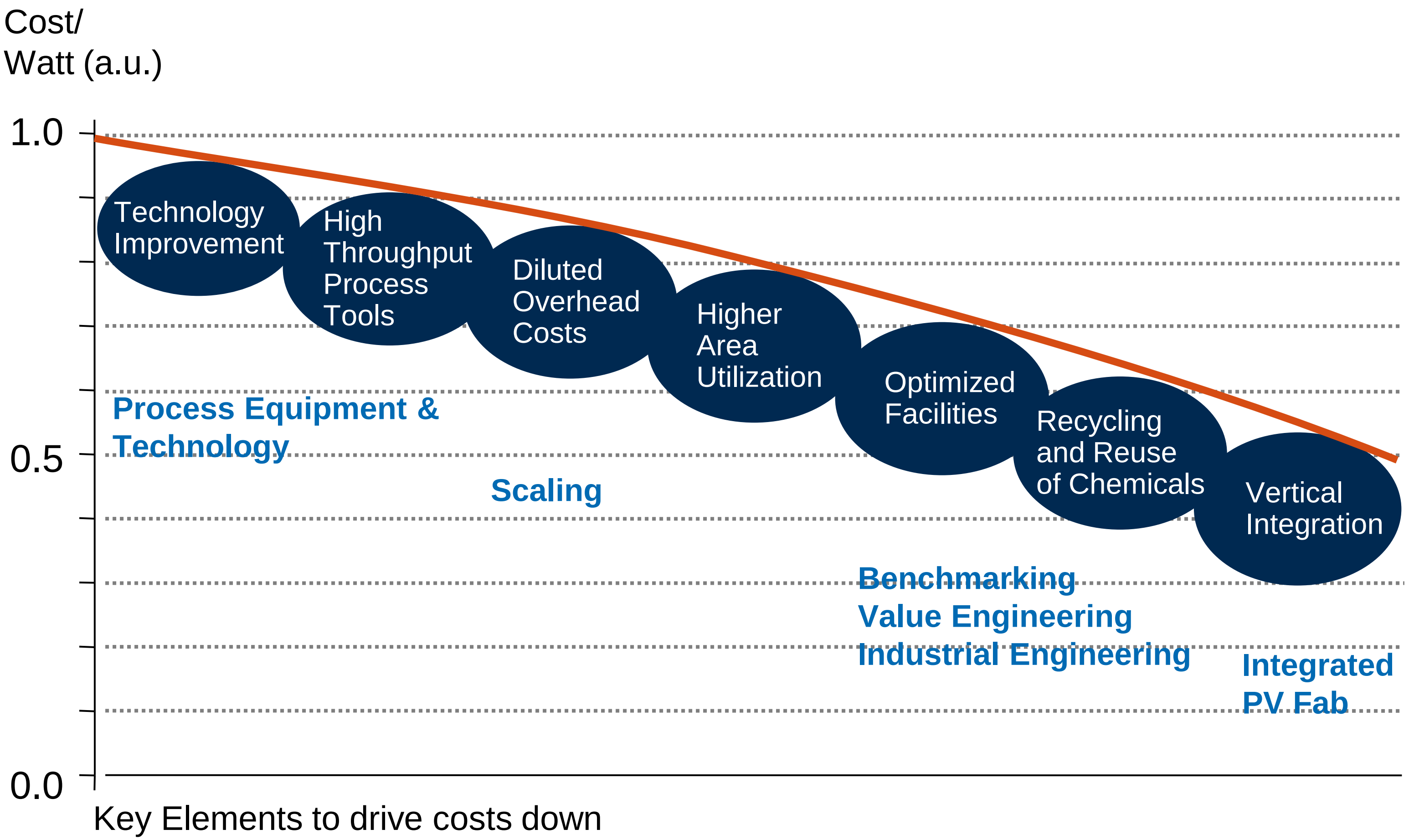
Key Elements to Drive Down Cost for PV Manufacturing



Source: M+W group, Dr. Klaus Eberhardt, European PV Technology Platform, September 2011

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Crystalline Silicon Technology Portfolio

Material quality

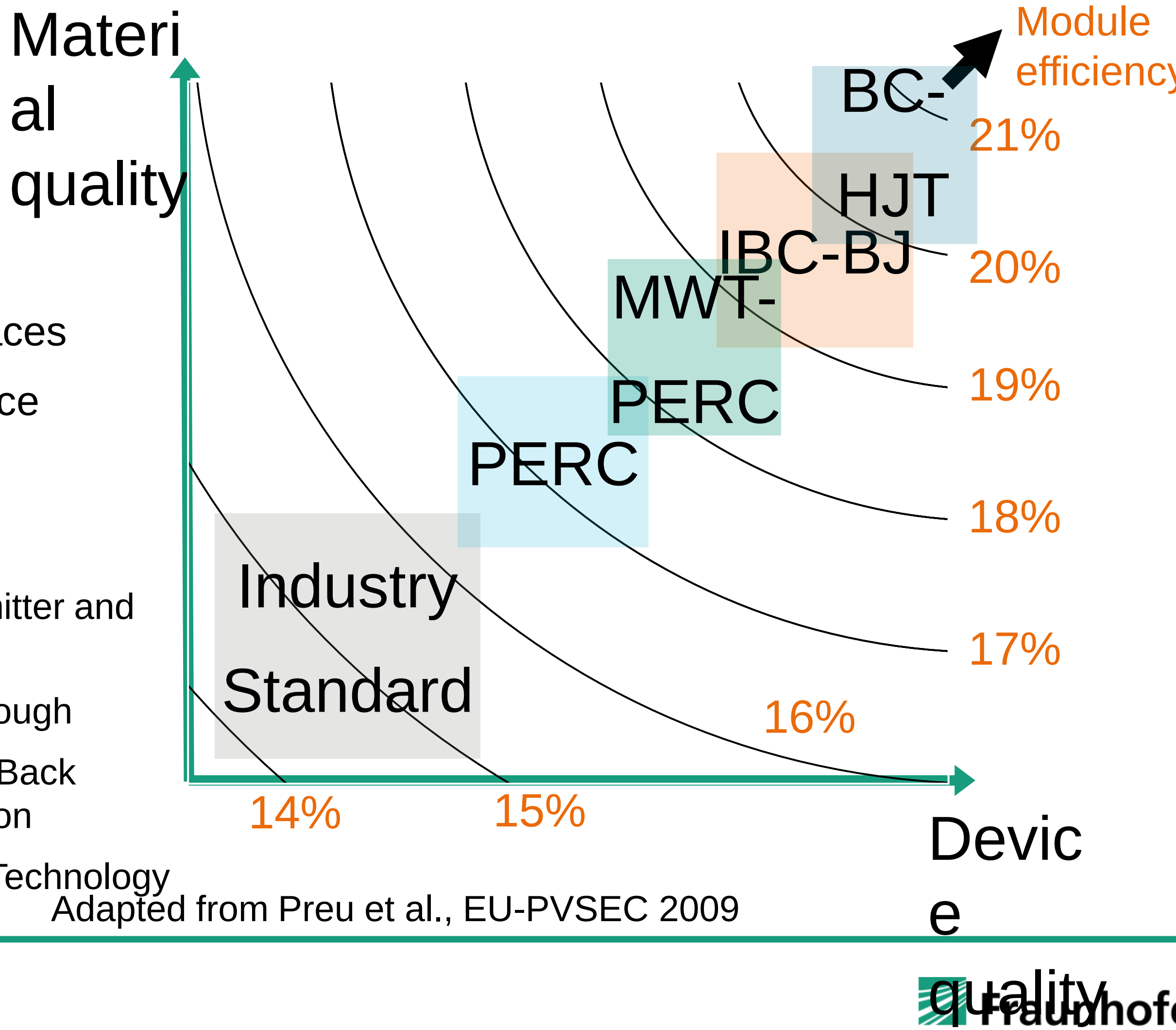
- Diffusion length
- Base conductivity

Device quality

- Passivation of surfaces
- Low series resistance
- Light confinement

Cell Structures

- PERC: Passivated Emitter and Rear Cell
- MWT: Metal Wrap Through
- IBC-BJ: Interdigitated Back Contact – Back Junction
- HJT: Hetero Junction Technology



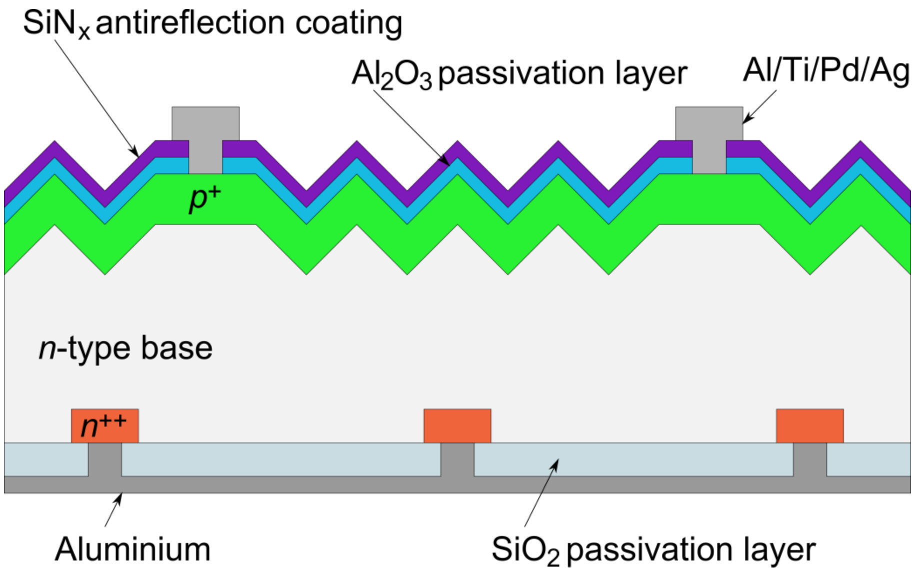
Adapted from Preu et al., EU-PVSEC 2009

High-efficiency n-type PERL Cells

Lab Results

- Excellent performance at cell level
- Only very thin ALD layer necessary

	V_{oc} [mV]	J_{sc} [mA/cm²]	FF [%]	η [%]
Best cell	**705**	**41.1**	**82.5**	**23.9***



