Energy Future
(Summary of lectures 1&2)

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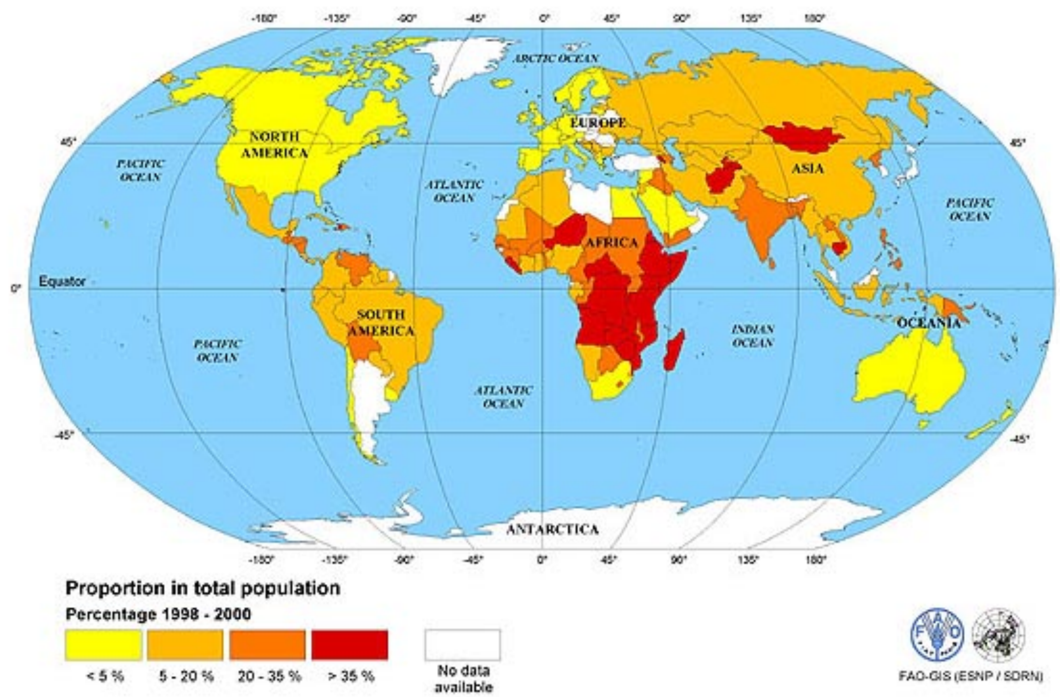

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Abstract

Renewable sources of energy, especially carbon-neutral ones, are our great hope for addressing the Energy-Development-Environment-Climate Challenge. This talk will discuss the ongoing development of solar and wind technology and resource utilization. It will explore the status of bio-fuels and storage options. An overview of the economic, technology and resource challenges will be presented. The talk will emphasize the need for breakthroughs in storage technology, both at the individual home and the grid scale, for realizing the potential of solar and wind.

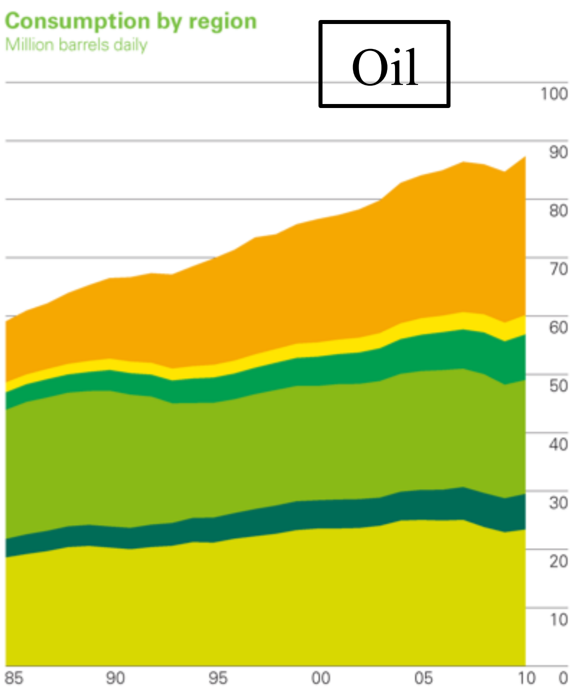
In the 21st century, the world will not stop using fossil fuels because there is not enough, but because there are cleaner & cost-effective alternatives

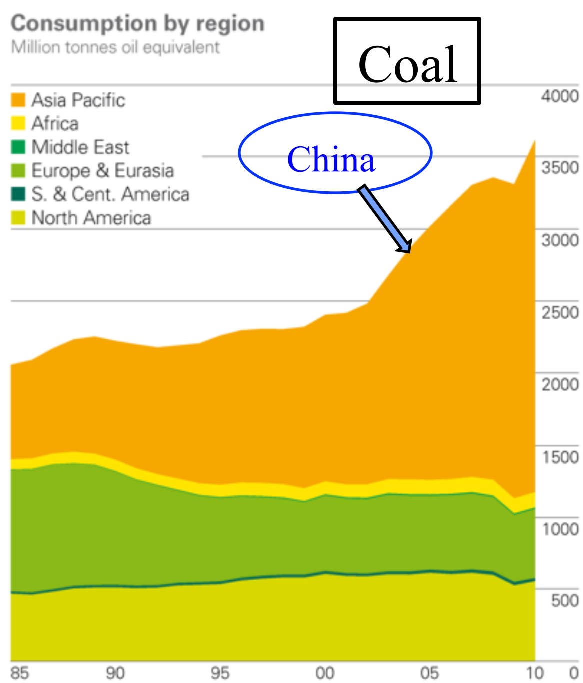
To prevent further accumulation of CO_2 in the atmosphere requires reducing emissions to pre-industrial levels – a few gigatons/year

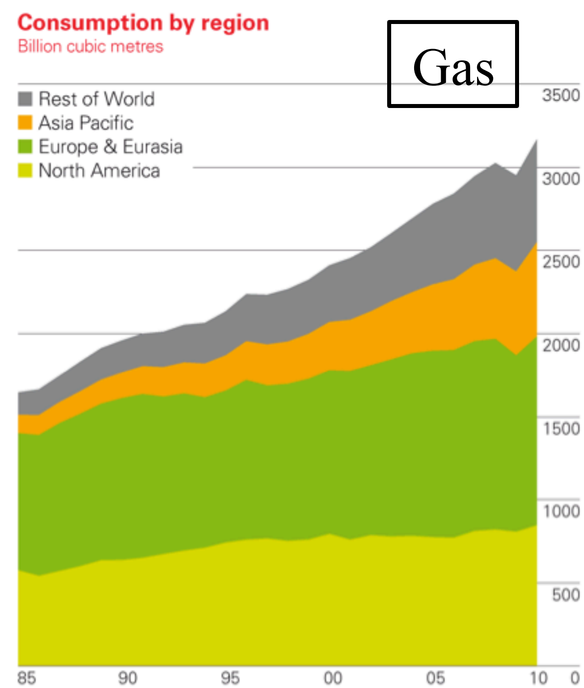
Historical (1985-2010) Growth trends:

driven by (a) demand (b) capacity for new additions

	Production 2010	Historical Growth	Historical growth as % of 2010 Prod.
Oil	86 MMbo/day	1 MMbo/yr	1.2%
Coal*	3.6 BToe	160 Mtoe/yr	4.4%
Gas	3150 B cum	60 B cum/year	1.9%







Source: BP Statistical Review 2011

Highlights of Lecture 1 & 2

- Coal usage dominated by ~20 countries
  - Future dominated by China, USA, India
  - Short-term growth to continue at >2.5%
- Natural gas is/will be the dominant fuel in many regions of the world–a much better fuel than coal
  - Reduce leakage & environmental impacts of extraction
- Urbanization is proceeding at a very rapid rate
  - Numbers of mega-cities and large cities are growing and will remain centers of economic activity
  - Large centralized power plants will continue to have the benefit of economy of scale
- Improve Efficiency (all aspects & cradle-to-grave)

2030: Coal and gas will fuel 3-4TW capacity

Countries that can switch coal→gas relatively easily

- USA
- Germany
- Poland
- Czech, Ukraine, Bulgaria, Romania, Greece, Turkey
- Russia
- Kazakhstan
- China
- Japan, Korea, Taiwan
- Vietnam
- Australia
- Indonesia
- India
- South Africa

4 major "island" nations: Japan, Korea, Taiwan, India

Natural gas role in power generation

Dominant in
- South America (after Hydro)
- North Africa
- Middle East
- Iran
- Central Asia
- Russia

Major fuel in
- North America
- Europe
- South-east Asia
- China (shale-gas?)

Cleaner, multipurpose fuel that provides backup to renewables.
GHG emissions make its widespread use a challenge

Solar, Bio-fuels, Wind, Storage (lecture 3)

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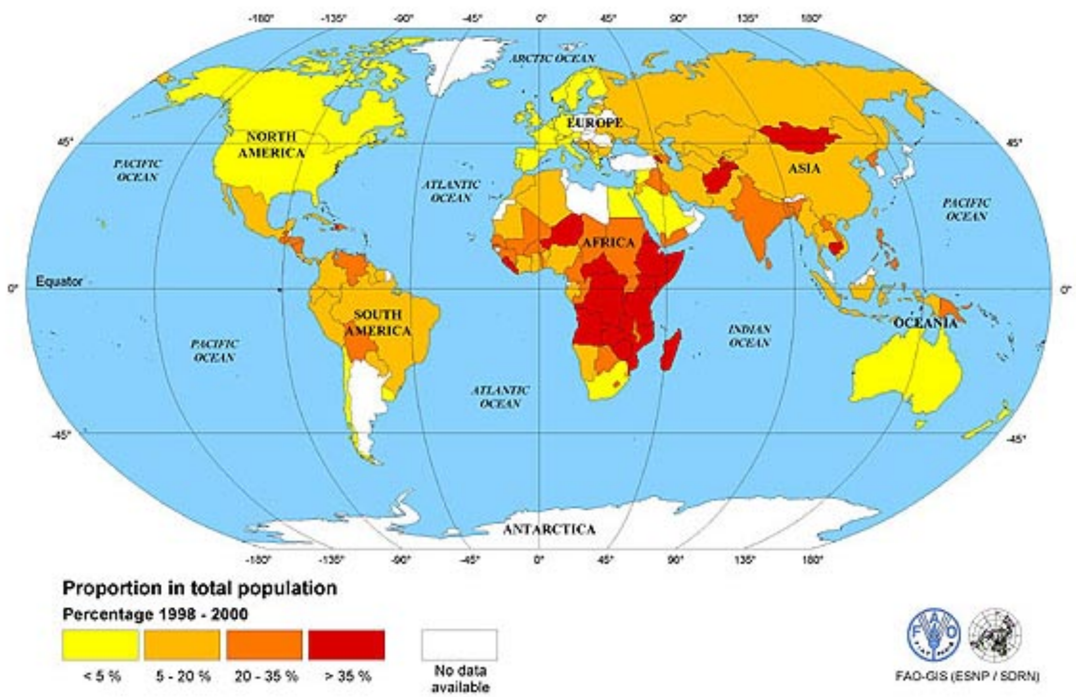

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Lecture 3 examines emerging alternatives

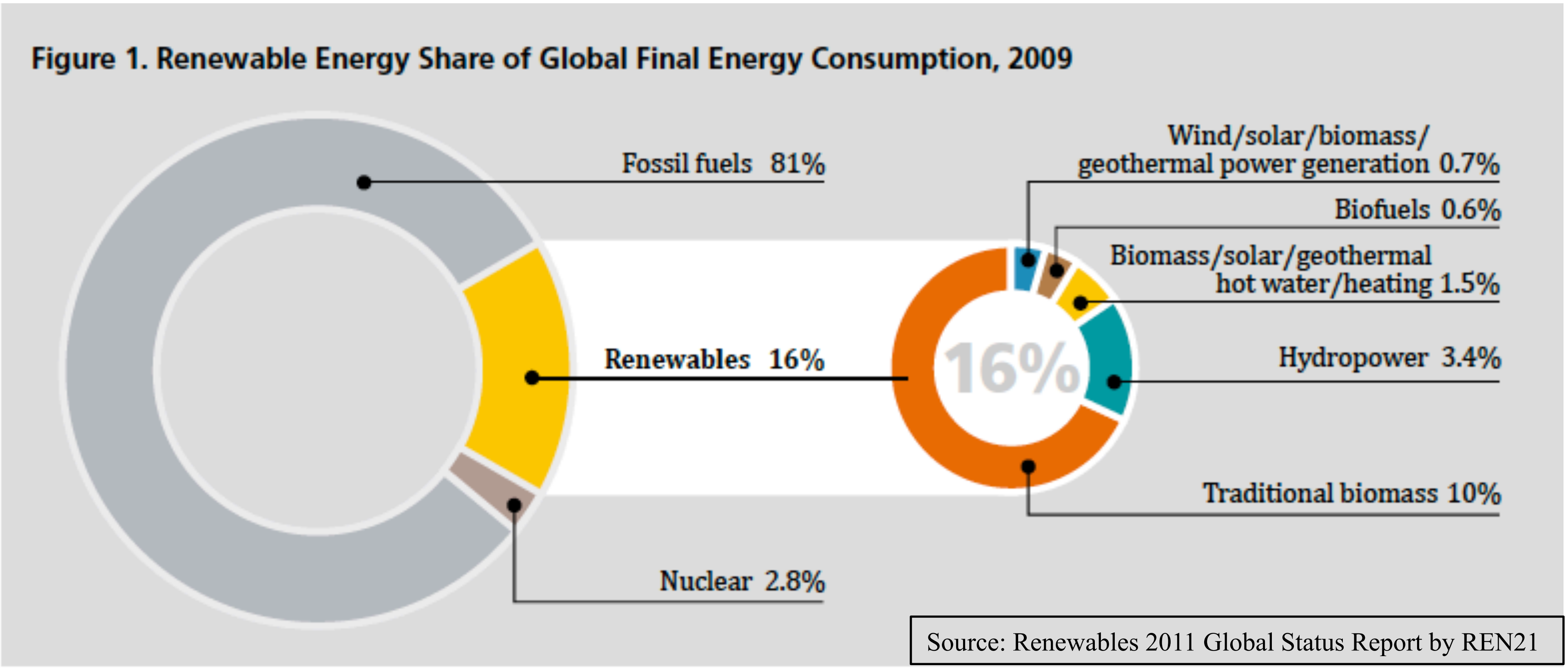
- Photovoltaic (PV)
- Concentrating Photovoltaic (CPV)
- On-shore Wind
- Off-shore Wind
- Storage for electrical energy
- Concentrating Solar Power (CSP)
- Bio-fuels

A changing mindset: a society that values the commons?

