

# **Leapfrogging energy system flexibility for integrating high share of renewable electricity**

Peter D. Lund

<sup>1</sup>Aalto University, School of Science

Espoo-Otaniemi, Finland

[peter.lund@aalto.fi](mailto:peter.lund@aalto.fi)

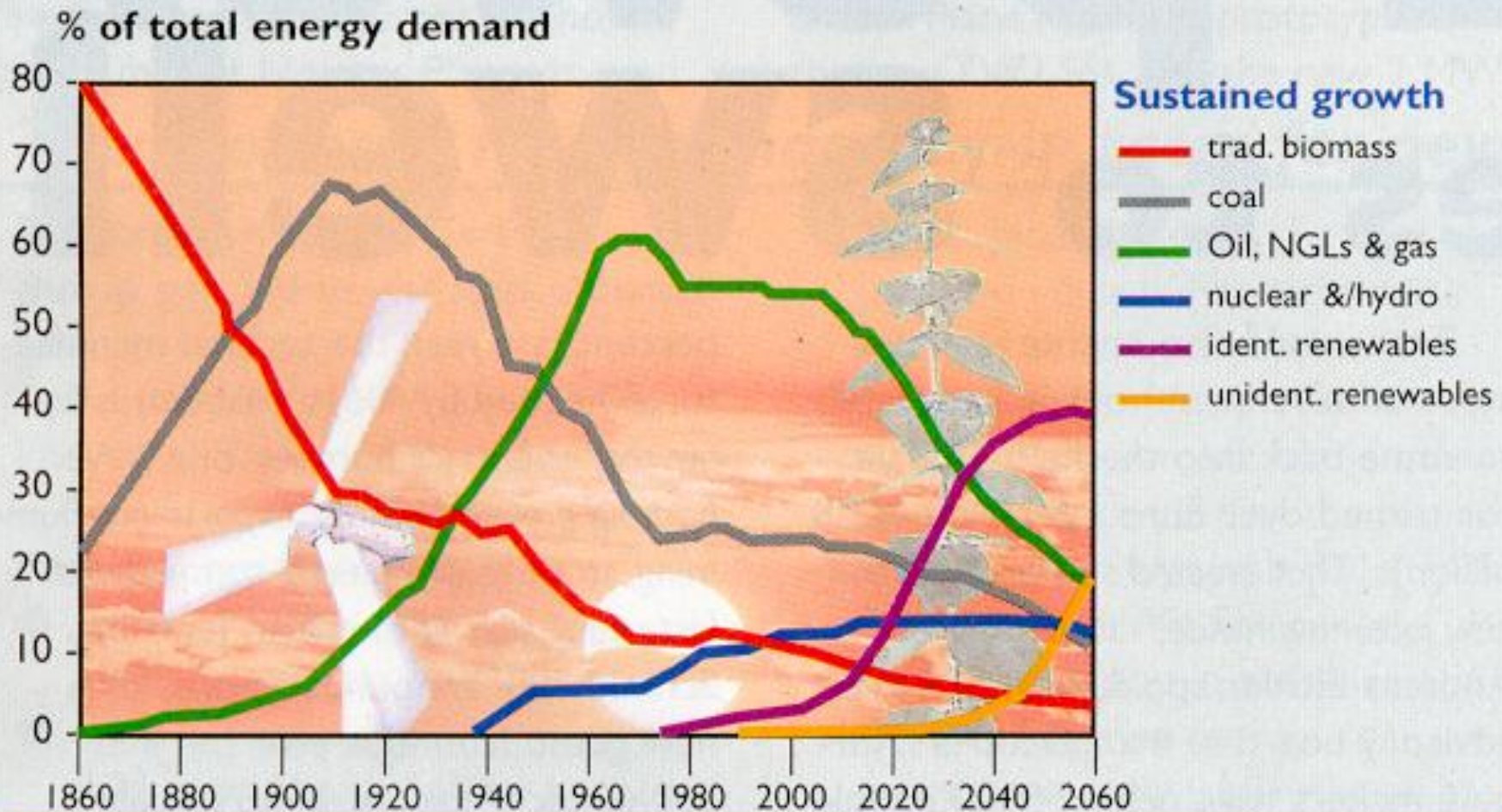
IEEE SEGE 2013, Oshawa 28-30 August 2013

# Outline

- **Global energy & climate nexus**
- **Sustainable energy transition**
- **Energy systems innovations**
- **Cases on high RE share**