*Confirmed at Fraunhofer ISE CalLab

ap = aperture area
(= bus bar included in illuminated area)

Benick et al., APL 92 (2008)
Glunz et al., IEEE-PVSC (2010)

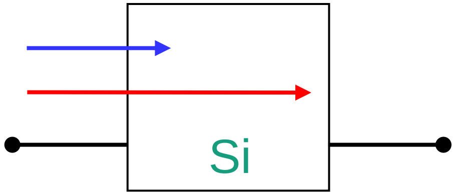
The efficiency limit for a single-material PV Cell

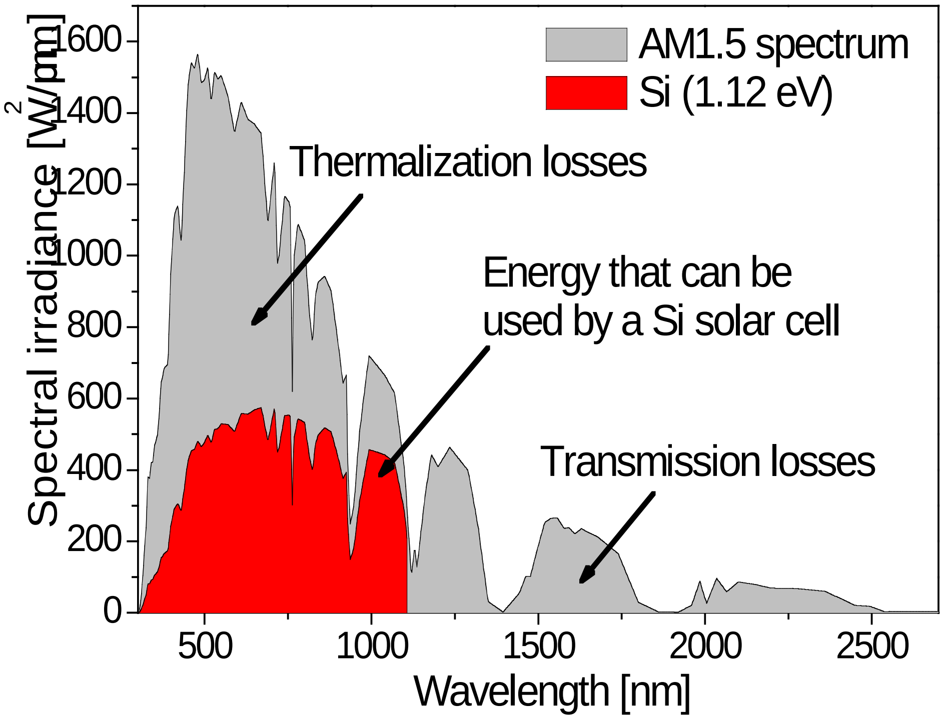
For Silicon:

(AM1.5g, 1000 W/m², 25° C)

$\eta_{max,\ theo}$ = 28 %

Lab cell = 24 %





The benefit of multi-junction solar cells

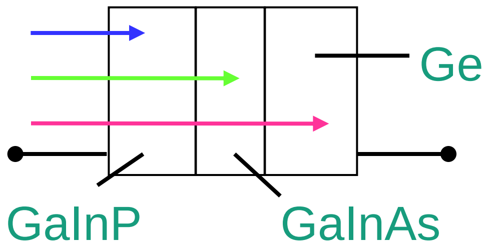
For triple-junction concentrator cells:

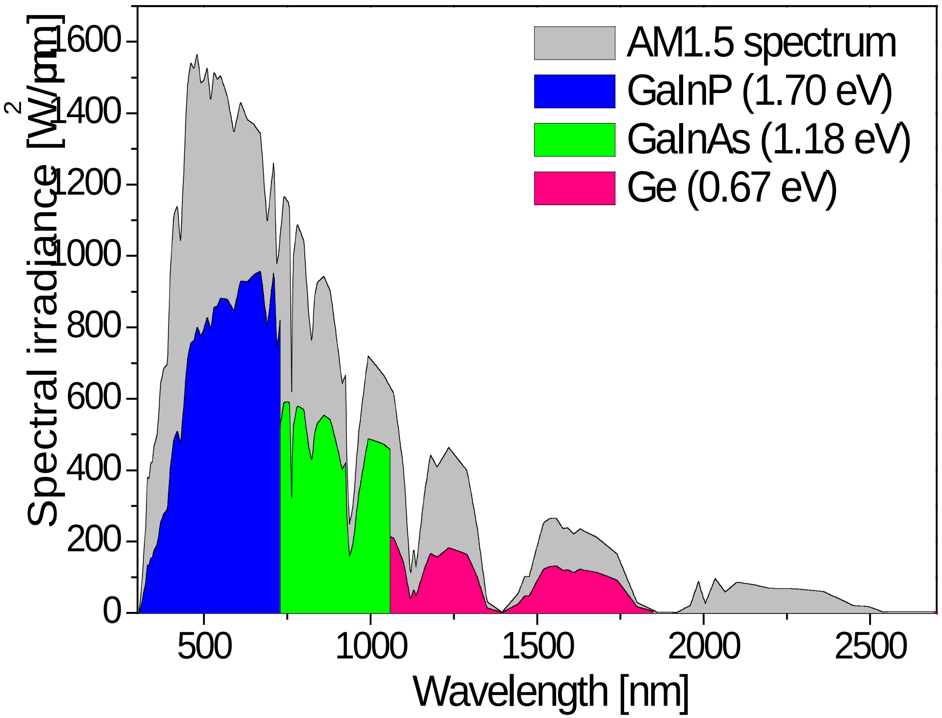
$\eta_{max,\ theo}$ = 61 %

(1000xAM1.5d, 1000 W/m²)

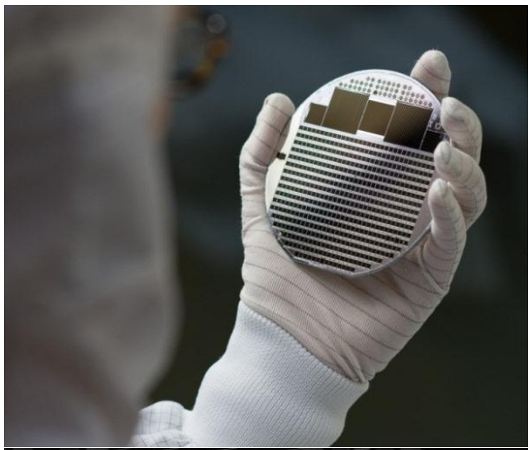
Lab. cell = 40.8 %

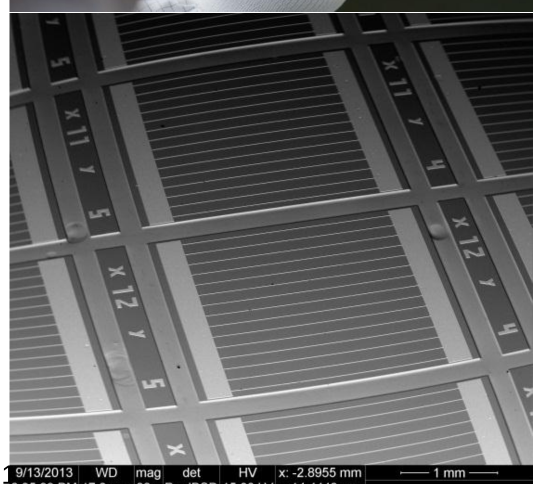
230xAM1.5d, 1000 W/m²)

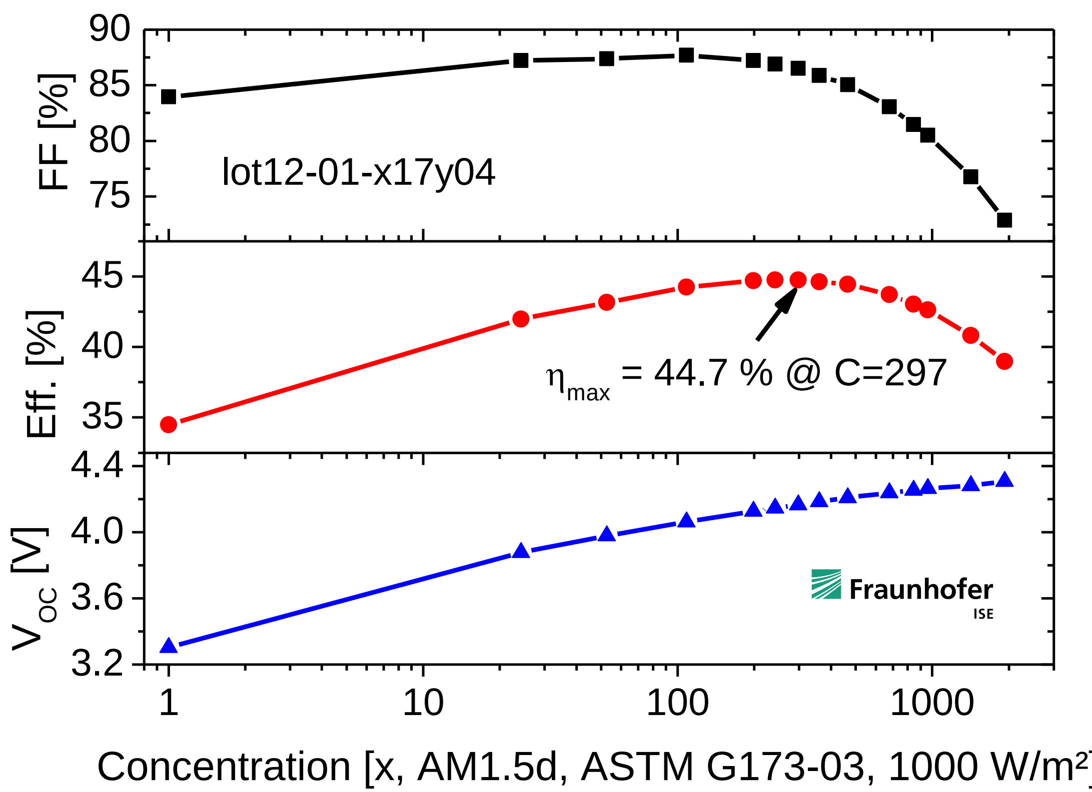




World Record 44.7 % Efficiency Solar Cell
Wafer-Bonded, 4-Junction Technology
Fh-ISE with SOITEC, Cea-Leti, HZB