Overall message [2012-2050]

- The challenge is not
  - Is there enough solar potential globally
  - Is there enough wind potential globally
  - Is there enough land
- The challenge is
  - Cost
  - Scaling up to a "solution wedge"
  - Associated Infrastructure & Integration
    - Transmission Lines
    - Control systems (dispatchable, reliable, secure power supply)
  - Impacts on other critical resources
    - Land, Energy Critical Elements, Water, …
- Solar and wind will, at best, be part of a solution

Status



Historical experience (economics, profit, ease of use) since the industrial revolution is stacked against renewable resources.
Challenge: Changing the mindset and valuing the commons

Solar

Goal in my Gedanken World:
4 TW_p installed solar capacity
= 1TW at 70% PLF

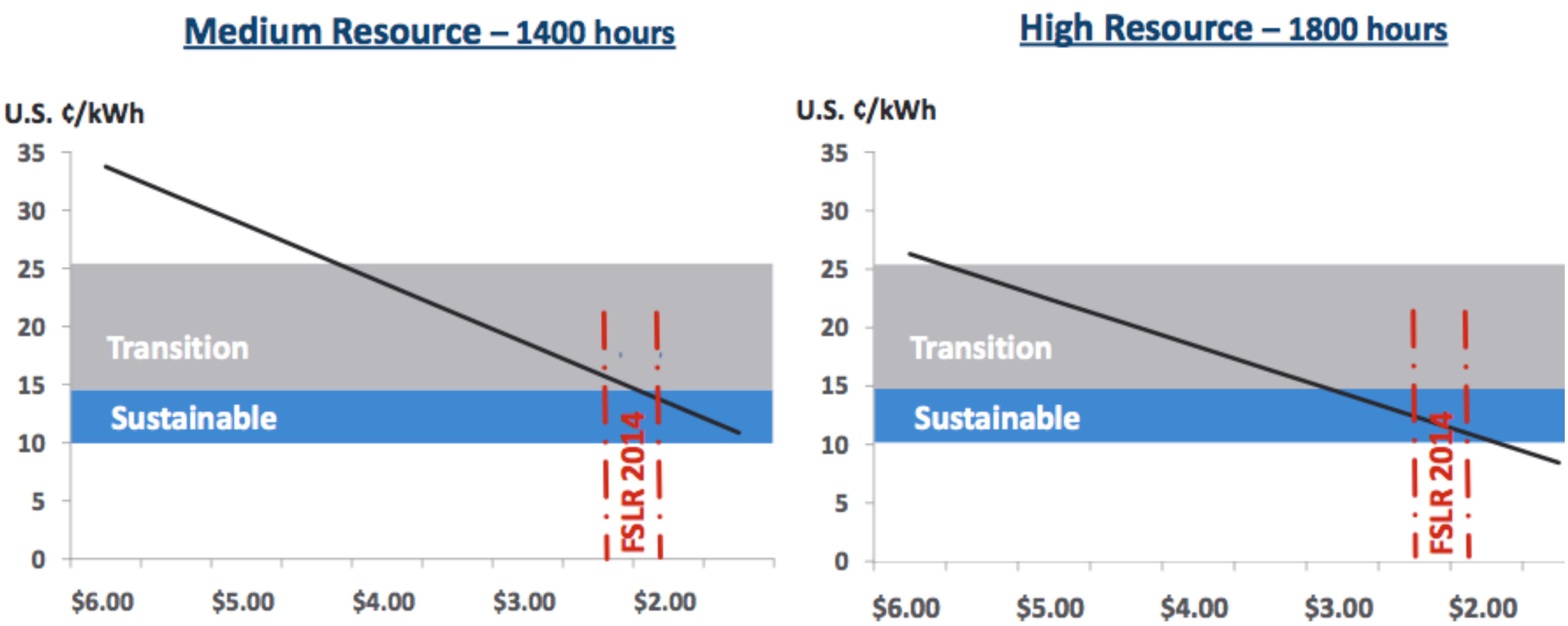
Niche for solar PV

- Off-grid and grid-connected electric power for individual homes
  - Photovoltaic (PV)
- Any 1.5–12V battery doable function can be powered by rechargeable batteries using PV
  - Room/space lighting using LEDs
  - Cell phones → Computers: access to global communications
  - ……
  - Automobile batteries
- Cost reduction + help with up front capital cost will allow the poor to share the benefits

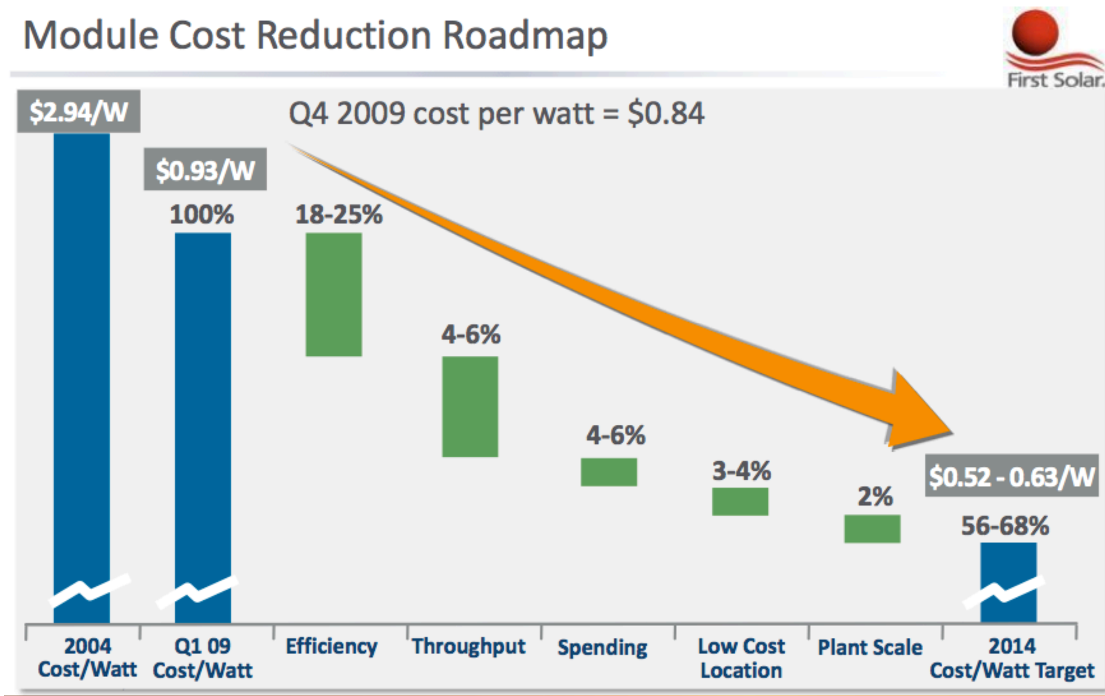
Utility Scale Plant

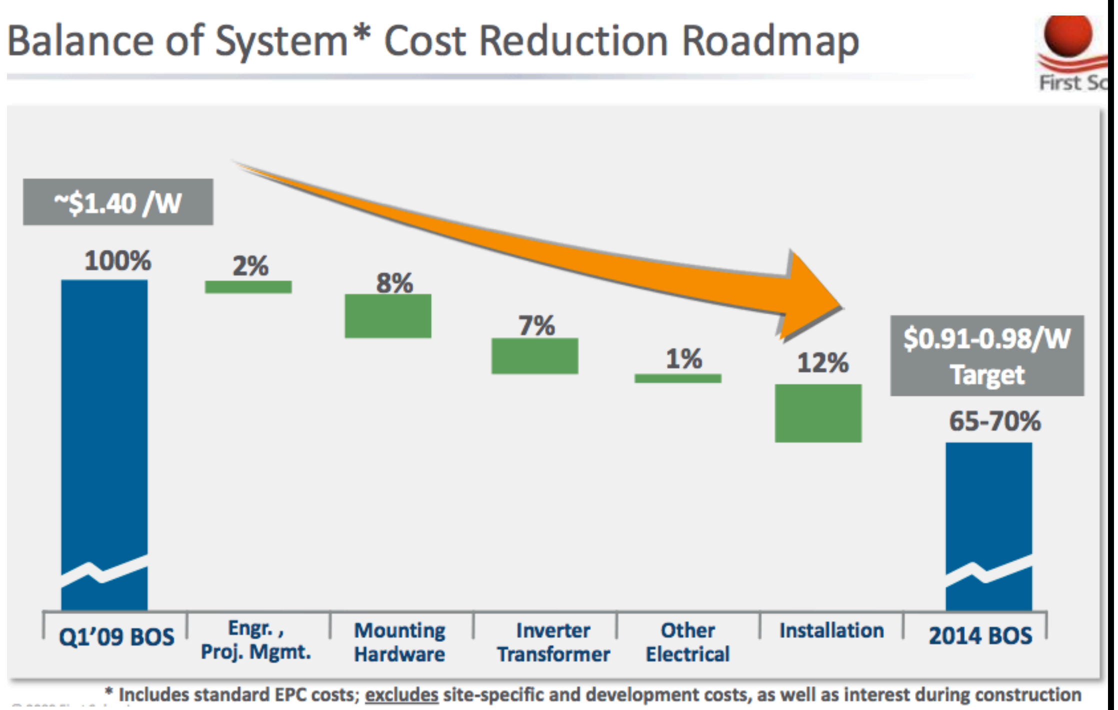
Cost Reduction – Solar Electricity (LCOE)

First Solar.



Note: Assumes 7.5% unlevered IRR, 10% ITC, 2.5% electricity power price escalator, FSLR panels, utility scale plant, install labor and site specific cost estimates. Includes owner development costs, financing costs and O&M.





Economics for home use:

If Insolation = 2000 kWh/m^2

Yearly output = 2 kWh/Watt$_p$

1 Watt$_p$ = 0.2 Watt (with degrading)

If installed cost = \$4/Watt$_p$

If home need = 1 kW

= 5 kW$_p$ (with degrading)

Capital Cost = \$20,000

If utility price = \$0.1/kWh

If grid feed-in tariff = \$0.1/kWh

⇒ no usage cost @1 kW

⇒ \$20K @ \$72/month = 23yr

Payback Time = 23 years

Challenges:

Owner: Pays interest on \$20K for 23yr

Utility Company: Bears cost of maintaining full capacity for backup

When is PV sustainable without subsidy?

- \$20K @ \$4/watt$_p$ buys a 5 kW$_p$ = 1 kW system
  - Monthly bill of 1kW @ \$0.1/kWh = \$73/month
  - Payback in 23 years if feed-in tariff is @ \$0.1/kWh
  - Write off \$20K investment as a quality of life issue
- If \$20K is financed at 5% interest rate for 23 years
  - Monthly Payments = \$122/month
  - Cost of electricity for breakeven = \$0.17/kWh

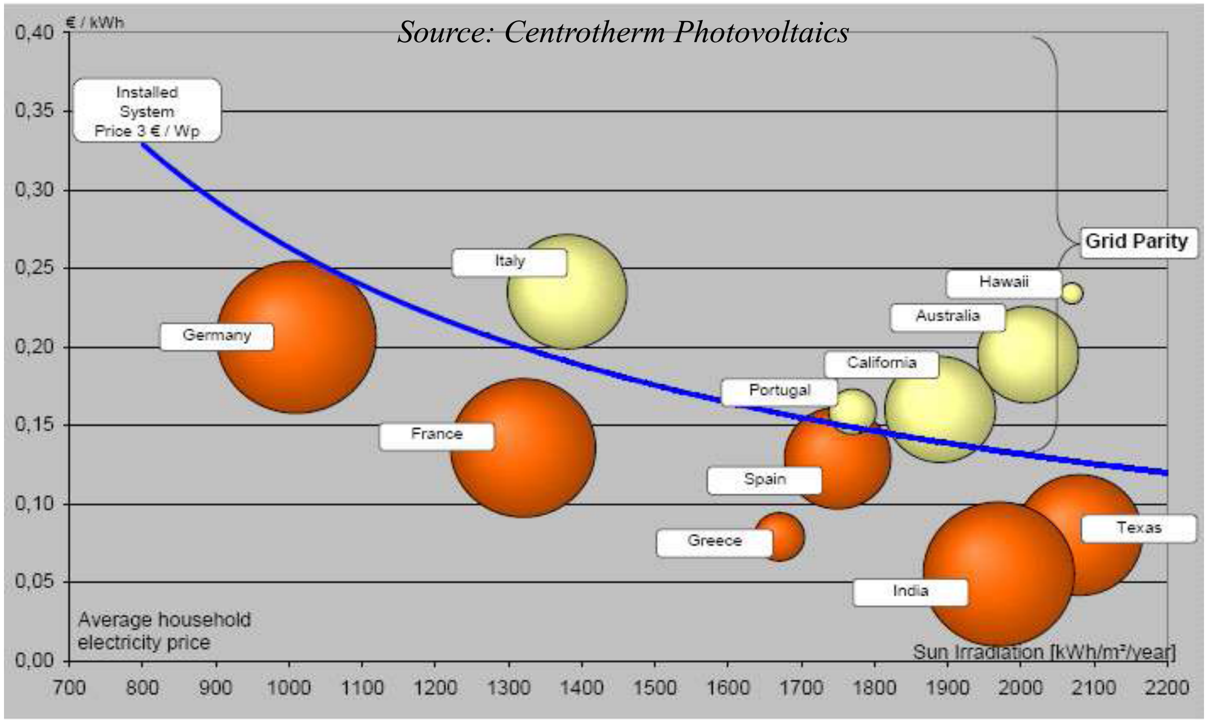
At grid parity (feed-in tariff = usage cost) PV is profitable at

- ~\$0.2/kWh for constant utility price
- ~\$0.1/kWh + 5%/year price increase in utility power

Business case for PV without storage?

- Solar PV = $2/Watt$_p$ installed (5 kW$_p$ system for 10K)
  - Grid feed-in tariff at parity = $0.2 / kWh = utility price
  - ✓ Monthly payment on $10K = $106 @ 5% mortgage for 10 years
  - X Utility companies have **Zero** incentive to provide grid connection at $0.2 / kWh with at par feed-in tariff
- Solar PV = $1/Watt$_p$ ($5K?) & Utility power @ $0.2/kWh
  - ✓ Grid feed-in tariff = $0.1 / kWh ----- Consumer happy on average use
  - X Utility companies provide capacity to overcome Intermittency
  - ? Is $1/W$_p$ feasible? Labor cost of home installation (20hrs×$100 = $2K)
- Utilities provide electricity @ $0.2/kWh + 2.5%/yr increase
  - Install and provide 20% electricity from solar/wind (2011 EMS)
  - Install new transmission from wind rich areas to population centers
  - Pay fossil-fuels tax @ $0.1/kWh that funds R&D and infrastructure

Same math in Europe



Optimistic case: Solar insolation = 2000 kWh/m^2/year
Grid parity is at €0.13/kWh ≈ $0.20/kWh at €3/Watt$_p$

Germans are willing to pay $0.3/kWh but still fall short since average insolation is 1000 kWh/m^2/year !