# Dynamics of the global energy system

## Shell scenario: Energy market 1860 - 2060





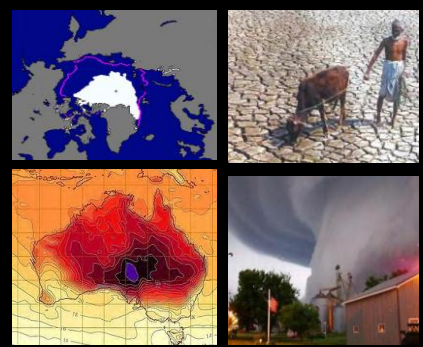
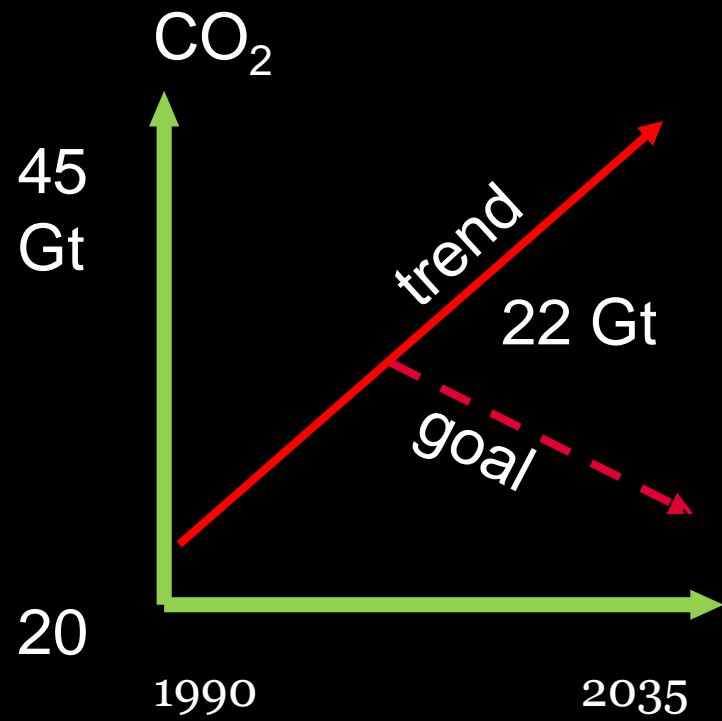
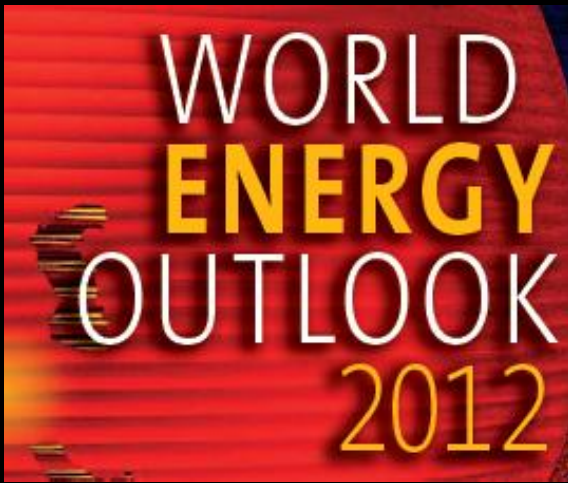
# **The Energy-Climate challenge ahead in simple terms**

- I. Fossil fuels >80% of energy, oil >98% of traffic**
- II. Coal (power) and oil (traffic) 80% of CO<sub>2</sub>**
- III. Goal: CO<sub>2</sub> down by 60% 2050, >80% in industrialized countries**
- IV. 65% of energy used in cities(80% in 2040)**
- V. Energy issues shifting from industrialized countries to emerging economies, e.g. in Asia**



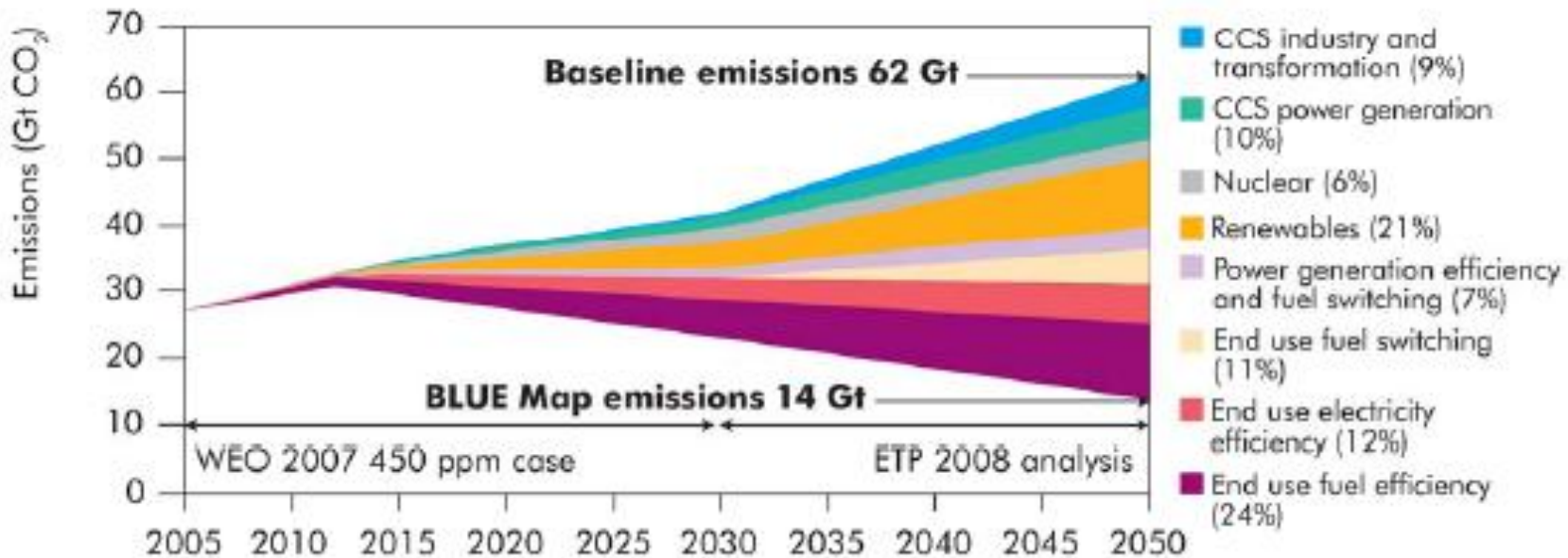
# Current trend: New record in human carbon emissions 2012