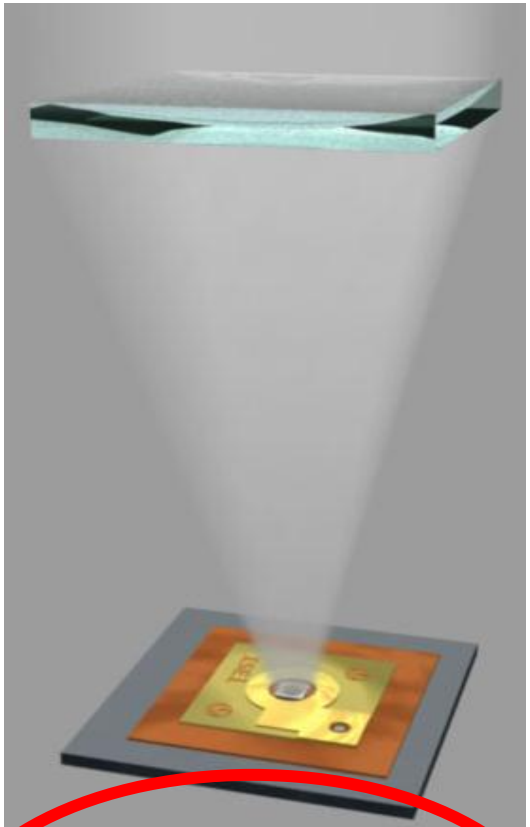






Soitec HZB Helmholtz Zentrum Berlin cea Leti Fraunhofer ISE

III/V Multijunction cells are used in Concentrated PV: CPV



2012: SOITEC SOLAR builds a 300 MW CPV installation, using a new 150 MW_p/yr factory near San Diego, CA!

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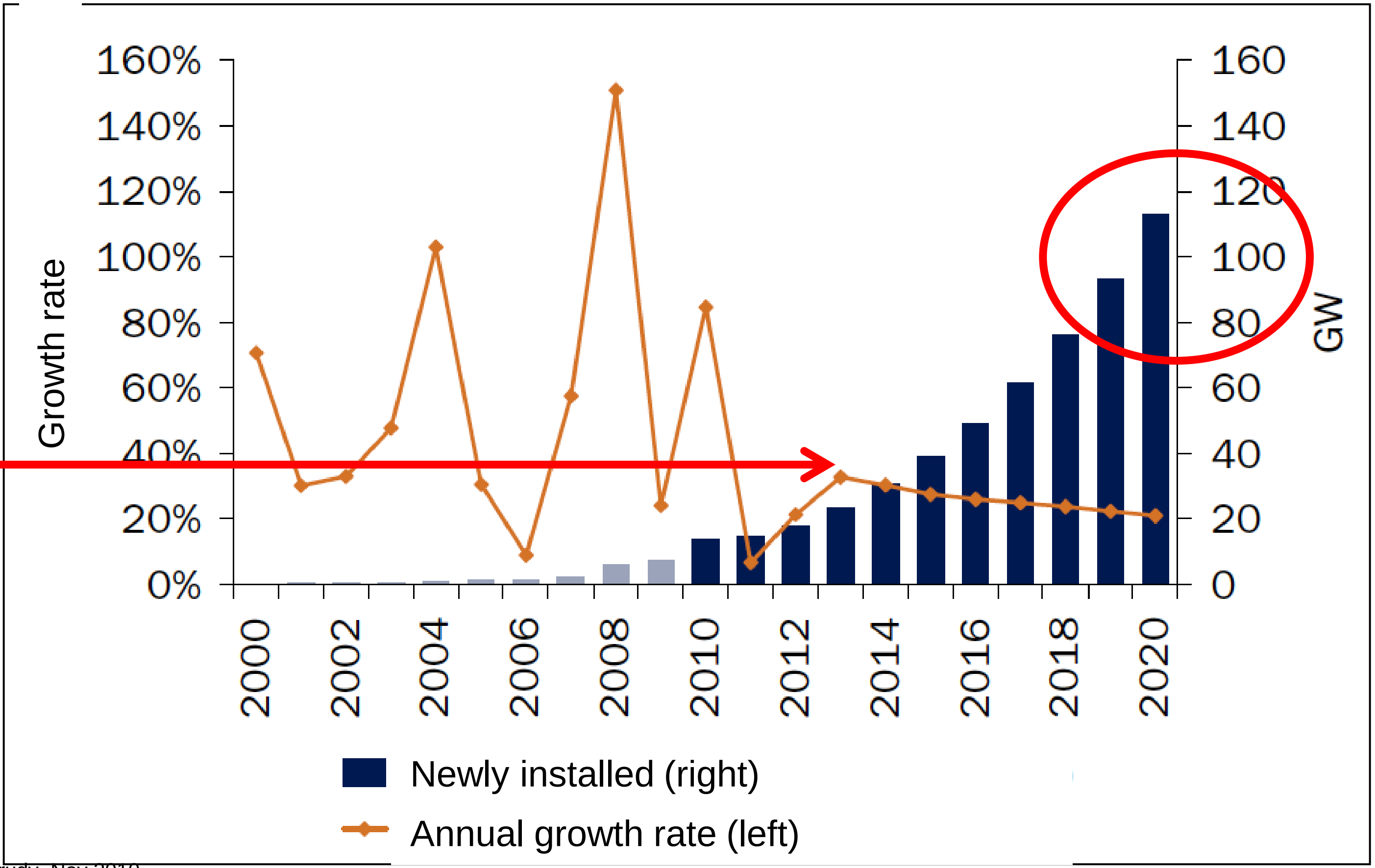
World market outlook: experts are optimistic
Example Bank Sarasin, Nov 2010

- **Market forecast: 30 GW_p in 2014, 110 GW_p in 2020**
  Annual growth rate: in the range of 20% and 30%

2013:
35-37 GW_p,
far above
forecast!



 Source: Sarasin, Solar Strudy, Nov 2010

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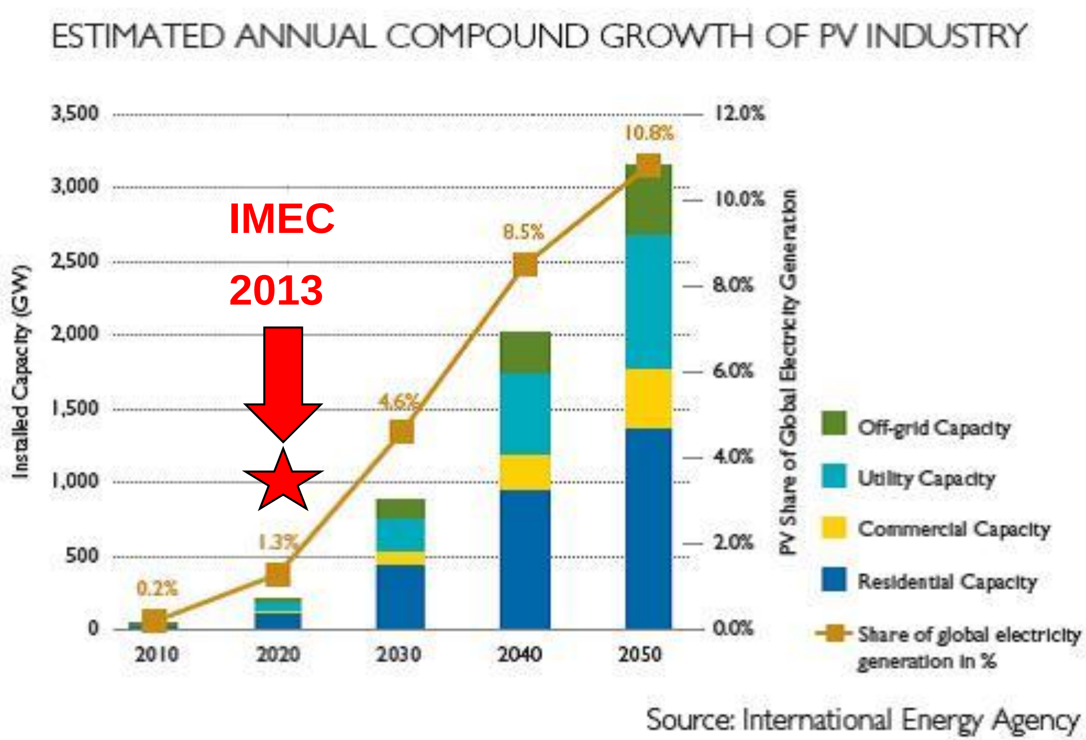
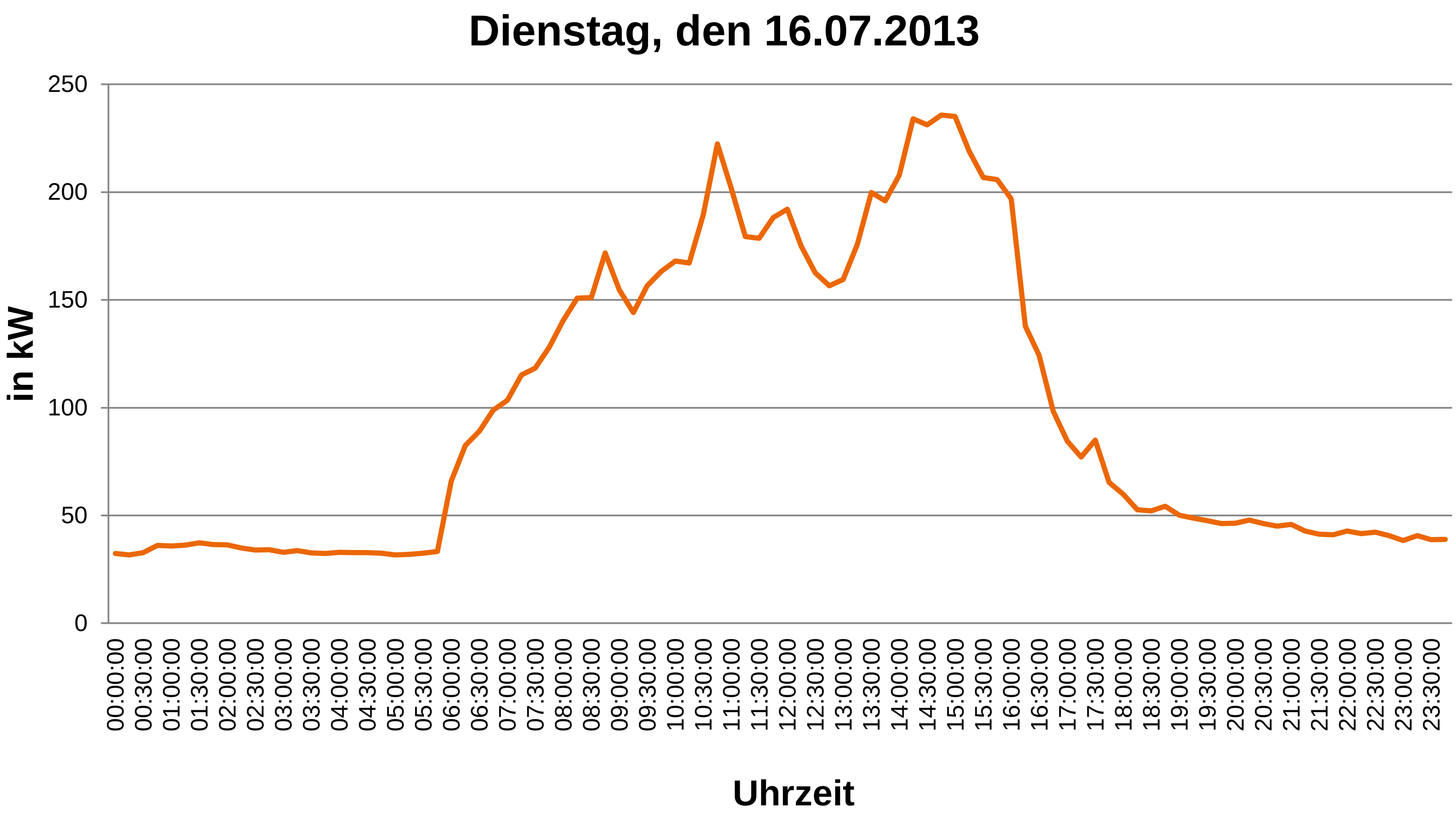
IEA Outlook on PV production world-wide