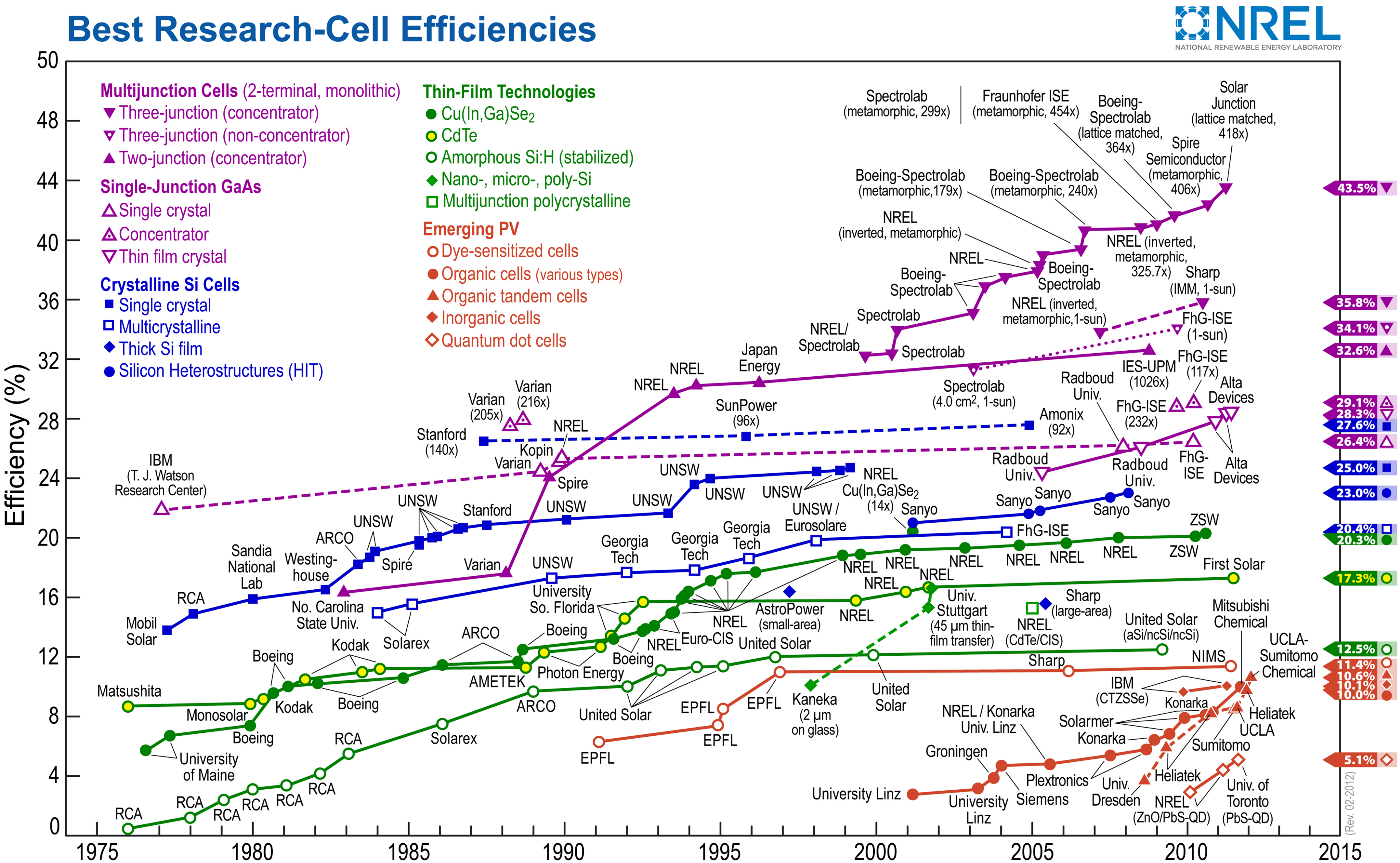
PV with storage: residential

- PV system: Invest $10K @ $2/watt$_p$ to buy a 5 kWp PV system
- Storage 20kWh
  - $4K for Lead Acid battery with 41 Watt-hour/kg
  - $11K for NiCad battery with 128Watt-hour/kg
  - + Cost of charging system @ 20kWh in 2-15 hours
  - + Home energy management system and smart appliances
- Payback in ~20 years if conventional power @ $0.2/kWh

Need to address

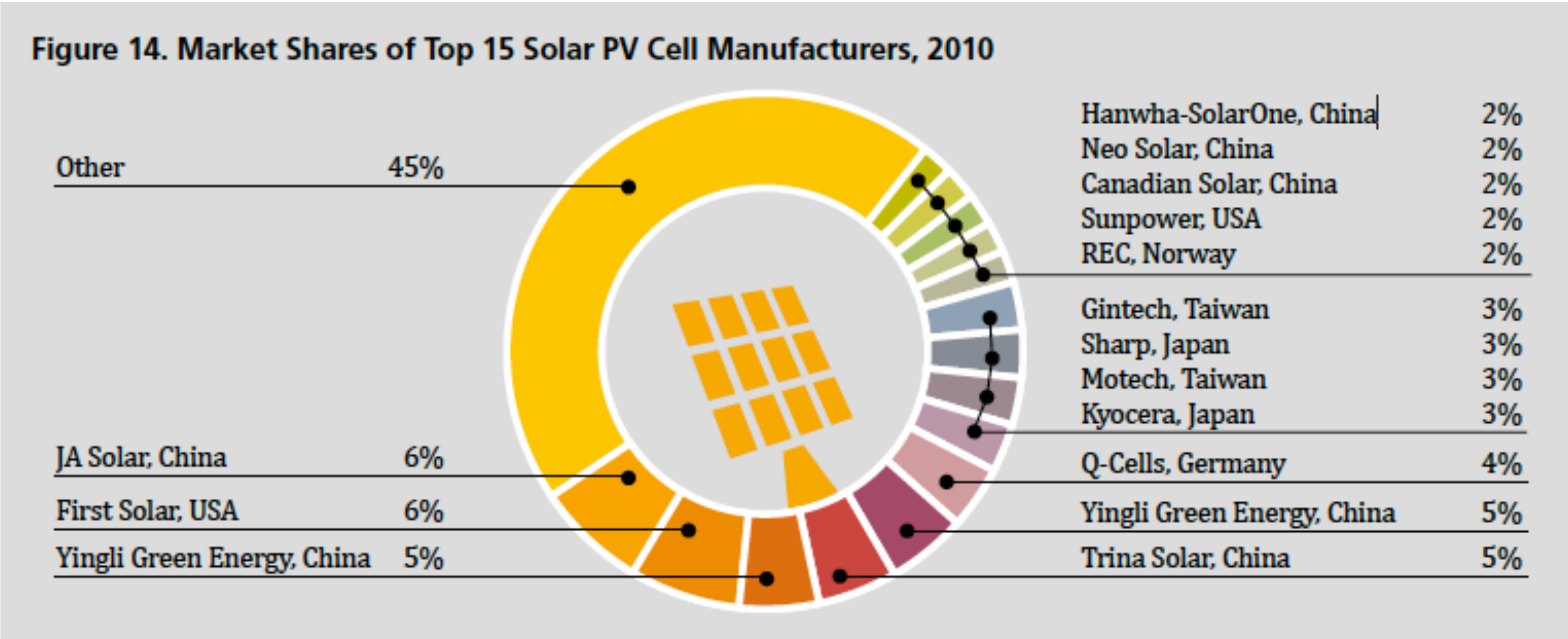
- Cost of living off-grid?
  - Will utilities be willing to provide backup service at say $0.5/kWh + monthly connection charge
- High current applications (Oven, air-conditioners, …)
- Cost of dealing with breakdowns and maintenance?

Best business case: design integrated solar–geothermal power, heating, cooling system at time of build



http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

Solar PV manufacturing capacity



Cost of PV modules: $1.30-1.80/Watt$_p$
Cost of installation: ~$1.50-2.50/Watt$_p$
Installed Cost: ~$4 / Watt$_p$

Source: http://www.ren21.net/Portals/97/documents/GSR/REN21_GSR2011.pdf
REN21, PV News

Industry Leaders

- First Solar (14.4% CdTe thin film technology)
- Sun Power (17% efficient polycrystalline)
- Sharp, Kyocera, Sanyo in Japan

Manufacturing capacity: 23.9GW in 2010

China	~50%
Taiwan	15%
EU	10%
USA	<10%
Japan	<10%

Energy Critical Elements: Tellurium (Te)

- Used in thin film PV
- 0.0000001% of Earth's crust
- By-product of copper mining
  - 2009 extraction: Te=200T versus Cu = 15.8 million Tonnes
  - 2009 cost: Te = $145/kg versus Cu = $5.22/kg
- 15% efficient PV with 3 micron Te layer requires
  - $15 gm/m^2 \rightarrow 0.1 gm/W_p$ ~ $100T/GW_p$
- Little is known of Te reserves and extraction efficiency

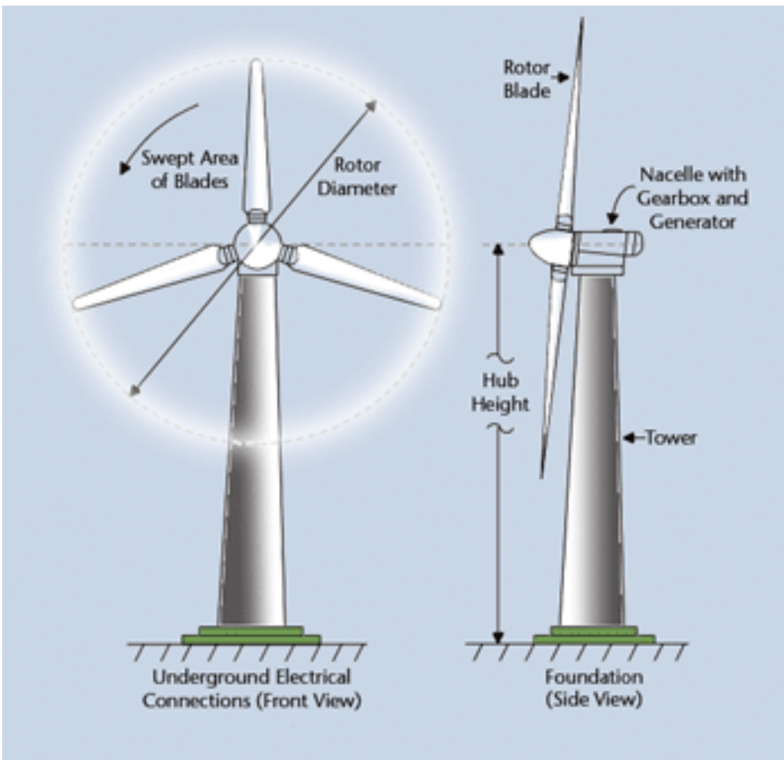
Will ECE resources limit growth?

Source: APS panel report on Energy Critical Elements 2011

Wind Power

Goal in my Gedanken World:
6 TW_p installed wind capacity
= 2TW at 70% PLF

A wind turbine is a large complicated fan

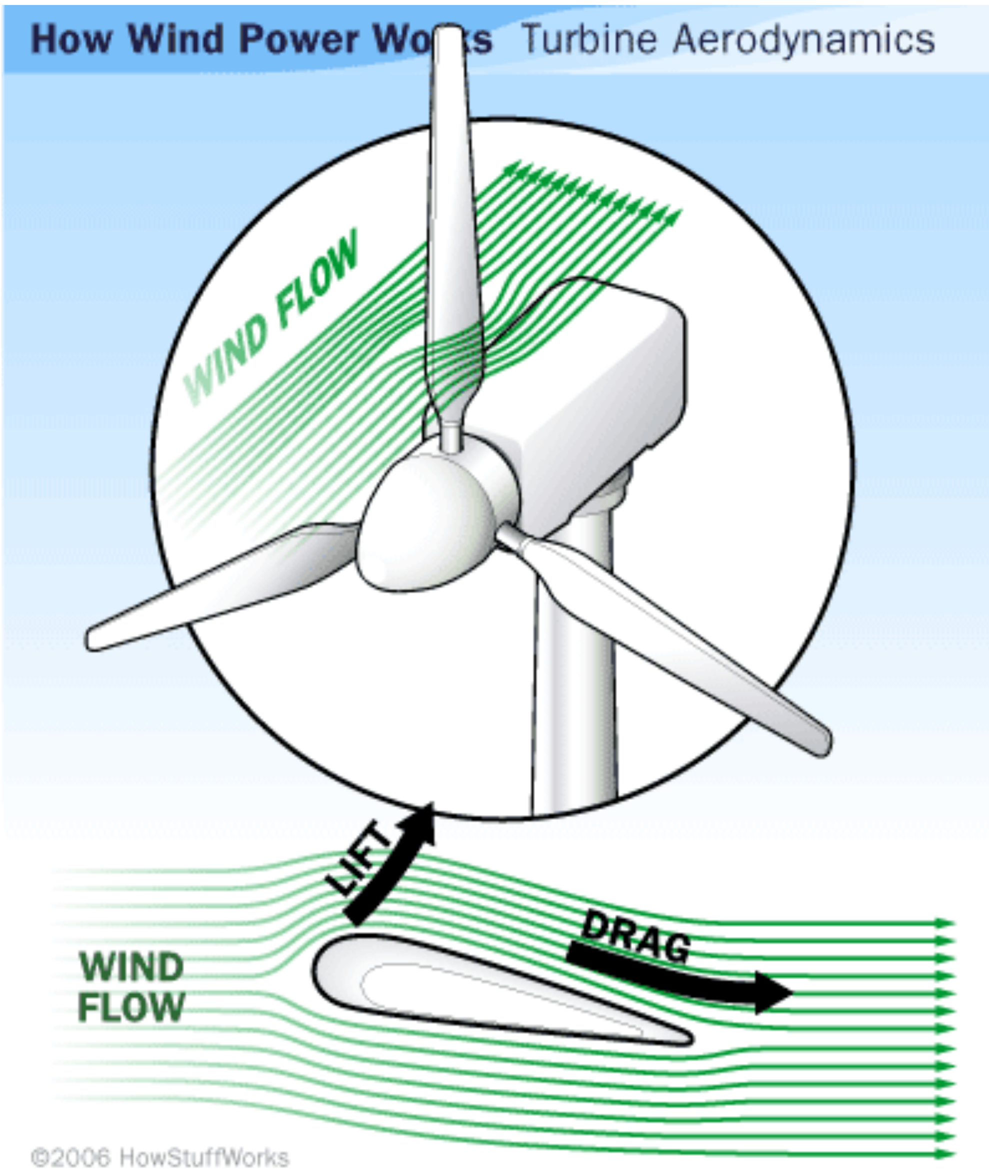


Drawing of the rotor and blades of a wind turbine, courtesy of ESN

- Speed of the blade tip
  - r = 60m, t = 0.001 hr
  - v = 2πr/t = 377 km/hr
- Difference in wind across 60 –120 meter wing span

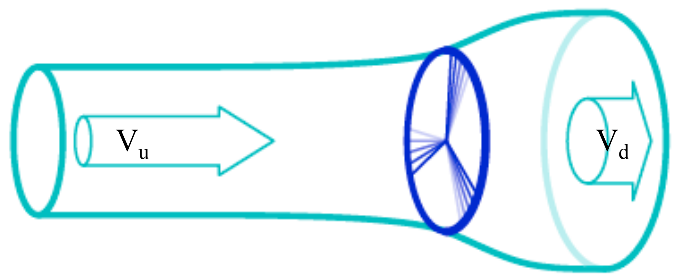
Torques & Flutter
→ R&D

Modern wind turbines use airfoil design



Incident energy

$\frac{1}{2} m v_u^2 = \frac{1}{2} \rho A v_u^3$

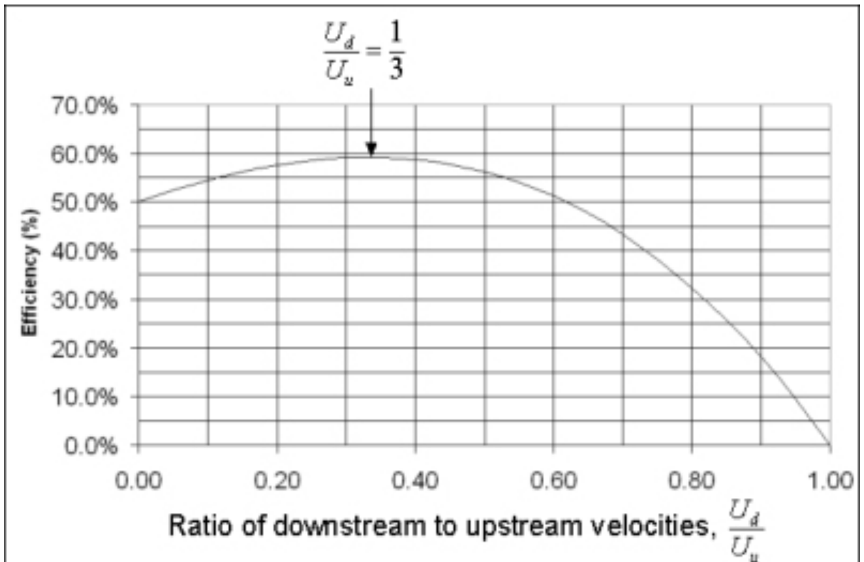


Energy Transfer

$\frac{1}{2} \rho A (v_u^3 - v_d^3)$

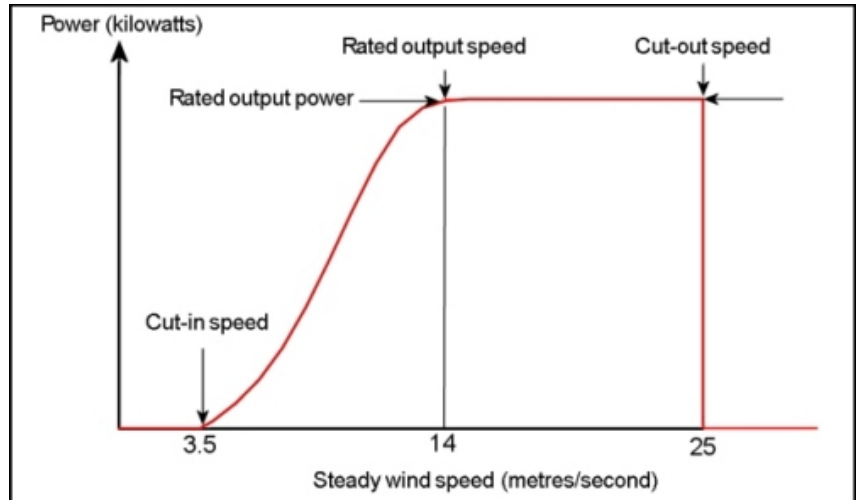
$$\eta = \frac{Power}{\frac{1}{2}\rho A_t U_u^3} = \frac{1}{2}\left(1 - \frac{U_d}{U_u}\right)\left(1 + \frac{U_d}{U_u}\right)^2$$