- Rapidly declining cost of PV generated electricity open up new market opportunities
- Current 30GW$_p$/a market will increase to a 100+ GW$_p$/a market in 2020; for 2050 more than 3000 GW$_p$ of globally installed PV capacity is expected
- Strong increase necessitates construction of GW-scale, highly automatic PV production plants

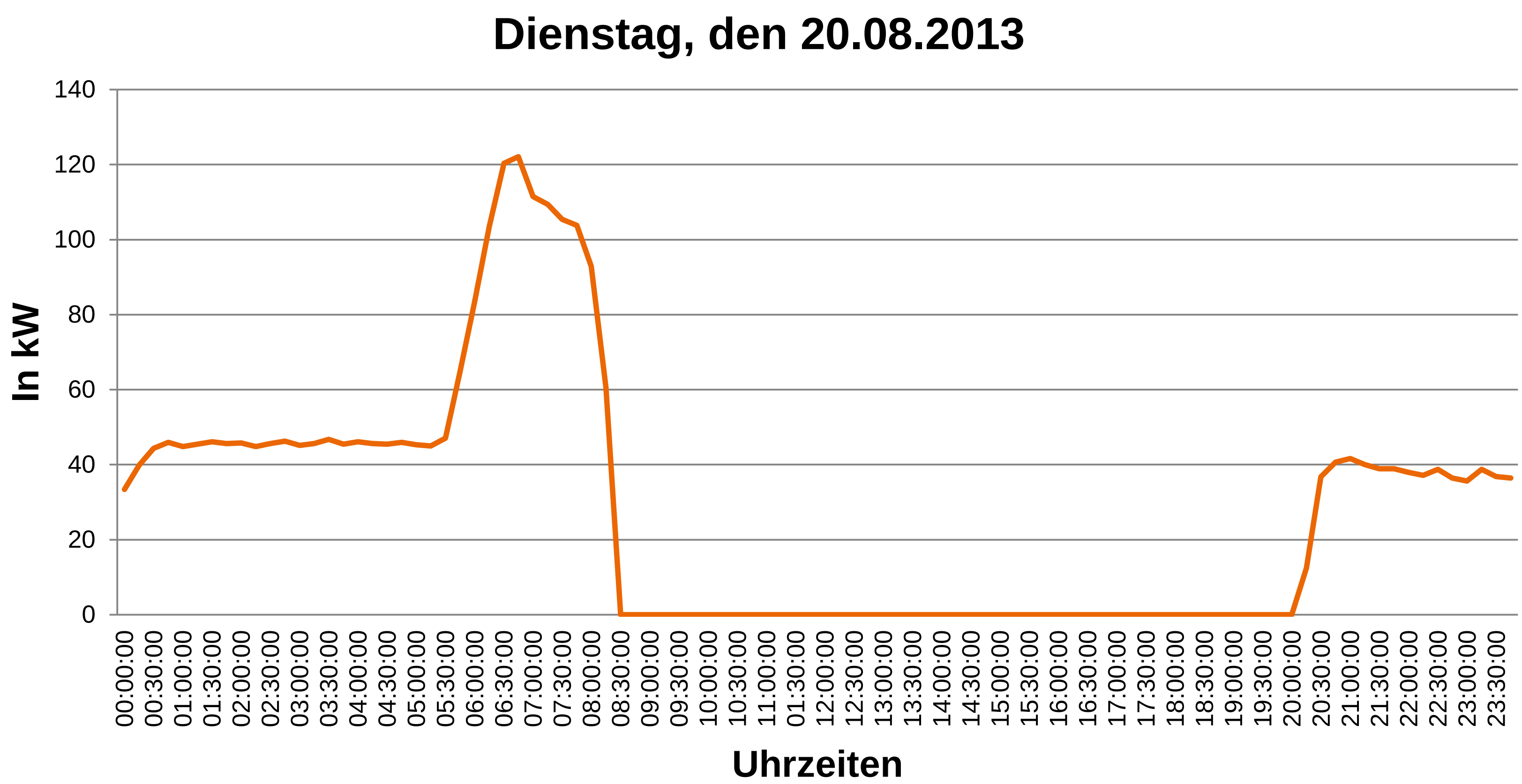


Daily Electricity Consumption – Juli Fab 5



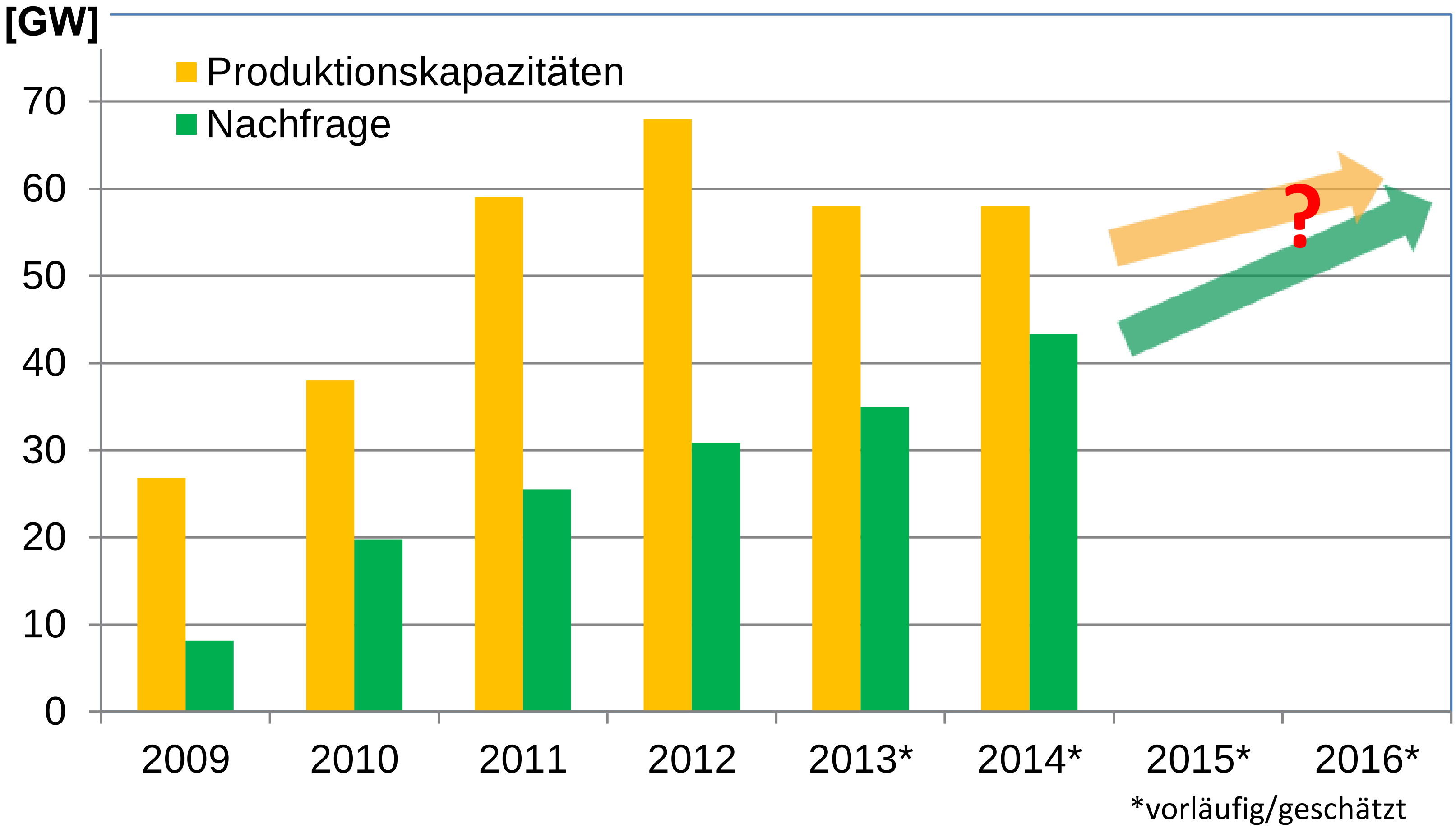
Graph Courtesy Ralf Hofmann, KACO

Daily Electricity Consumption – August Fab 5 with 2 MW PV System



Graph Courtesy Ralf Hofmann, KACO

The Gap between global PV Production Capacity and Sales is Closing!