Betz Limit and Efficiency

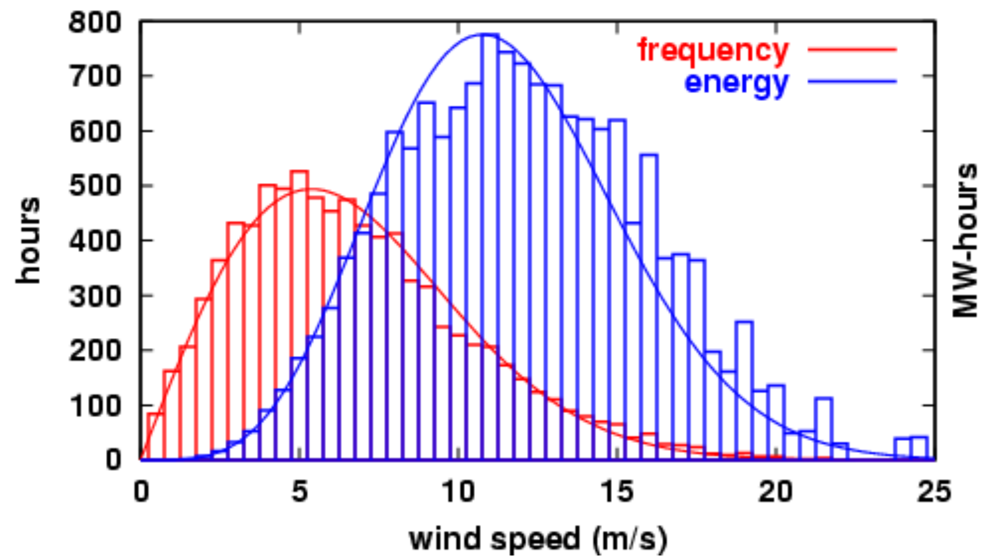


Variation of efficiency with the ratio of downstream to upstream velocity

$$\eta = \frac{Power}{\frac{1}{2}\rho A_t U_u^3} = \frac{1}{2}\left(1 - \frac{U_d}{U_u}\right)\left(1 + \frac{U_d}{U_u}\right)^2$$



Typical wind turbine power output with steady wind speed.



http://www.wind-power-program.com/betz.htm

Economics

- Capital cost: 2 MW on-shore turbine @ $1/watt$_p$
  - Yearly payment (5% interest rate for 20 years) = $160K
- Operation and maintenance: 5%/year of capital cost
  - $100K per year
- 2000 hours production = 4 GWh/year
  - 4 GWh/year @$0.065/kWh = $260K

Other Costs (not including profit margin)

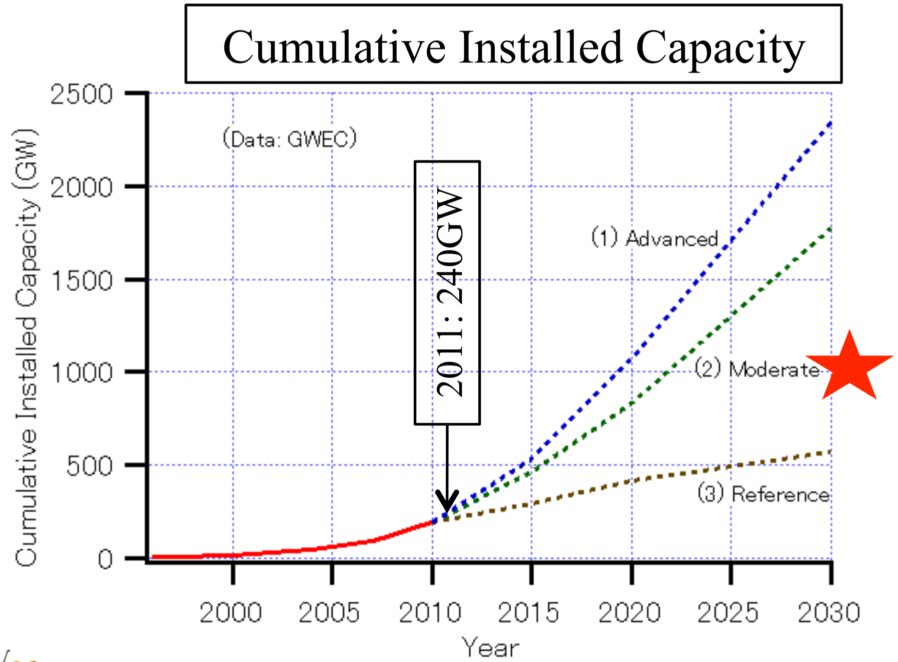
- Maintaining the access/service roads year around?
- Cost of transmission + distribution + backup?
- Land lease or purchase

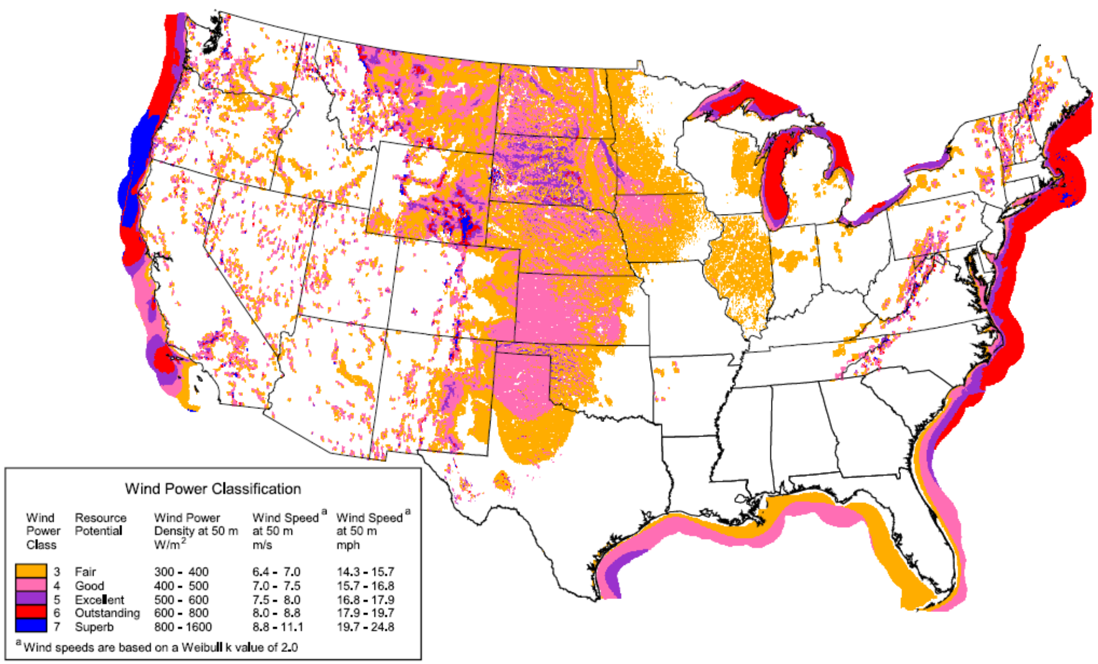
Business Case: ~$0.15/kWh

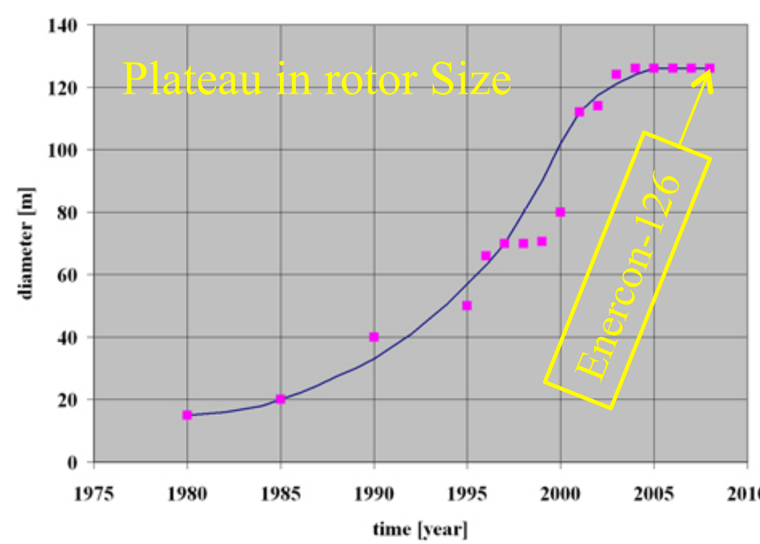
What a 3 MW Onshore Turbine Needs

- Spacing: A 100m diameter WT requires ~1km^2 land
  - Average power captured/unit land area is ~2Watts/m^2
- Concrete: Foundation requires 300-400 Tonnes
- Steel: 200-300 Tonnes (80-105 hub height)

Wind Resource and its Future



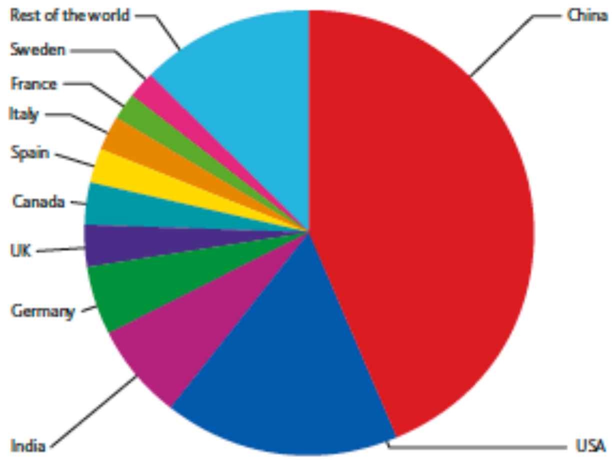




Slowdown? New global capacity addition ~40GW in 2009, 2010, 2011

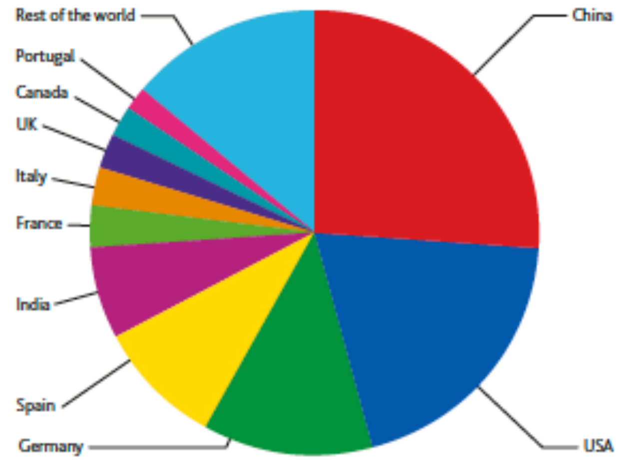
Capacity: New and Total

TOP 10 NEW INSTALLED CAPACITY JAN-DEC 2011



Country	MW	% SHARE
China**	18,000	44
USA	6,810	17
India	3,019	7
Germany	2,086	5
UK	1,293	3.1
Canada	1,267	3.1
Spain	1,050	2.5
Italy	950	2.3
France**	830	2.0
Sweden	763	1.9
Rest of the world	5,168	12.5
Total TOP 10	**36,068**	**87.5**
World Total	**41,236**	**100.0**

TOP 10 CUMULATIVE CAPACITY DEC 2011

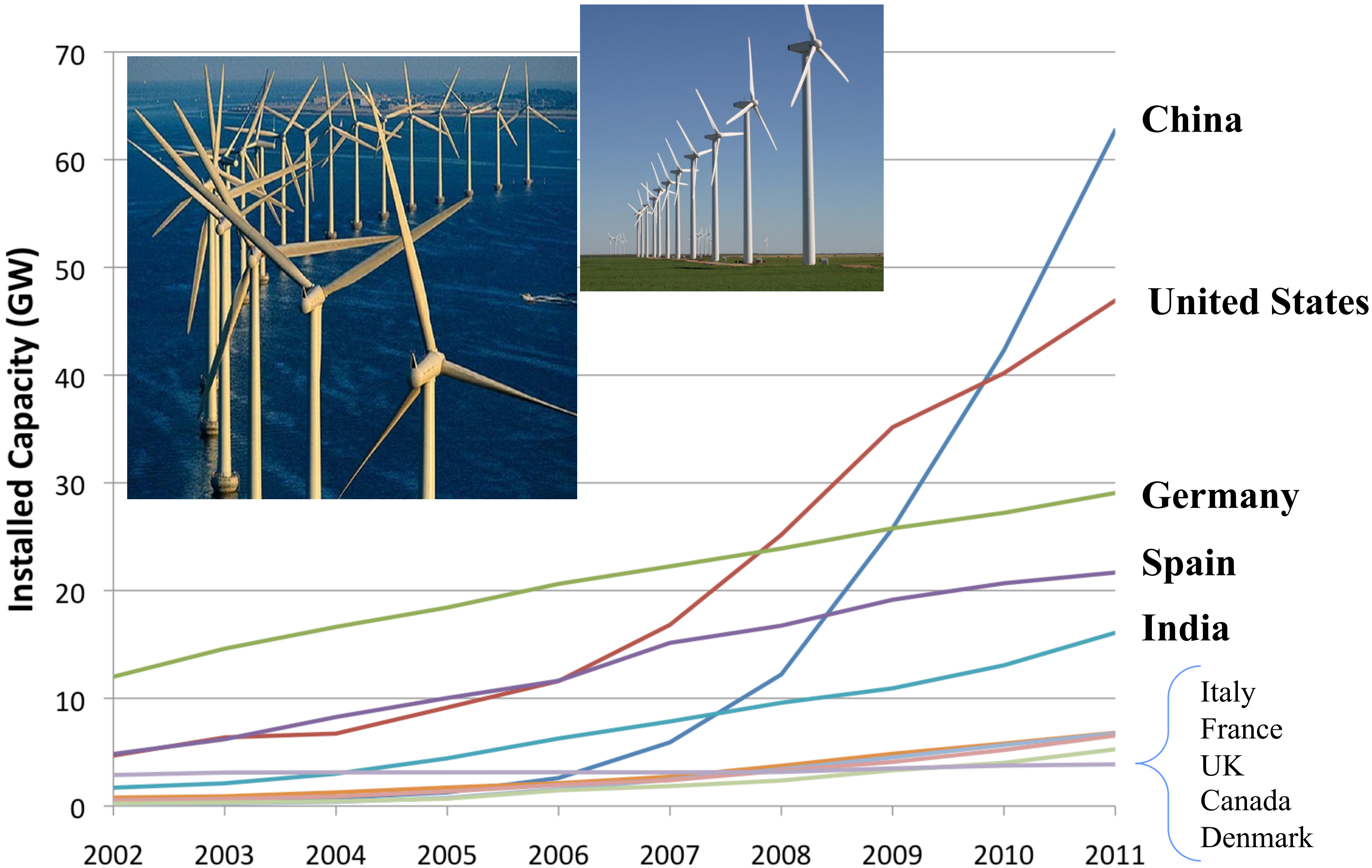


Country	MW	% SHARE
China**	62,733	26.3
USA	46,919	19.7
Germany	29,060	12.2
Spain	21,674	9.1
India	16,084	6.7
France**	6,800	2.9
Italy	6,747	2.8
UK	6,540	2.7
Canada	5,265	2.2
Portugal	4,083	1.7
Rest of the world	32,446	13.6
Total TOP 10	**205,905**	**86.4**
World Total	**238,351**	**100.0**

** *Provisional Figure*

http://www.gwec.net/

Installed Wind Capacity – Top 10 Countries



Source: Global Wind Energy Council

Compiled by Curtt Ammerman

Top Wind Turbine Manufacturers

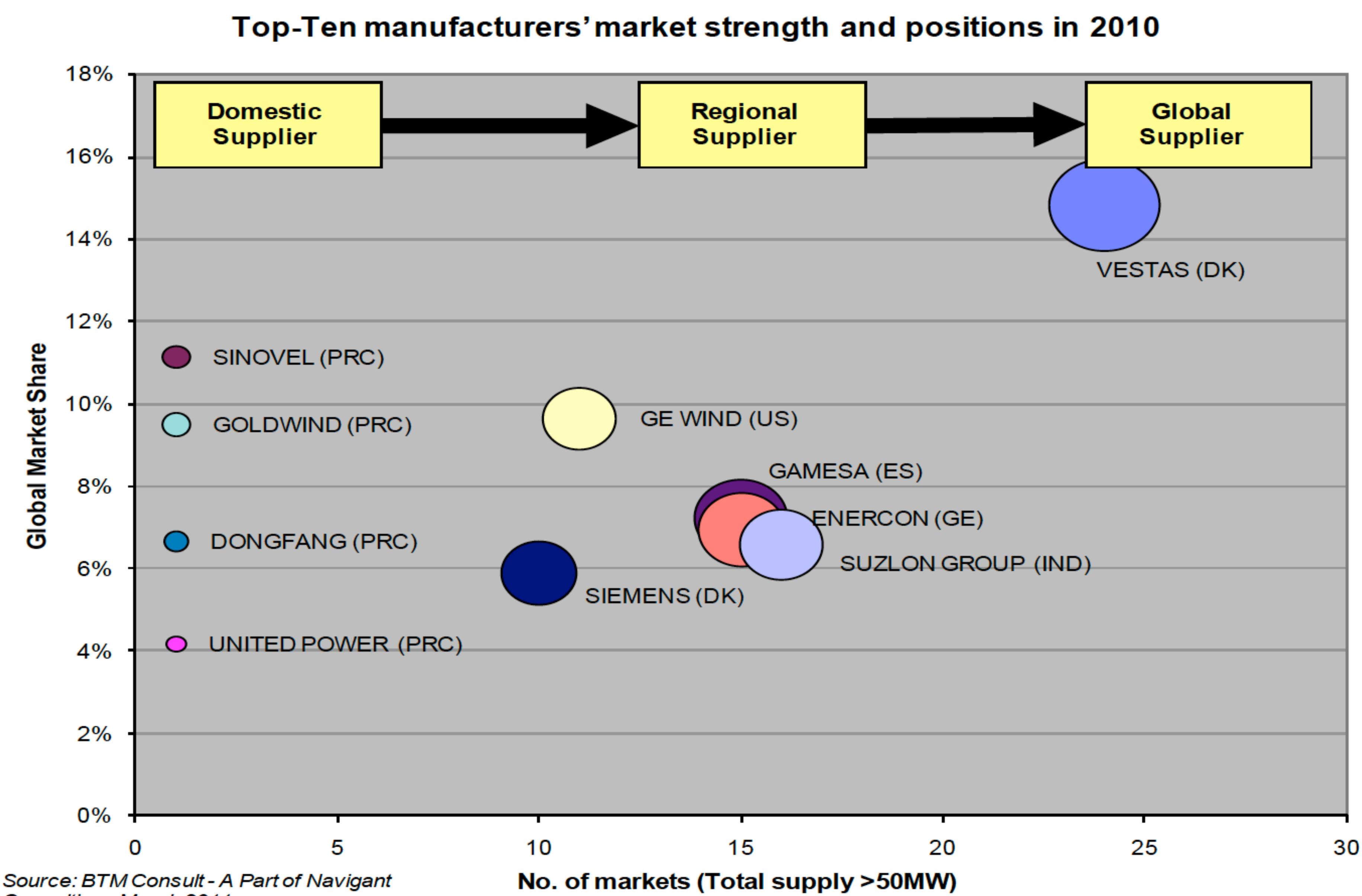
2006 (15.2 GW)	
27%	**Vestas** (Denmark)
15%	**Gamesa** (Spain)
14%	**General Electric** (US)
14%	**Enercon** (Germany)
7%	**Suzlon** (India)
7%	**Siemens** (Germany)
3%	**Nordex** (Germany)
3%	**Acciona** (Spain)
3%	**Goldwind** (China)
3%	**REpower** (Germany)
3%	(others)

2010 (39.4 GW)	
14.8%	**Vestas** (Denmark)
→ 11.1%	**Sinovel** (China)
9.6%	**General Electric** (US)
→ 9.5%	**Goldwind** (China)
7.2%	**Enercon** (Germany)
6.9%	**Suzlon** (India)
→ 6.7%	**Dongfang** (China)
6.6%	**Gamesa** (Spain)
5.9%	**Siemens** (Germany)
→ 4.2%	**United Power** (China)
→ 3%	**Mingyang** (China)
2%	~~**REpower** (Germany)~~
→ 2%	**Sewind** (China)
2%	**Nordex** (Germany)
→ 1%	**XEMC** (China)
11%	(others)

38% China

Source: BTM Consult
Compiled by Curtt Ammerman

Top Ten suppliers' market share and presence in 2010



Source: BTM Consult - A Part of Navigant Consulting - March 2011

Annual Electric Power Manufacturing Capacity

	China	India	Total 2011
Thermal (Coal)	~**100 GW**	**5-7 GW**	
Nuclear	Developing standardized LWR, HWR, FNR with cost goal of $2000/kW	Standardized 660 MW *PHWR yet to be commercialized*	
Hydro T&G sets	**~20 GW**	**~2 GW**	
Solar cells & modules	**12 GW**	**1.5 GW** *imports wafers from China*	**24**
Wind Turbines	**16 GW** *Local Content Law 2004-09*	**2.8 GW** *One global company = Suzlon*	**42**

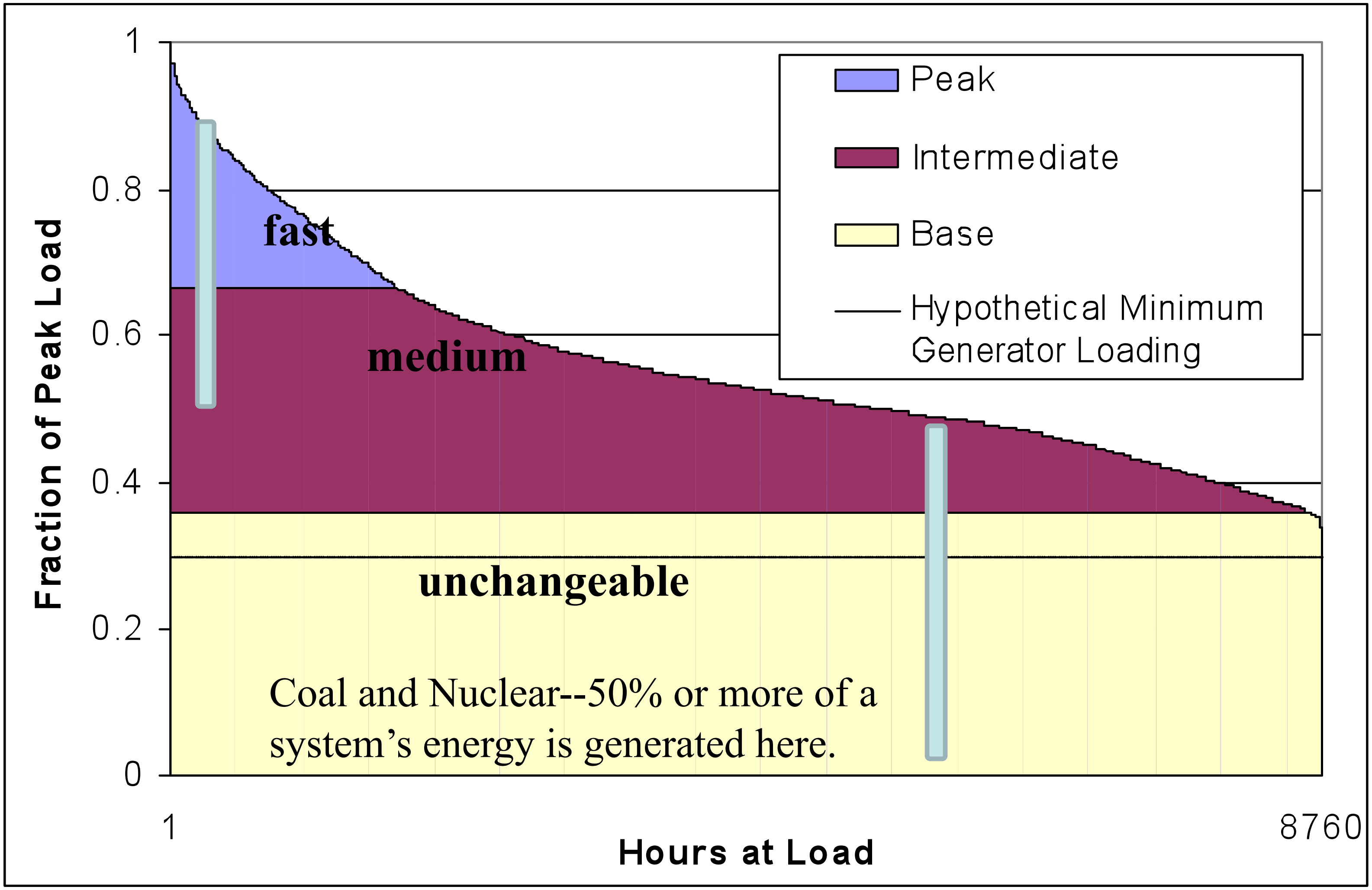
Both countries need to maintain Quality and Markets

Maintaining dispatchable power

Load Profiles,
Intermittency,
Energy Storage

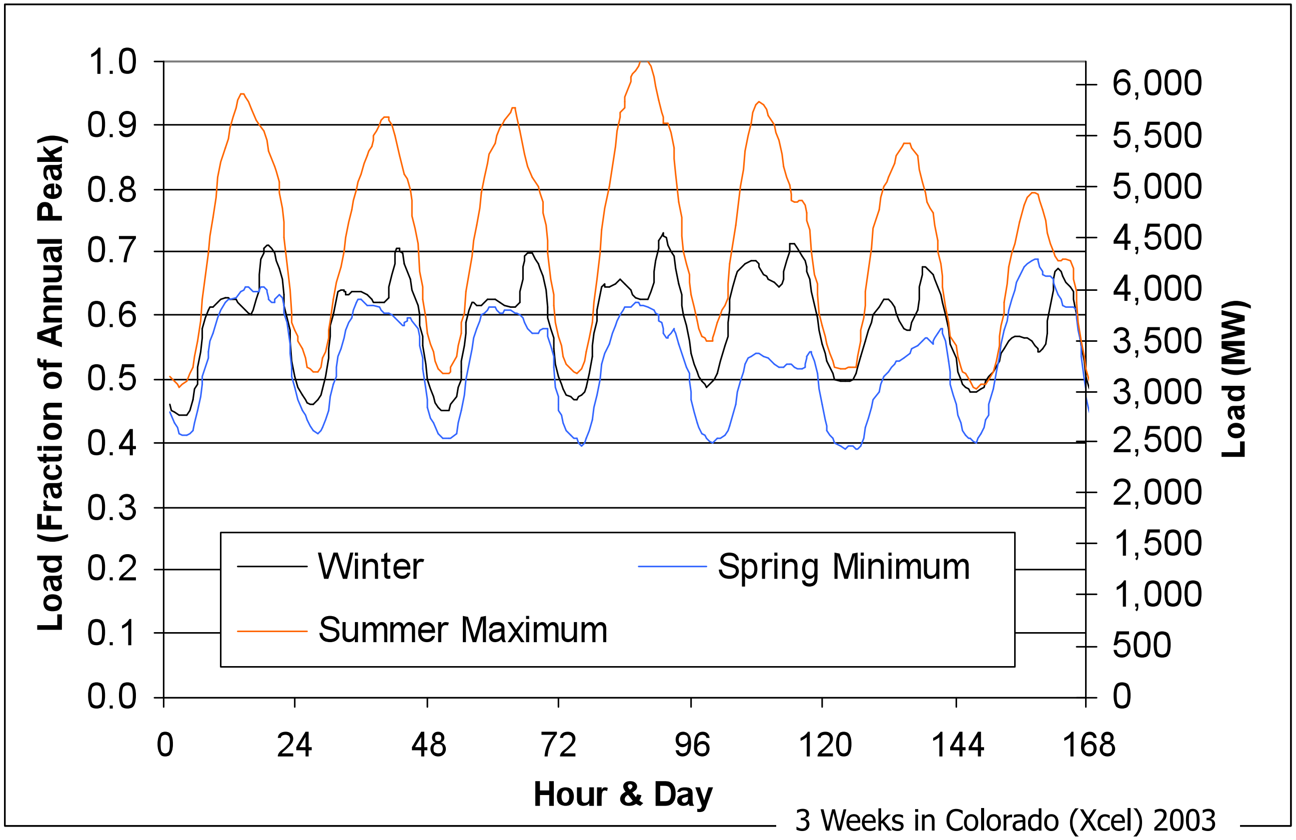
The utility grid has a hard lower bound on flexibility

Courtesy Paul Denholm, NREL (via Al Migliori)



Peak [and intermediate] loads are unpredictable

Courtesy Paul Denholm, NREL (via Al Migliori)