- **Non-competitive PV fabrication lines are closing worldwide**
- **Demand > 50 GW 2015 might result in shortage of PV modules!**

Slide courtesy Tobias Kelm, ZSW; data from EPIA, Mercom, iSupply, BNEF, IEA, Photon, SW&W, Bloomberg, Solarbuzz, and own estimates

Deutsche Bank
Markets Research

North America
United States
Industrials
Clean Technology

Industry
Solar

Date
6 January 2014
Industry Update

2014 Outlook: Let the Second Gold Rush Begin

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Demand Could Surprise to the Upside

While we have been generally constructive on the global demand outlook, we are raising our 2014 and 2015 demand expectations to ~46GW and ~56GW respectively. We believe upside demand surprises from the US, Japanese and Chinese markets could continue in 2014. We expect streamlined incentive programs in China, additional subsidy cut signals in end 2014, and decreasing financing constraints to act as catalysts for upside. Similar to the '05-07 capacity rush, we expect another gold rush by downstream installers to add recurring MW ahead of policy changes over the next 2-3 years. Moreover, we expect grid and financing constraints to improve from 2014.

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Solar Thermal System Typology

Driving temperature	Collector type	System type
Low (60-90° C)		Open cycle: direct air treatment
		Closed cycle: high temperature cooling system (e.g. chilled ceiling)
Medium (80-110° C)		Closed cycle: chilled water for cooling and dehumidification
		Closed cycle: refrigeration, air-conditioning with ice storage
High (130-200° C)		Closed cycle: double-effect system with high overall efficiency
		Closed cycle: system with high temperature lift (e.g. ice production with air-cooled cooling tower)

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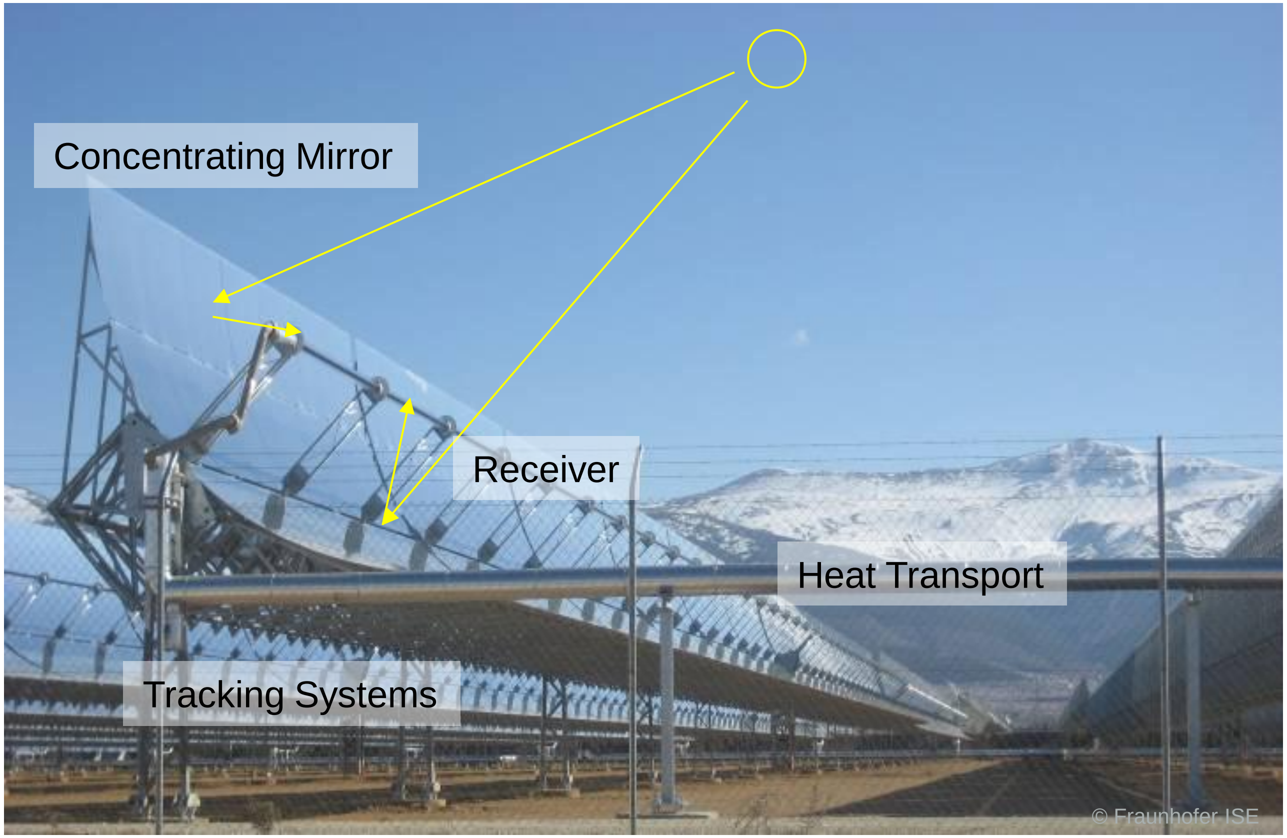
Solar Thermal Power Plants



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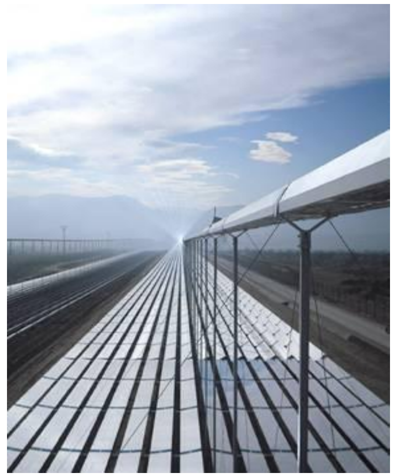
Concentrated Solar (Thermal) Power CSP Technologies

Parabolic Mirrors	Fresnel Mirrors	Stirling Dish	Solar Tower (Fresnel)
			
C ~ 70-90 commercial η_a ~ 12%-14% LEC_{2020} ~ 5ct/kWh	C ~ 60-120 demo η_a ~10%-12% LEC_{2020} ~ 5ct/kWh	C ~ 300-4000 demo η_a ~ 14%-18% LEC_{2020} ~ ?	C ~ 500-1000 comm. demo η_a ~ 10%-15% LEC_{2020} ~ 5ct/kWh

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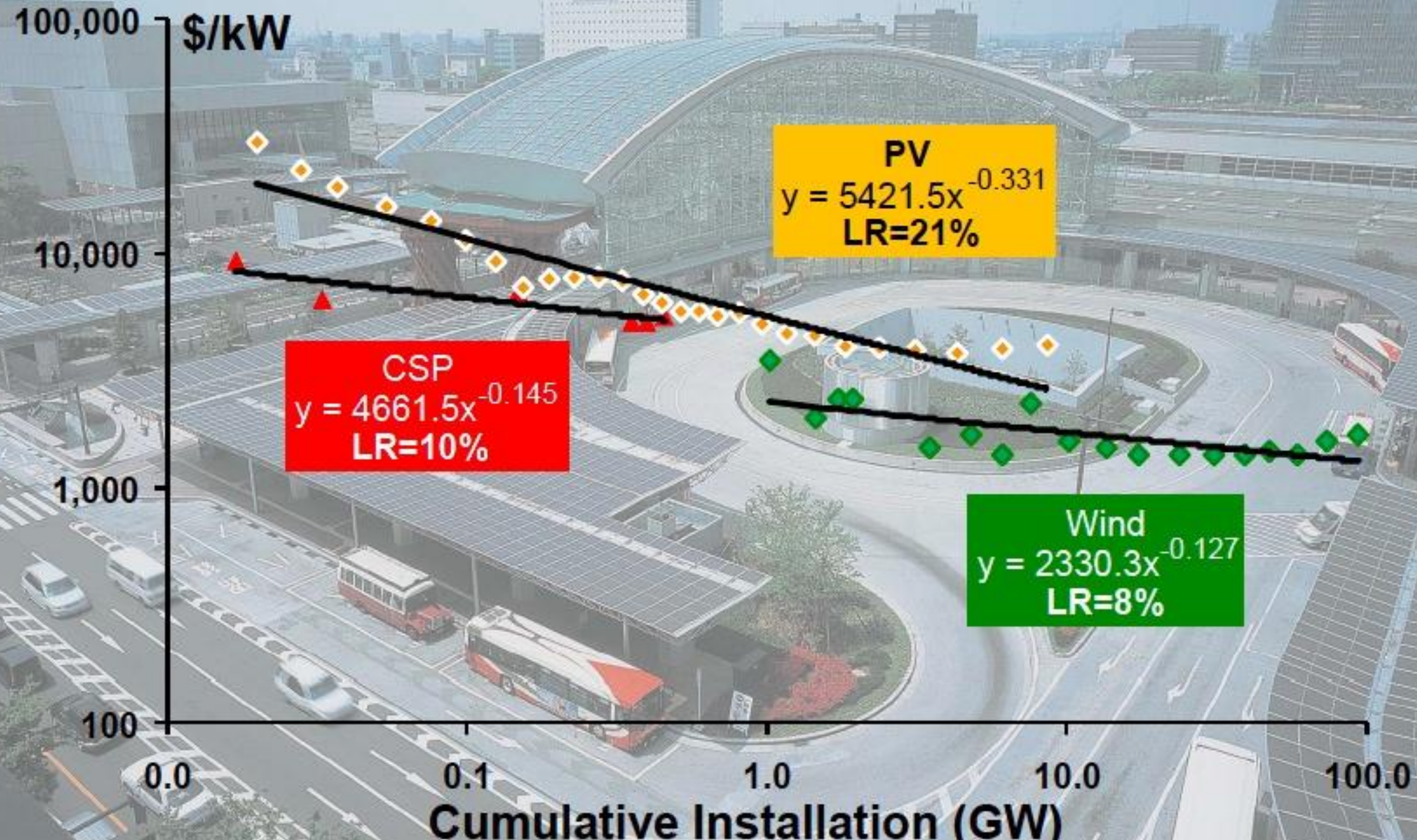
EXPERIENCE CURVES FOR SELECTED RENEWABLE ELECTRIC POWER TECHNOLOGIES