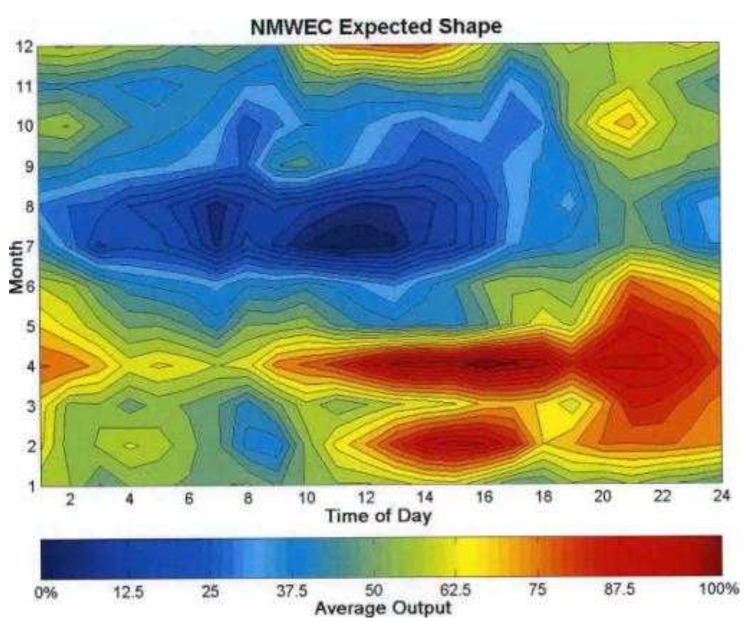


Dilemma of Utility Companies:

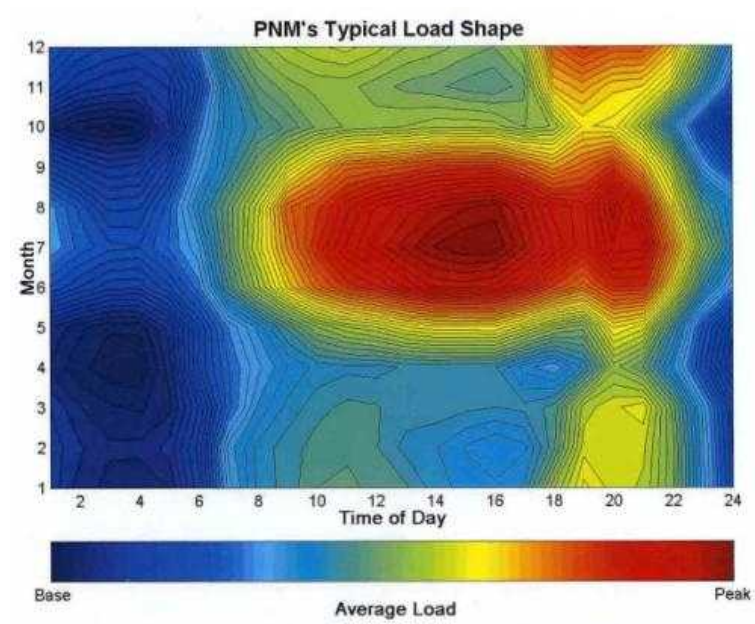
For efficiency and economics they run coal and nuclear plants at constant output leaving peak and intermediate load for gas & renewable resources. Integrating renewables makes load and generation variable and unpredictable

Intermittency & Variability

- Challenges
  - Short-term (hours) due to clouds, …
  - 24 hours (mismatch between daily peak load and resource)
  - Seasonal



NM Wind Resource



PNM Typical Load

Grid scale storage for wind & solar

- Pumped Storage Hydro
  - Not enough capacity locally or globally
- Gas Combustion Turbines
  - CO_2 emissions

$\leq$ 24 hours

- Dams with reservoirs
  - Environmental impacts
  - Vulnerable to weather patterns, droughts, climate change

Seasonal

- ~~CSP plants (thermal storage)~~

Long-term goal

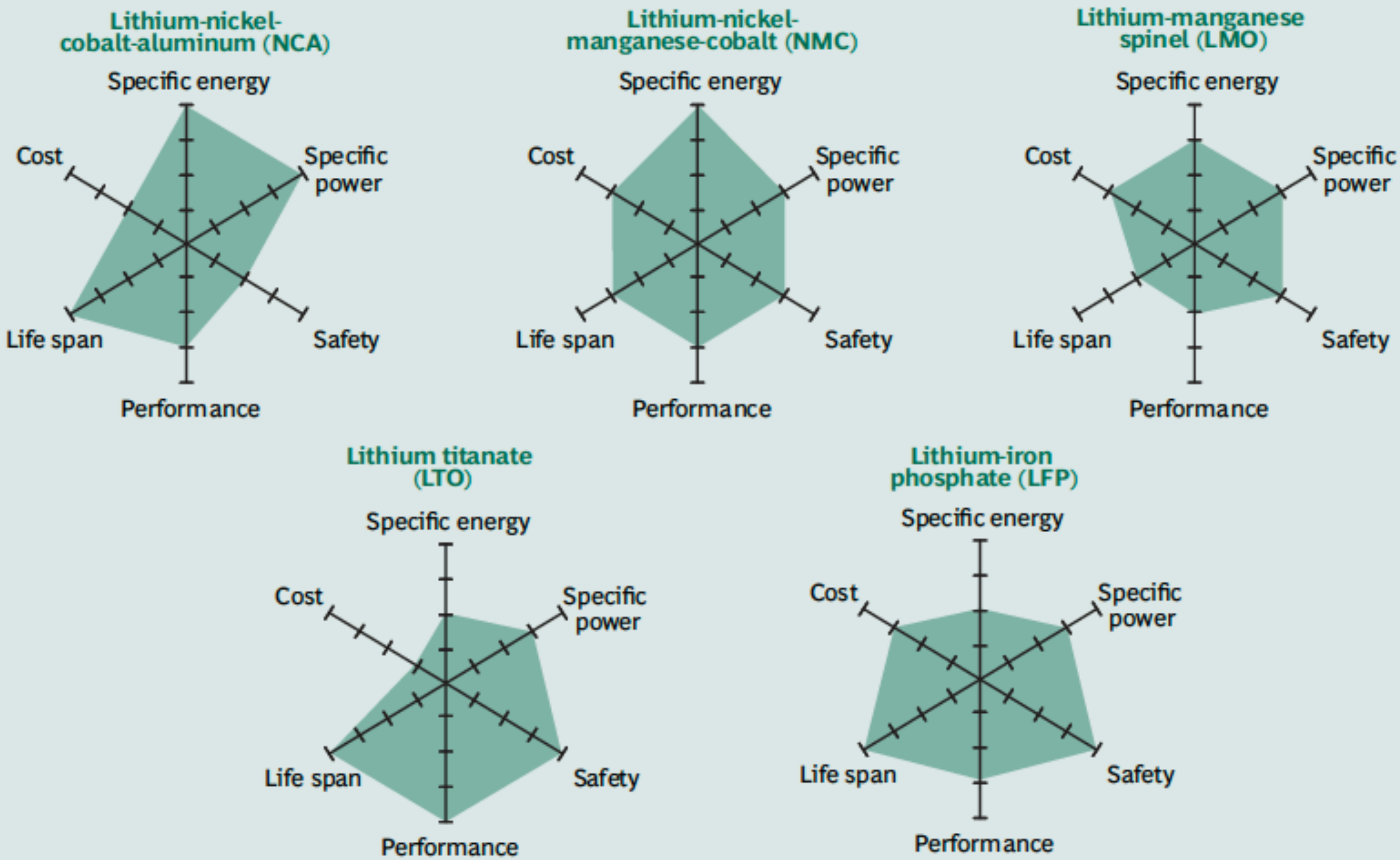
Develop the resource integration and control tools to make both generation and load dispatchable

Smart Green Grid

Batteries for Electric vehicles

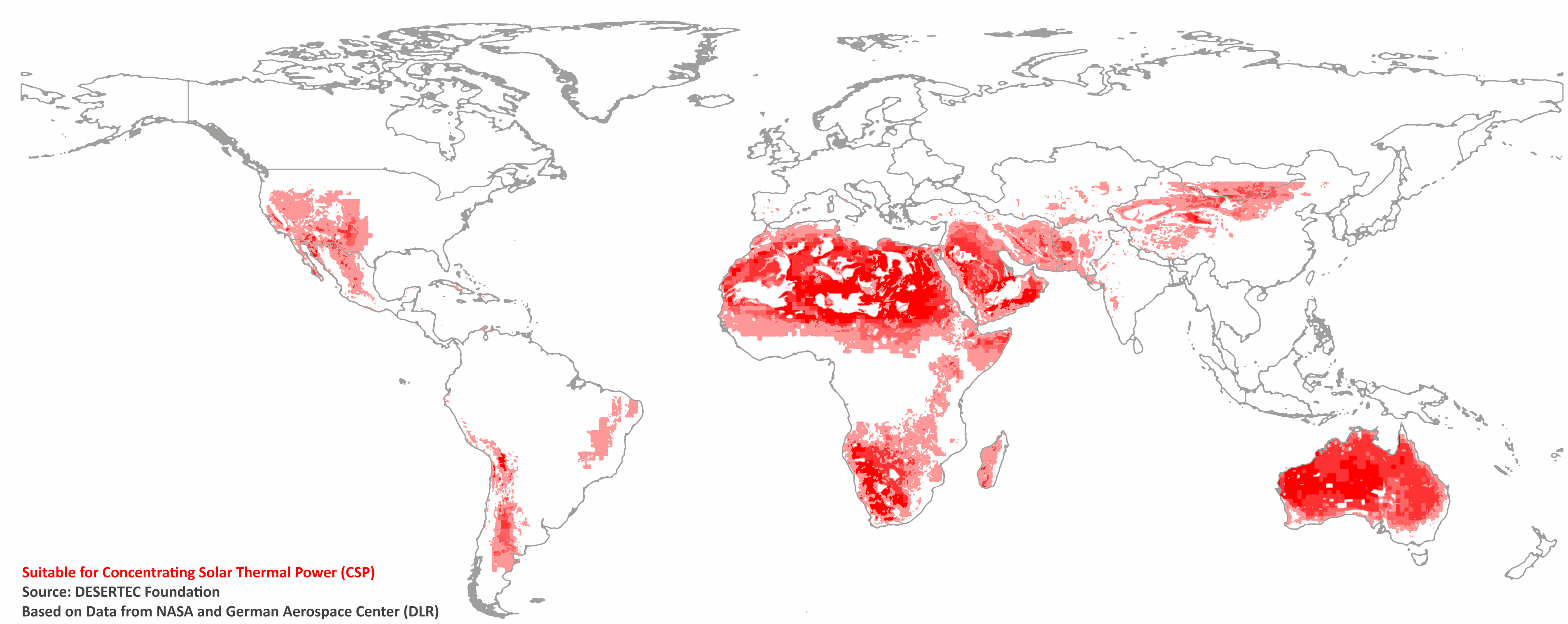
- Goal: ~40 kWh for a 300 km range in a small car weighing ~1200 kg (Honda Civic)
  - BMW mini E has a 35 kWh battery with 160km range
- Lithium Ion Batteries
  - Typical specific energy of cells : 140-170 watt-h/kg
  - Battery pack: 90-140 watt-h/kg
  - Envia claims to have tested cells at 400 watt-h/kg
    - 40kWh @ 400 watt-h/kg = 100 kg
- Charging time of 15kWh battery :
  - 10 hours plugged into 120 volts outlet
  - 2 hours with High-Amperage Charging Box
- Cost goal: $250/kWh
  - current cost is ~$1000/kWh → a 40 kWh battery costs ~ $40K

Five Principal Lithium-Ion Battery Technologies



Source: BCG research.
Note: The farther the colored shape extends along a given axis, the better the performance along that dimension.

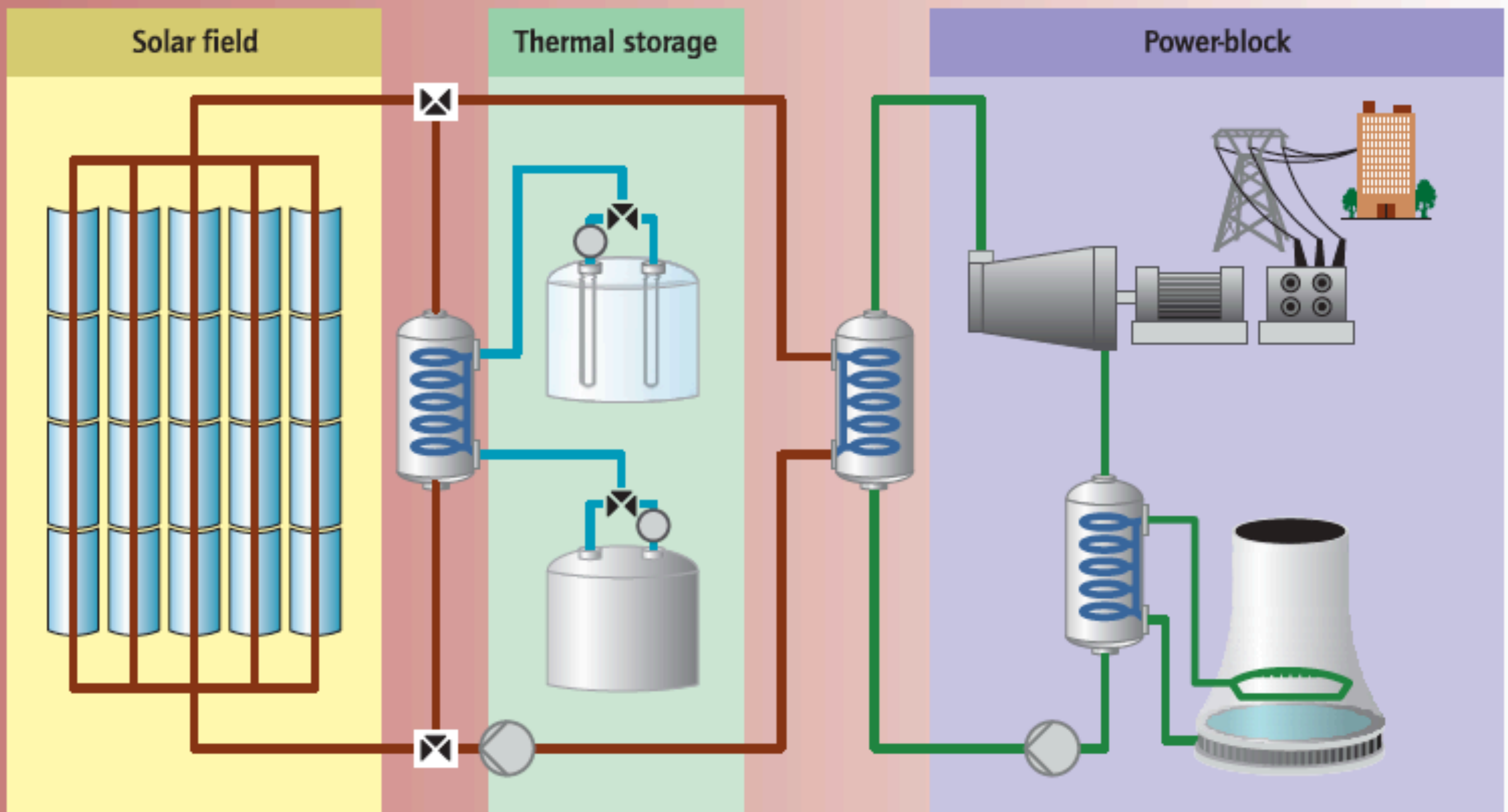
Harvesting the Deserts: CSP



2011 World demand of 20000 TWh requires 325x325 km^2

Concentrated Solar Power (CSP)

Storage system in a trough solar plant



This graph shows how storage works in a CSP plant. Excess heat collected in the solar field is sent to the heat exchanger and warms the molten salts going from the cold tank to the hot tank. When needed, the heat from the hot tank can be returned to the heat transfer fluid and sent to the steam generator.

Source: SolarMillennium.