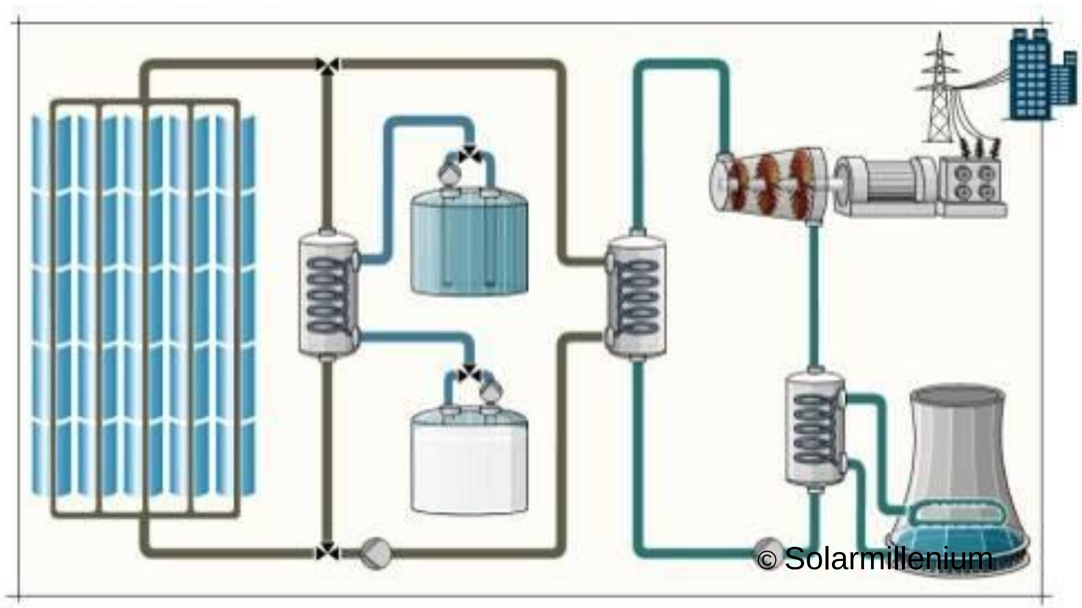
Source: Byrne *et al. [2009] A Review of Solar Energy Technology, Markets and Policy*. Prepared for the Climate Change & Clean Energy Development Research Group, World Bank

Center for Energy and Environmental Policy

Solar thermal power plants may include storage!

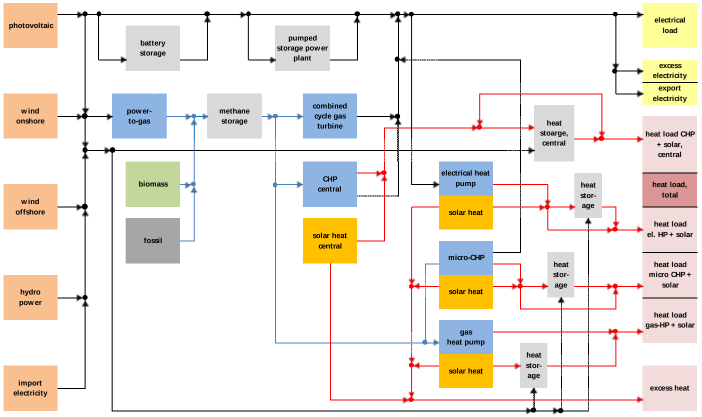
Components:

- Solar collector field
- Tubing and heat exchanger
- Storage – optional
- Power plant
- Cooling - wet- or dry cooling



ISE Model of a future German Energy System Combining Electricity, Gas and Heat *

Near-100% 24/7/365 reliable renewable energy from wind, sun, hydro & biomass at minimum total cost!



PV:	220 GW,	214 TWh
Wind:	253 GW,	596 TWh
Hydro	5 GW,	21 TWh
Biomass:		50 TWh

Energy Efficiency of Buildings: - 50%

Maximum Demand: 132 GW
Maximum Generation: 321 GW – Storage!

Total Cost: same as 2012!

Source: H. Henning, A. Palzer, Fraunhofer ISE 2012

*Without Transport, Import-Export!

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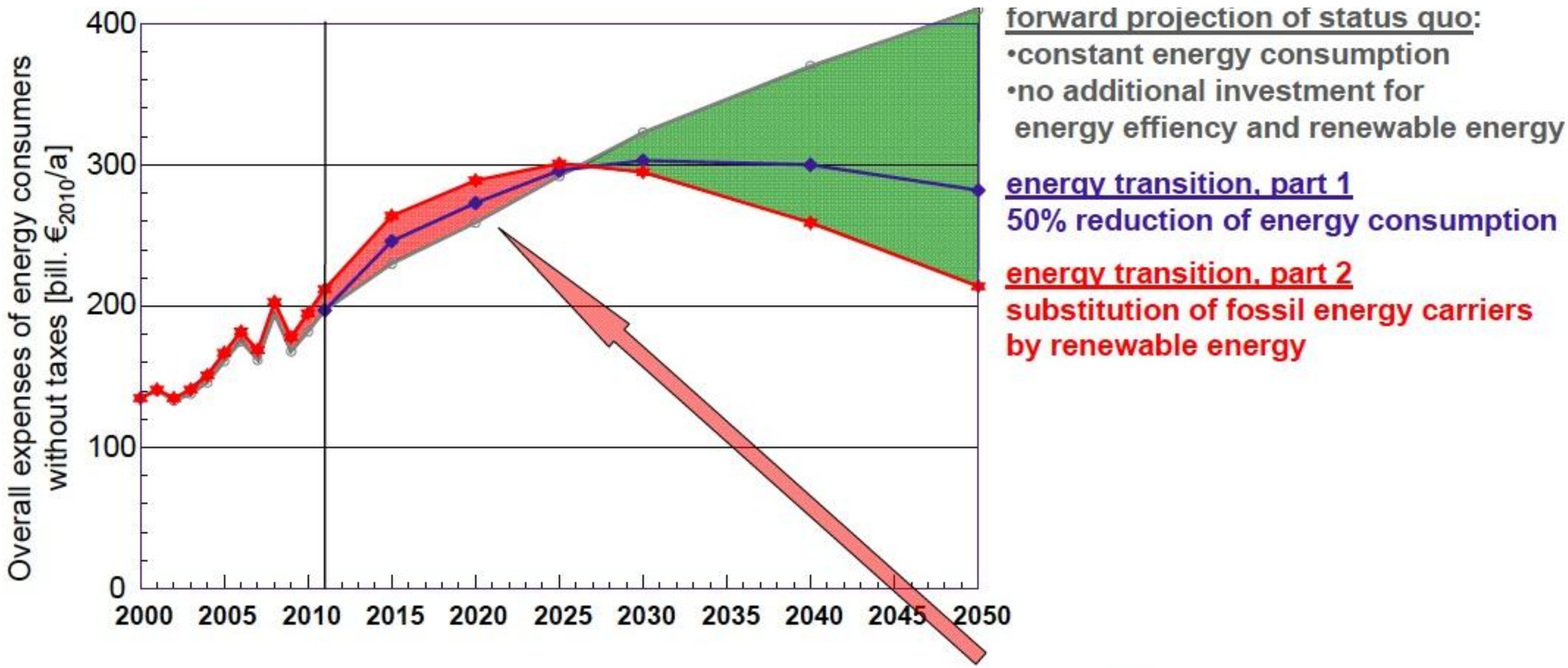
Example Germany: The Cost of the Energy Transition



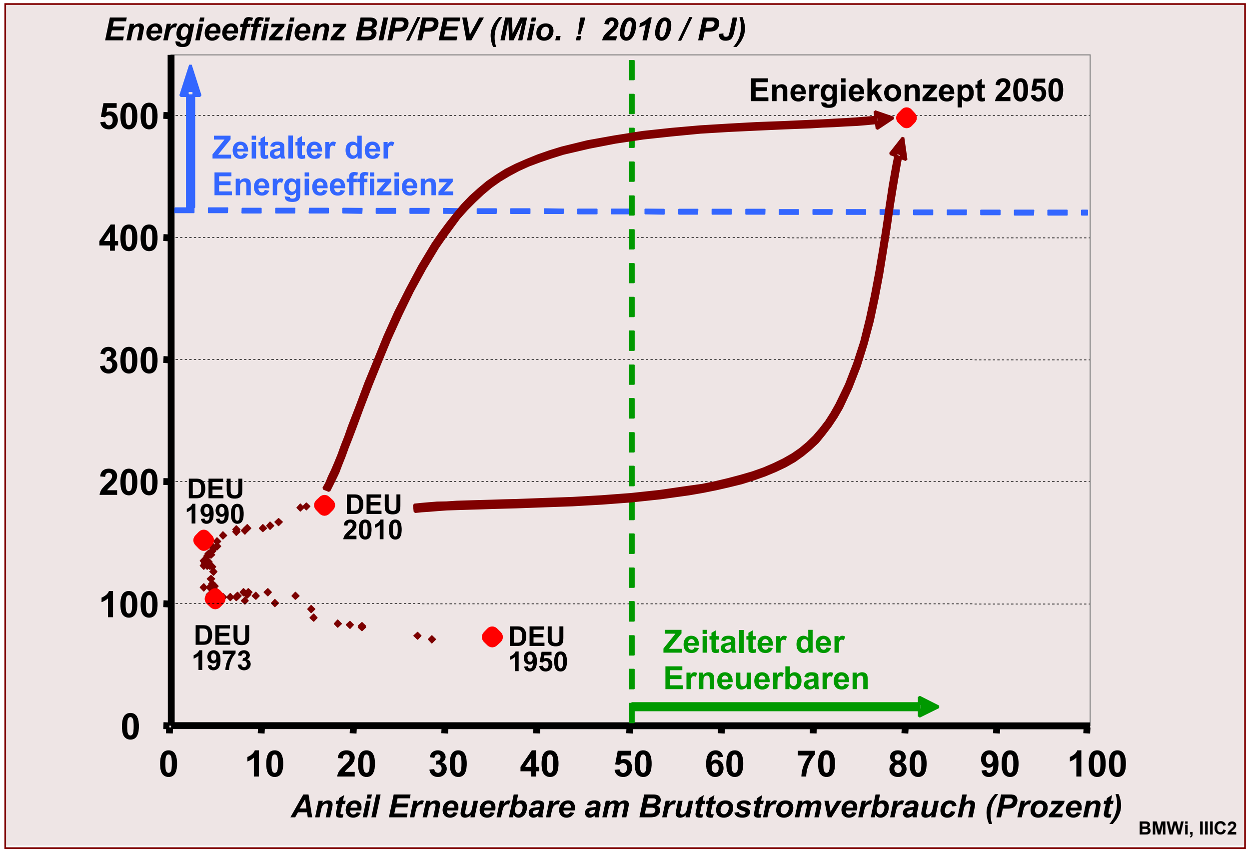
→ The extra cost for the energy transition is in the range of 5% to max. 8% of total energy expenses and will be needed until about 2025 (total: about 300 bill. €).

→ In the longterm this is profitable against a forward projection of the status quo.

Slide courtesy F. Staiss 2013, based on data from BMU

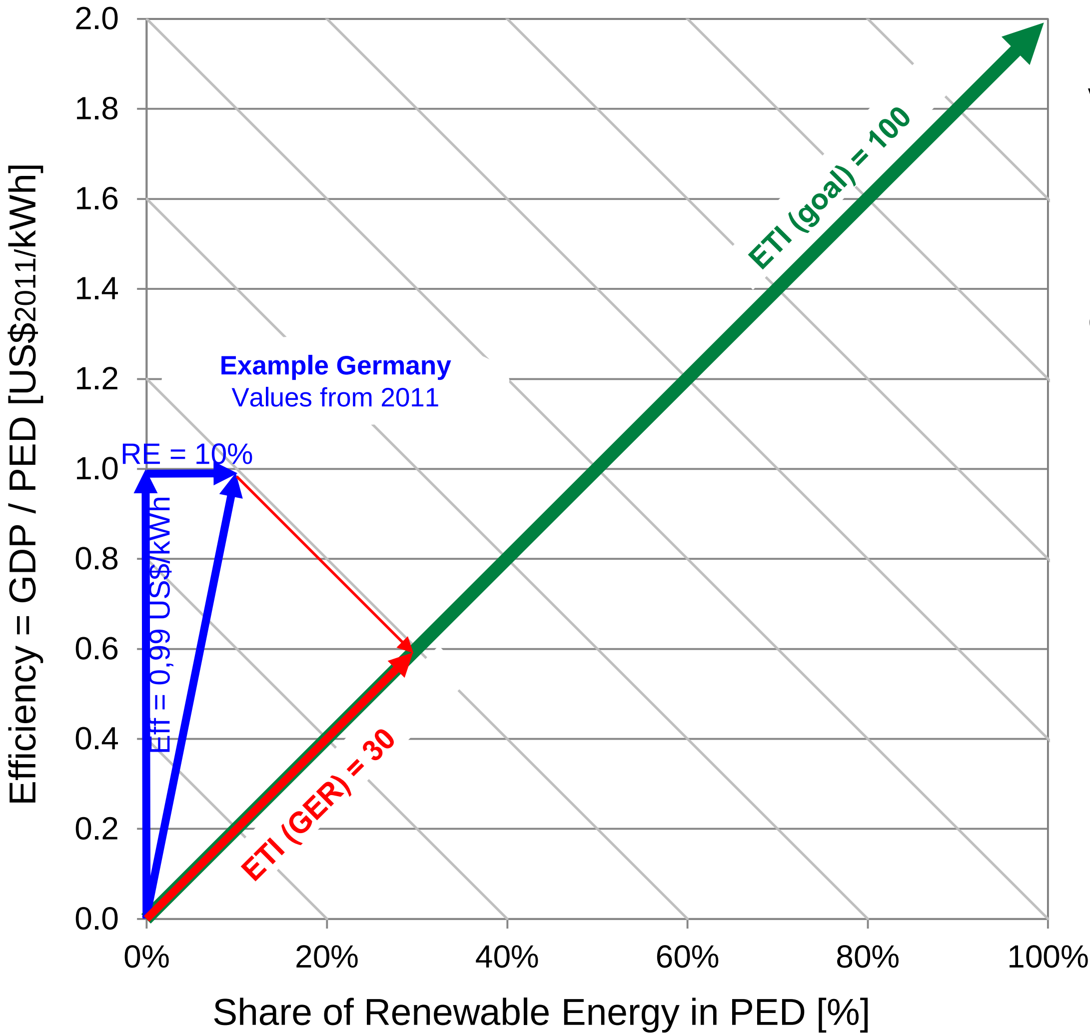
The Road Towards the Energy Transformation: Energy Efficiency and Renewable Energies

We should describe progress on this road by an index: ETI



Graph: K. Kübler, BMWi, FVEE 2011

Energy Transformation Index ETI - Definition



ETI = Normalized length of the vector in the Eff / RE diagram

Eff = Efficiency = GDP/PED [US-$$_{2011}$/kWh]

Eff_n = Eff / 2 $/kWh

GDP = Gross Domestic Product [$$_{2011}$]

PED = Primary Energy Demand [kWh]

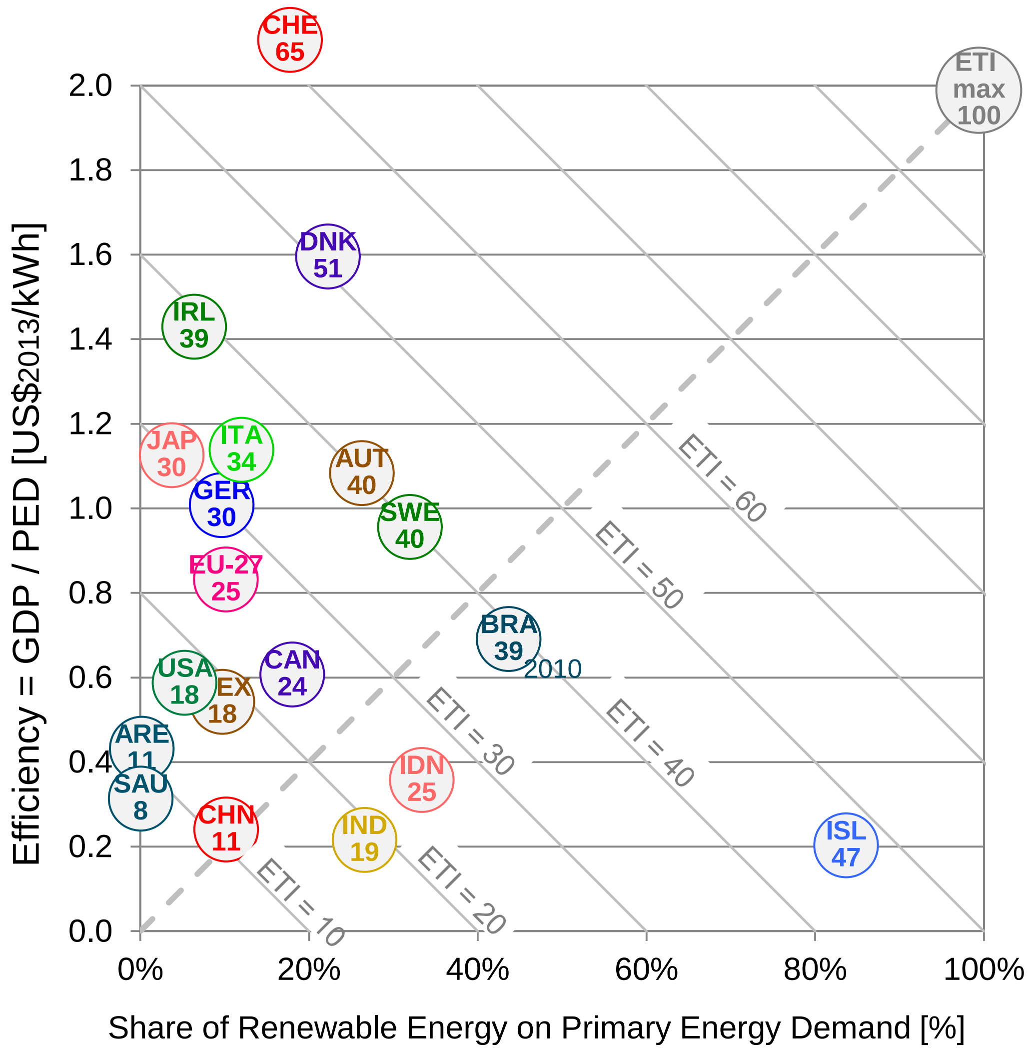
RE = Share of Renewable Energy [0.….1] (1 means 100%)

ETI = 100 * (Eff_n + RE)/2

[0…….100…..]

ETI: = average of Eff_n and RE!