Four Configurations: Parabolic Trough

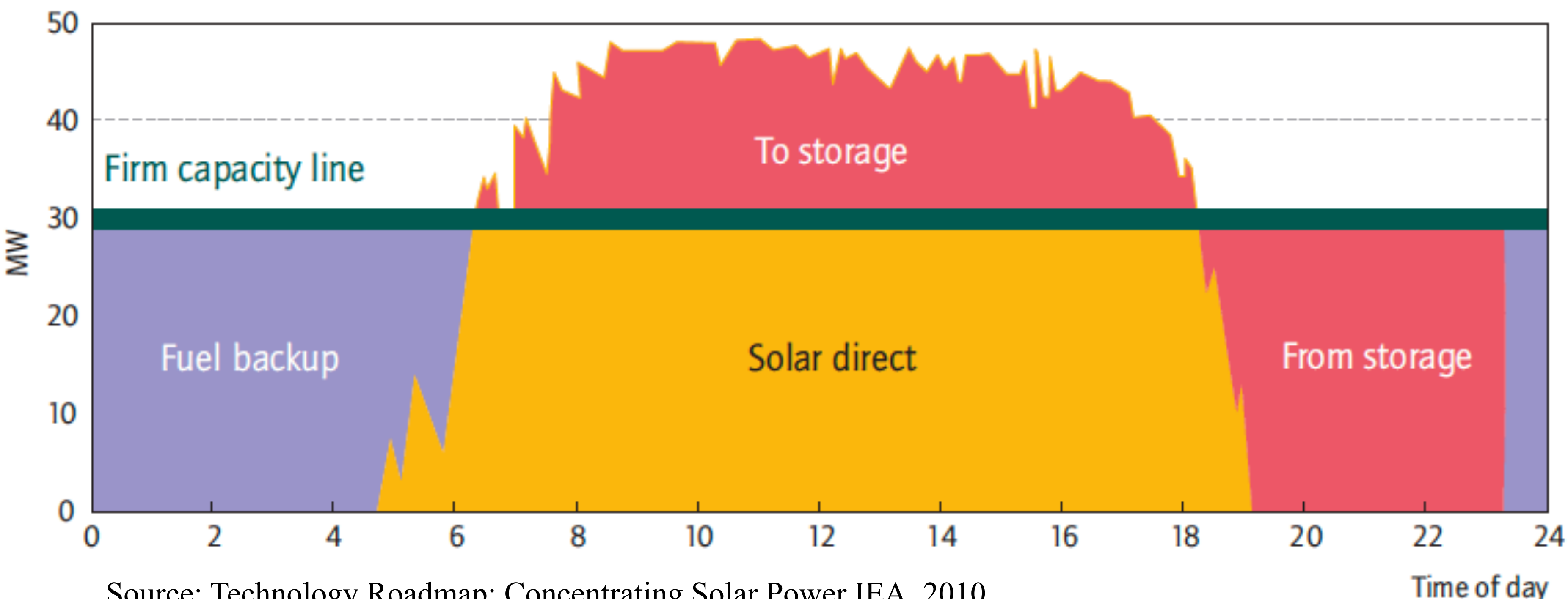
	Solar farm size multiplier	Storage	Turbine Size (MW)	Productive Hours
Intermediate Load	1.1-1.5	Small	250 MW	800–1900
Delayed Intermediate Load	1.8–2.0	Medium	250 MW	1200–2300
Base Load	2.5–3.5	Large	120 MW	00–2400
Peak Load	3–5	Large	620 MW	1100–1500

Molten Salt: Hot – 565C; Cold – 293C

Source: Technology Roadmap: Concentrating Solar Power, IEA, 2010

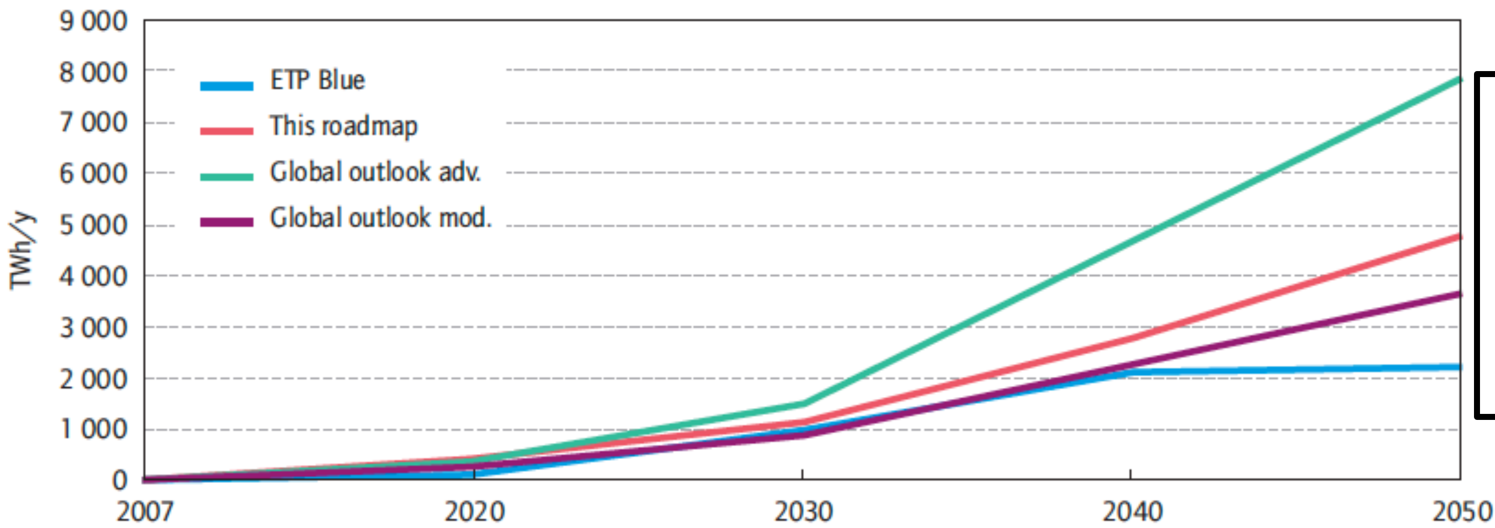
Combination of storage and hybridization in CSP

- Large solar farm multiplier
- Supplementary fuel burners
  - Dispatchable power
  - Raise temperature from 390C to 565C or higher
- Back up power plants



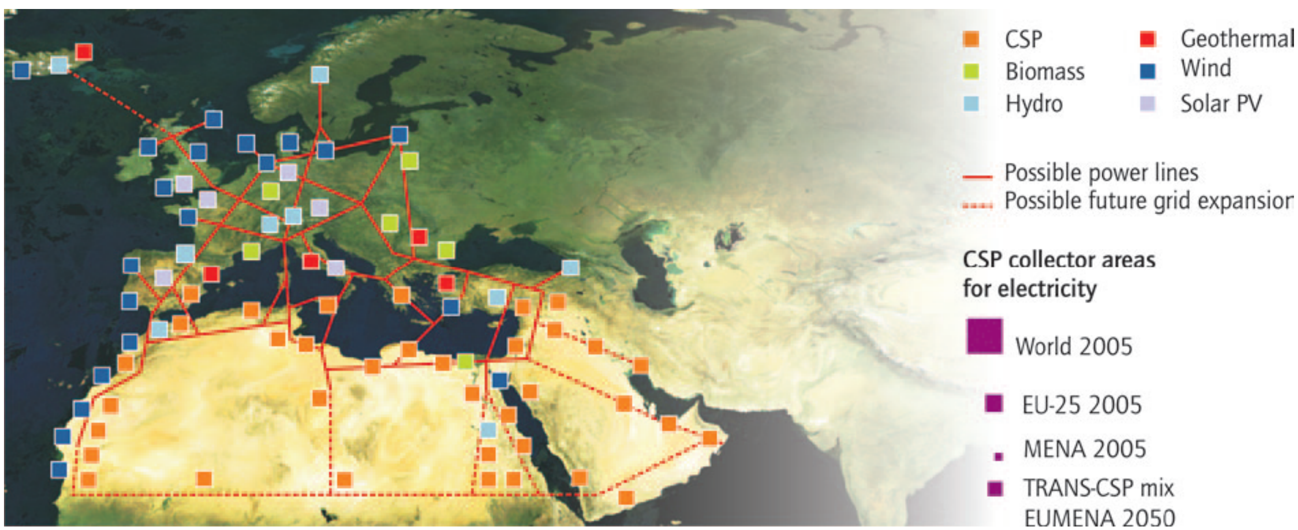
Source: Technology Roadmap: Concentrating Solar Power IEA, 2010

CSP Forecast: Is it Credible?



1.5TW by 2050 with 59% capacity factor.

2011 = 1.75GW

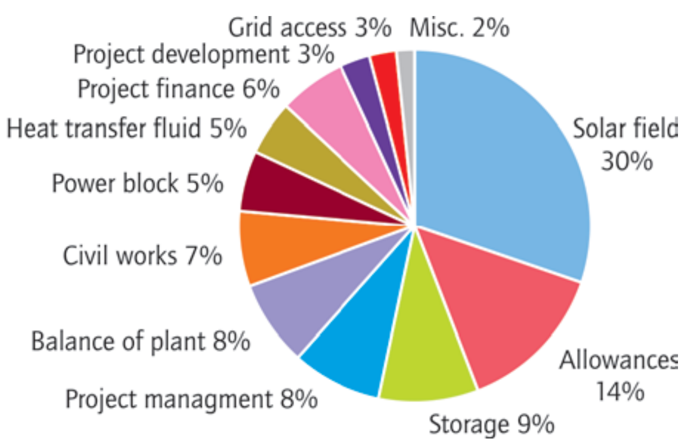


DESERTEC
North Africa–Middle East Supplying Europe

Source: Technology Roadmap: Concentrating Solar Power IEA, 2010

Economics of Large Trough Plants

- Capital Cost: \$4.2-\$8.4 per watt (depending on ……)
- Levelized Costs: \$0.2–\$0.295/kWh
- Wet Cooling: 3000L/MWh
- Transmission Lines



Breakup of investment costs of a 50 MW parabolic trough plant with 7-hour storage

Source: Technology Roadmap: Concentrating Solar Power IEA, 2010

Developing HR capability: Integrated systems

- Current capacity and power generation from wind and solar is a few percent
- Very large potential for growth
- Need to develop the human resource
- Clean Development Mechanism (CDM) is facilitating installations and helping develop expertise
- Pilot wind/solar farms in Egypt, Morocco are successful

Ain Beni Mathar Integrated Solar CCGT power plant, Morocco (20_{solar} + 450_{gas} MW)

Role of CDM

Bio-fuels

Alternative to petroleum for liquid transportation fuel which contributes ~1/3 global GHG emissions

Solution Wedge in my Gedanken World = 10MMboe/day

Bio-fuels

Ethanol, Bio-diesel, Jet fuel, …

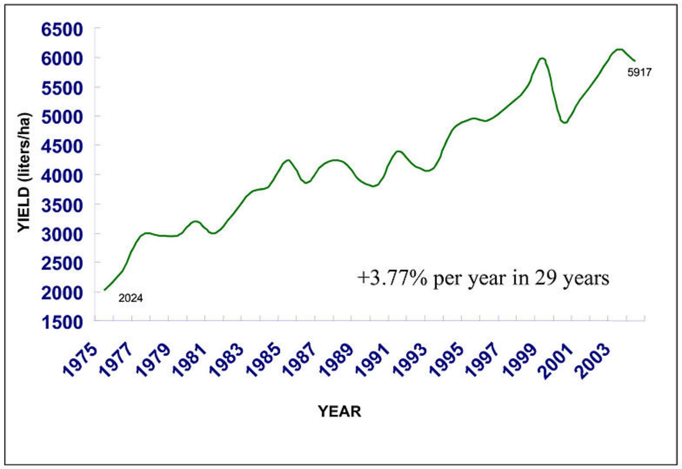
- **Water availability will be a key driver**
- **Impact of increased use of fertilizers**
  - **All bio-mass needs nitrogen and potassium**
- **Governments will have to weigh**
  - **Food versus fuel**
  - **Environmental Impacts**

Ethanol

- Cane Sugar → Ethanol
  - Sugarcane
- Starch → Sugar → Ethanol
  - Corn
- Cellulose → Hydrolysis → Ethanol
  - Sugarcane bagasse, corn stover, switchgrass, miscanthus, woodchips, forest residues

Sugarcane Ethanol

- Sugarcane Growing
  - Tropical hot sunny areas
  - Growing period 270-365 days
  - Water need 15-25 kT/hectare (200:1)
- Sugarcane yield (Brazil)
  - 70 tonnes/hectare (average)
  - 150 tonnes/hectare (best)
- Conversion
  - 1T cane → 135kg sugar + 130kg bagasse + 735kg water
- Overall current ethanol yield
  - **6000L/hectare/yr**
  - Best 6800-8000L/hectare
- Energy Balance: output-energy / input-energy
  - 8.3-10.2



(1) José Goldemberg (2008-05-01). "The Brazilian biofuels industry". *Biotechnology for Biofuels* **1** (6): 4096. doi:10.1186/1754-6834-1-6
(2) http://en.wikipedia.org/wiki/Ethanol_fuel_in_Brazil

Corn Ethanol

- Growing Corn
  - Temperate wet, semi-dry/humid climate
  - Growing season 130-150 days
  - Water requirement 5-8 kT/hectare (500–800:1)
- Corn yield (USA)
  - 165 bushels/acre (US 2009 record yield)
  - 10.5 tonnes/hectare
- Conversion
  - 1kg corn → 0.57 kg starch → 0.448L ethanol
- Overall current ethanol yield
  - 10.5 tonnes/hectare → **4700L/hectare/yr**
- Energy Balance: output-energy / input-energy
  - 1.3-1.6

(1) http://www.ontariocorn.org/classroom/bushel022405.htm
(2) http://en.wikipedia.org/wiki/Ethanol_fuel_energy_balance
(3) Farrel et al. Science http://rael.berkeley.edu/ebamm/FarrellEthanolScience012706.pdf

Cellulose → Ethanol: 6-step process

Industry in demonstration stage

- Pretreatment Phase: making the lignocellulosic material amenable to hydrolysis
- Cellulose hydrolysis (cellulosis): breaking down the molecules into sugars
- Separation of the sugar solution from the residual materials, notably lignin
- Microbial fermentation of the sugar solution
- Distillation to produce roughly 95% pure alcohol.
- Dehydration by molecular sieves to bring the ethanol concentration to over 99.5%

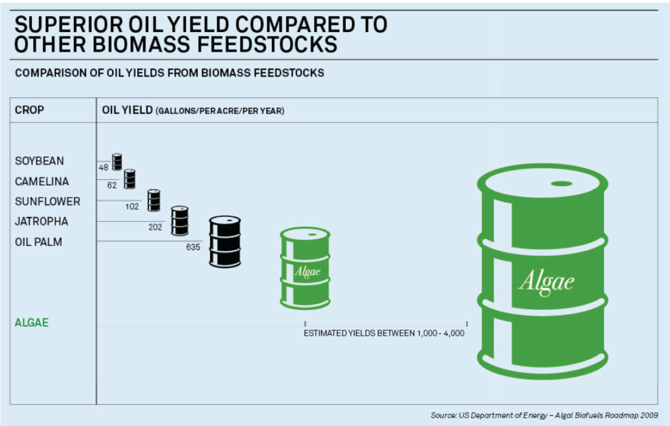
Potential to take US bio-fuels from 1→2 MMbo/day

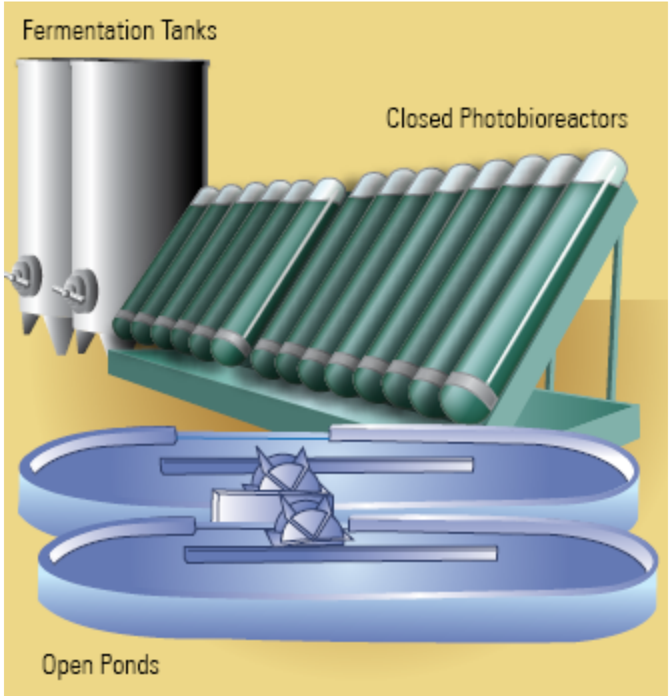
Algal Oil

- Crop based production of bio-diesel yield is
  - ~1000L/hectare (rapeseed, peanut, sunflower)
  - ~5000L/hectare (palm oil)
  - ~35000L/hectare/year = 3.5L/m^2 (Algae Oil)
- Land and water use
  - 20,000 km^2 for 1 MMboe/day
  - 1000-6000L Water / Liter of Algal oil
- 3.5Liters of Algae oil per m^2 per year
  - Retail: 3.5L of conventional gasoline ~$3
  - Algae oil production cost should reduce to ~$1/gallon ~$1/m^2 to displace petroleum

The issue is not quality of water but quantity.

At 3000:1 One MMboe/day will need ~ 5x10^{11}L = **0.5km^3 water/day**



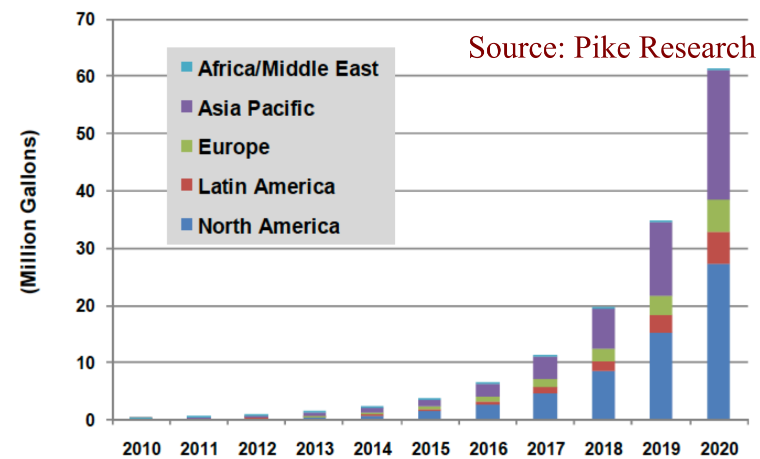


http://en.wikipedia.org/wiki/Biodiesel

Algal Bio-fuels

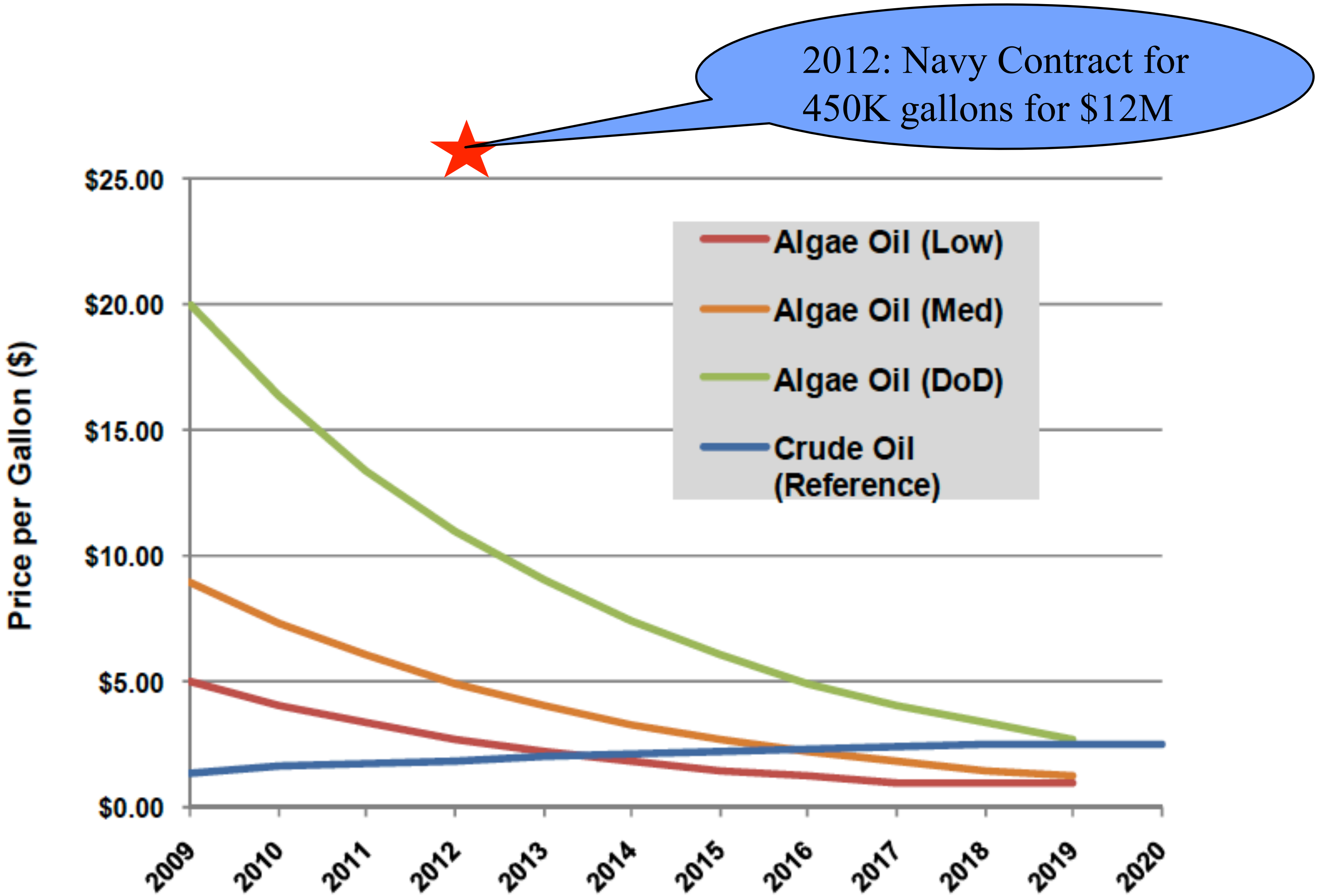
Industry in R&D stage

- Even if 35000L/hectare/year Algal oil yield is realized
  - Other crop based bio-diesel production will persist
    - Different types of land (farmland versus wasteland)
    - Farmers will still grow rapeseed…palm oil if gasoline > $1/L
    - Subsidies will be considered reasonable if
      - Production provides other social benefits such as employment
      - environmental risks are small/mitigated
  - Growth of industry will depend on cost of petroleum versus algal oil and overall liquid-fuel demand
  - Unlikely to achieve industrial scale production (1MMboe/day) before 2030



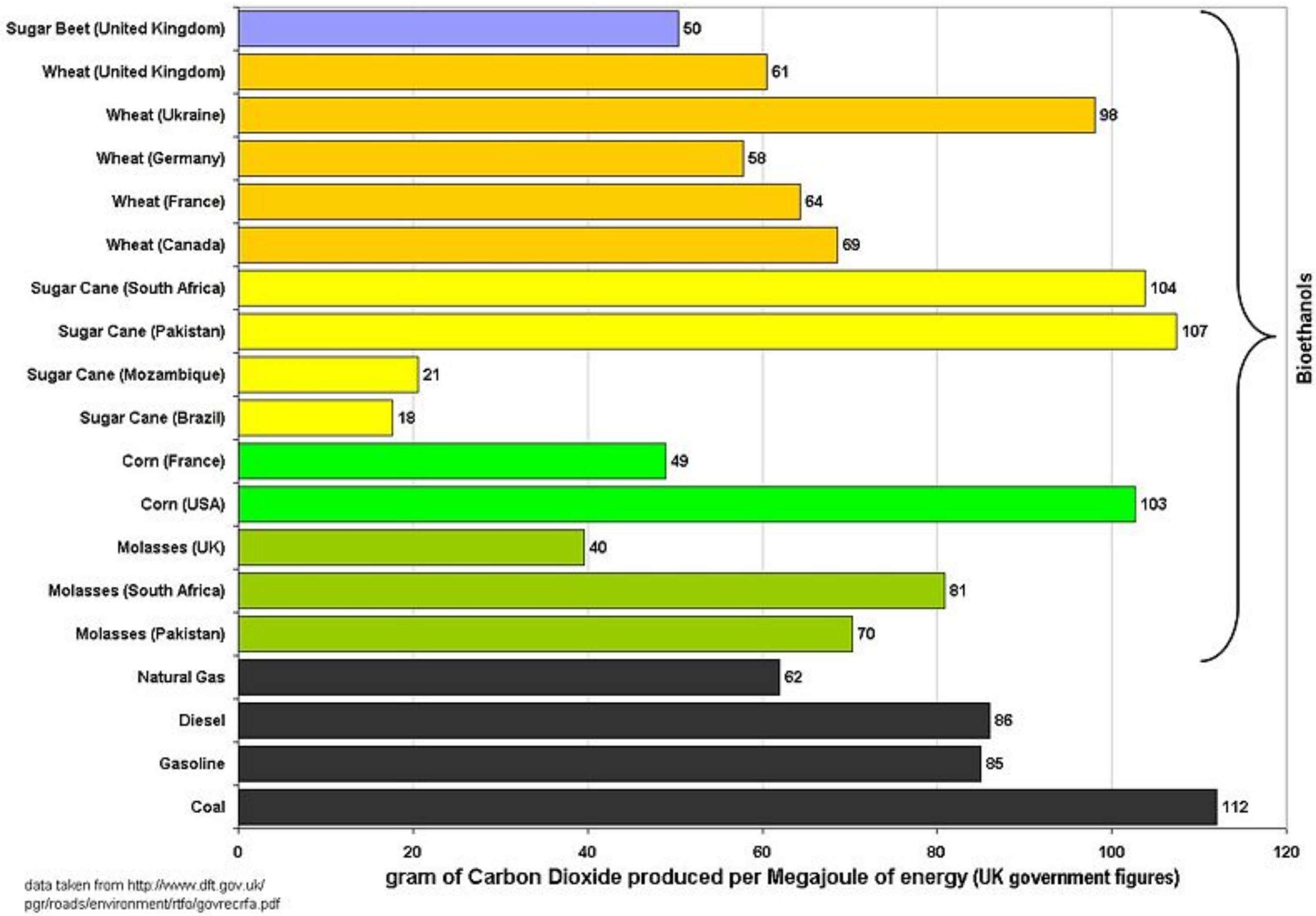
60 MM gallons ~ 1.5 Mmboe/year

Cost of Algal Oil → fuel



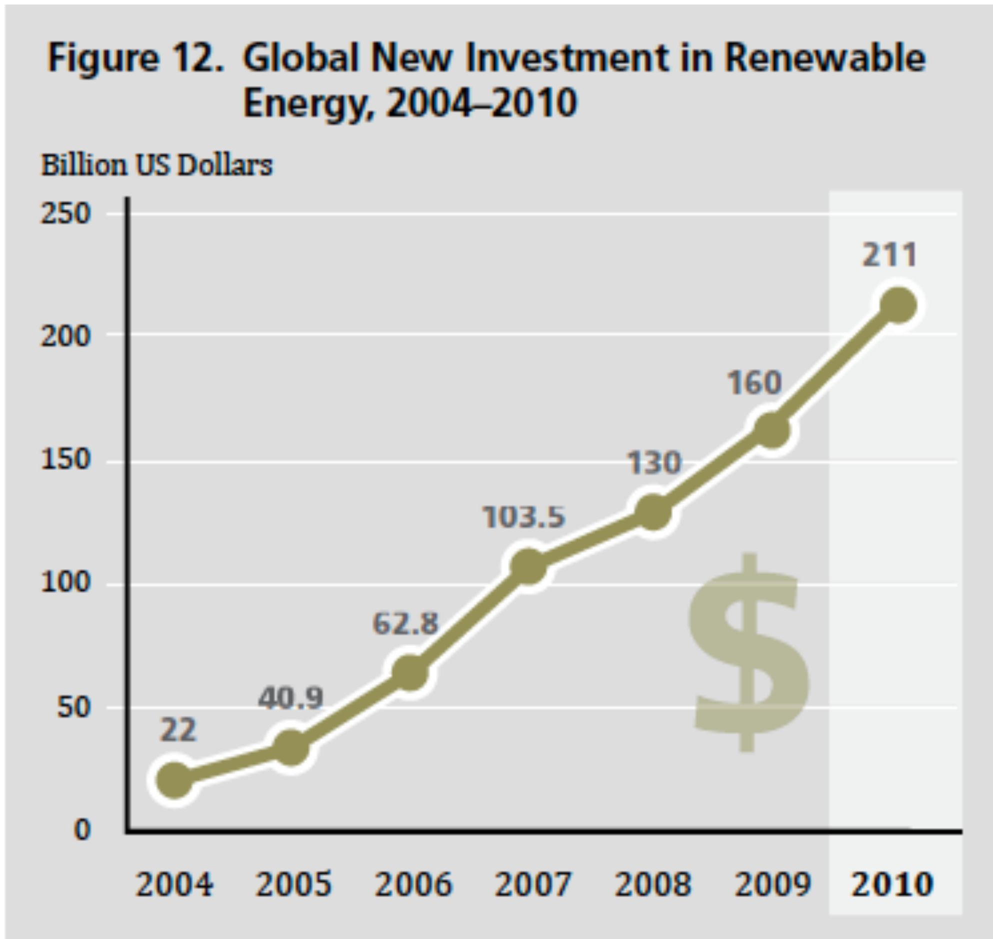
Source: Pike Research

CO2 intensity of fuels



(1) Carbon and Sustainability Reporting Within the Renewable Transport Fuel Obligation. Department of Transport (UK). January 2008.
(2) http://en.wikipedia.org/wiki/Ethanol_fuel_in_Brazil

Good News: investment in renewable systems continues to grow



Source: REN21

CO_2 reduction methods that work, can scale, and are economical *today*

- Energy Efficiency (cradle to grave)
- Geothermal with heat pumps for heating and cooling (HVAC) individual family homes
- Solar water heating (best in areas of direct sunlight)
  - Domestic and limited scale industrial
- PV for individual family homes in areas with more than 1800 kWh/year insolation due to incentives (profitable by 2015)
- On-shore and Off-shore wind in regions requiring short transmission lines and have hydro for backup

Why is adoption so slow?

Nuclear remains the only large-scale low-carbon option for base load

Lecture 4: Potential for growth of Nuclear Power

- Growth of capacity with existing technology
- New technology
- Showstoppers
  - Waste management
  - Proliferation
  - Accidents
  - Terrorism

Acknowledgement

- Curtt Ammerman
- Jose Oliveras
- Al Migliori

Comparison of Oil and PV

- At $2/gallon bio-diesel competitive for electric power generation
  - 3.5L Gives ~40kWh (thermal) or 23 kWh electric (CCGT) → [$0.09/kWh]
- 20% efficient PV in 1800kWh/m^2/yr insolation
  - Generates ~360 kWh/m^2/year electric
  - Capital Cost ~$400 @ $2/W$_p$ = $36/year → [$0.10/kWh]