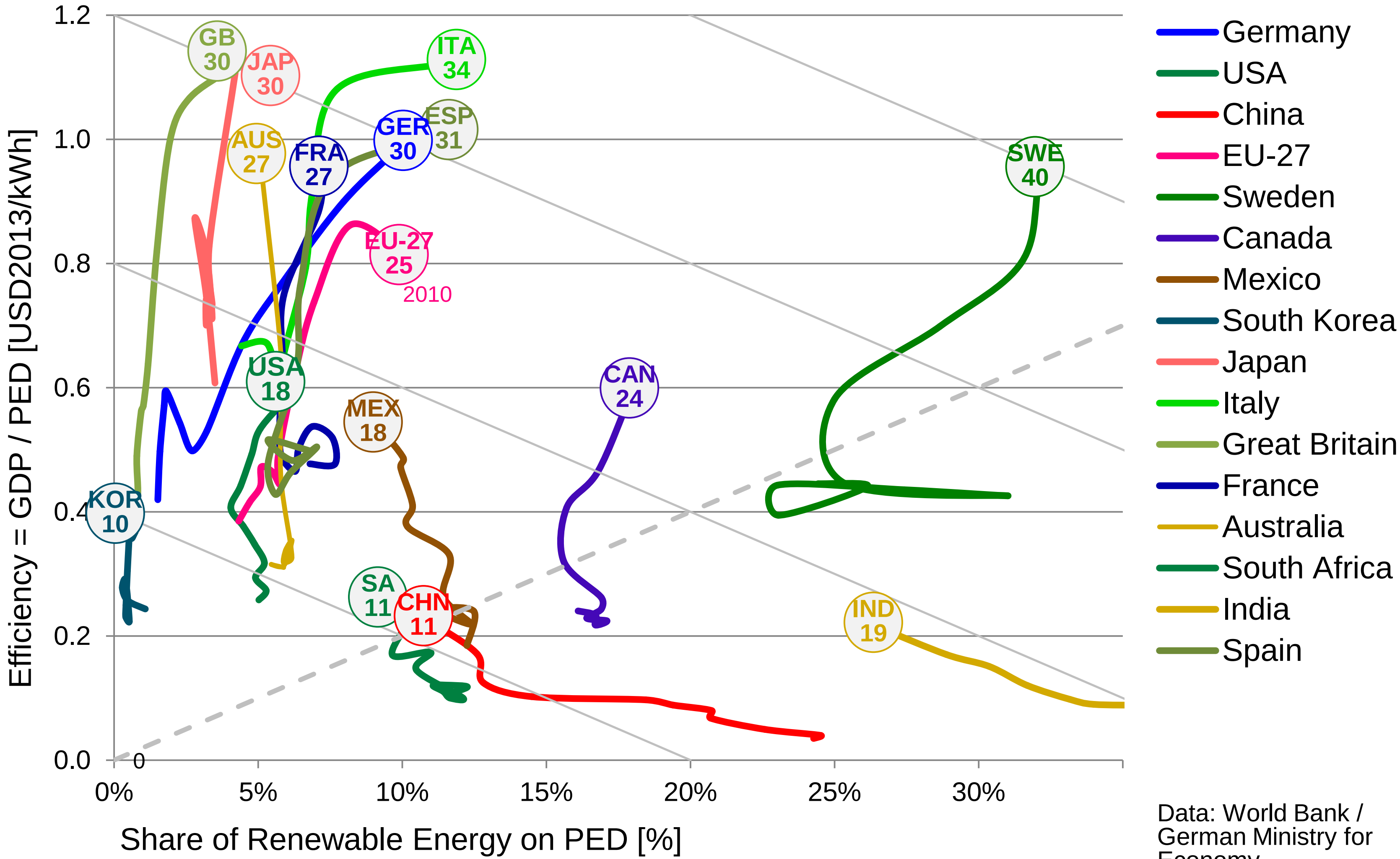
Energy Transformation Index ETI for different countries



ARE United Arab Emirates
AUT Austria
BRA Brazil
CAN Canada
CHE Switzerland
CHN China
DNK Denmark
EU-27 European Union
GER Germany
IDN Indonesia
IND India
ITA Italy
IRL Ireland
ISL Iceland
JAP Japan
MEX Mexico
SAU Saudi Arabia
SWE Sweden
USA United States

Data: World Bank / IEA, German Ministry for Economy

Development of ETI for selected countries 1990-2011



Data: World Bank / German Ministry for Economy

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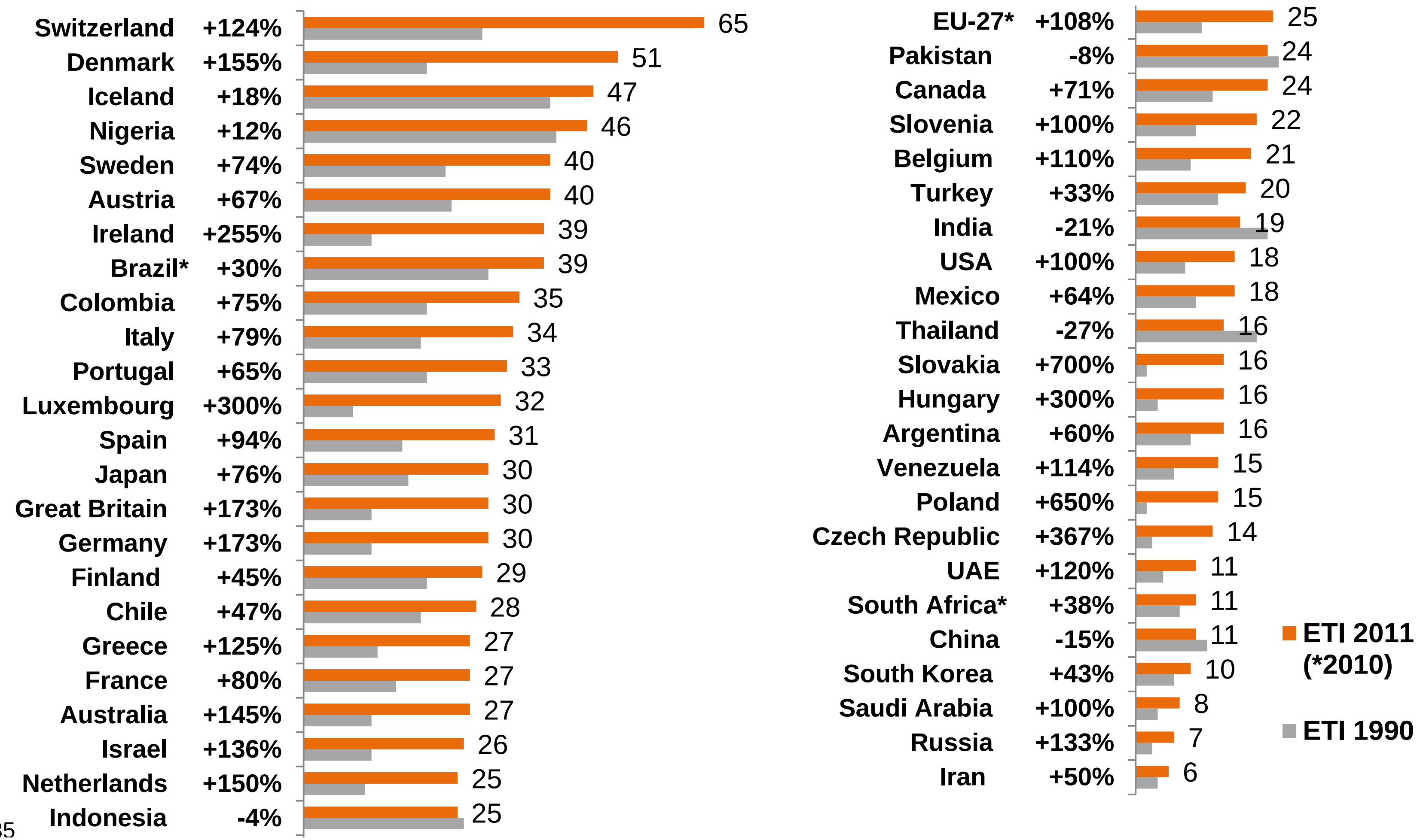
ETI-Ranking for 47 countries

and growth between 1990 and 2011 (percentage)



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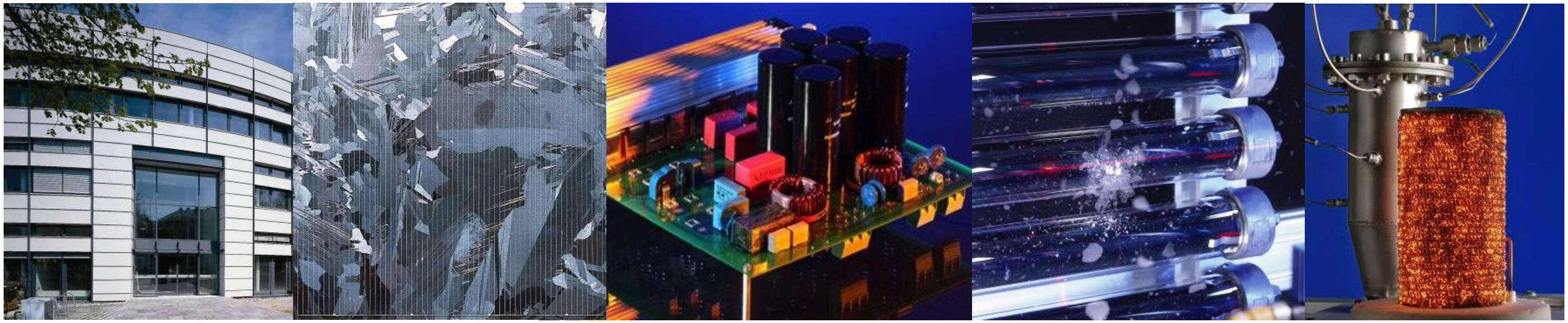
The Role of Solar Energy in our Future Energy System

- A near-100% renewable energy system is possible, at similar cost as today's energy supply – no more need for imported fuels, almost all is spent domestically
- PV will be one of two main pillars – with drastically reduced prices of € 1.00-1.20 /Watt installed LCOE of PV electricity is below 10 ct/kWh, will go down further
- Small, distributed battery systems combined with large storage systems and grid interconnection will guarantee secure power supply
- The use of solar thermal energy harvestingen makes especially sense in sun-rich countries; low-T ST for warm water, CS(T)P with storage for electricity
- CSP without storage is not longer cost-competitive compared with PV
- In regions with high DNI, CPV is most attractive as it offers the maximum number of hours per day
- Progress in the energy transformation process will be easily monitored by our new ISE / ISES ETI

Thank you for your Attention!



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Eicke R. Weber with Ralf Preu, Harry Wirth, Klaus Kiefer…

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Winner
Non-Governmental Organisation
Sixth annual Zayed Future Energy Prize
Fraunhofer Institute for
Solar Energy Systems ISE