- 20% of population use 80% of all [energy] resources
- 1/2 of all people earn less than 2\$ a day



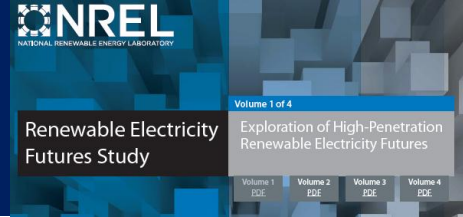
# Energy technology options by 2050 (IEA 2008)

Contribution of emission reduction options, 2005-2050

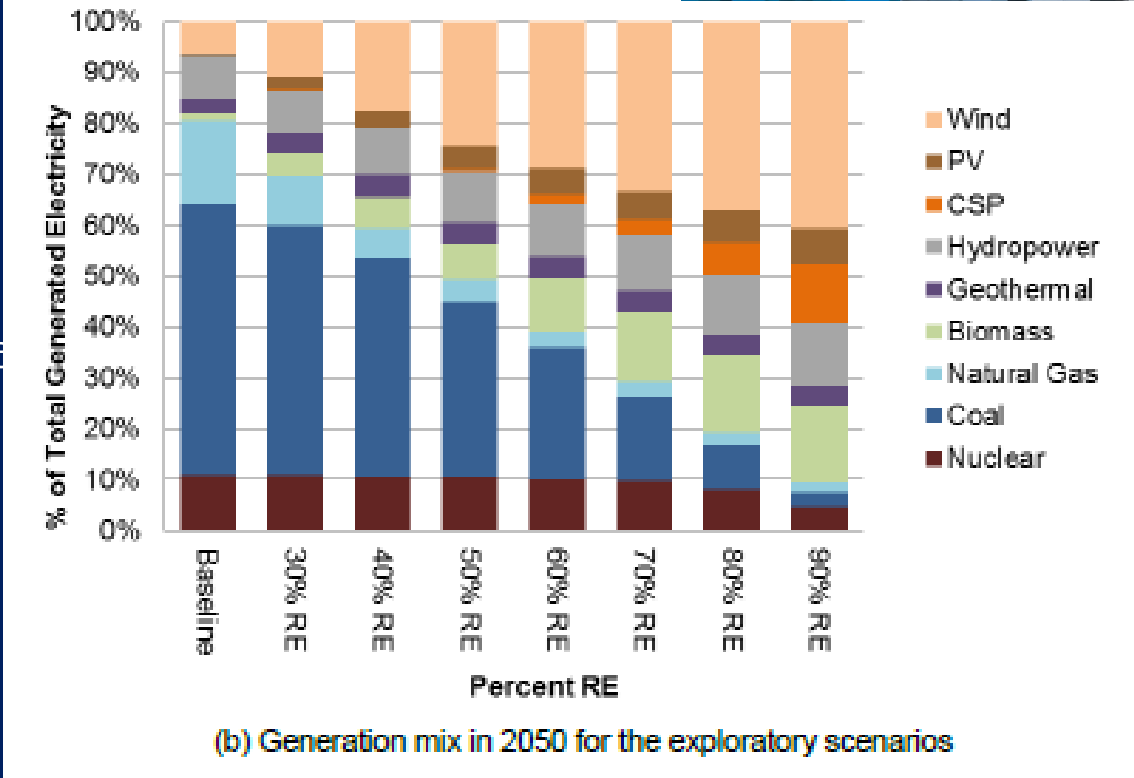


© OECD/IEA, 2008

# U.S. Renewable Electricity Futures Study (RE Futures)



- **Renewable electricity is more than adequate to supply 80% of U.S. electricity in 2050;**
- Increased electric system flexibility is needed (supply- and demand-side options);
- Multiple combinations of renewable technologies possible.



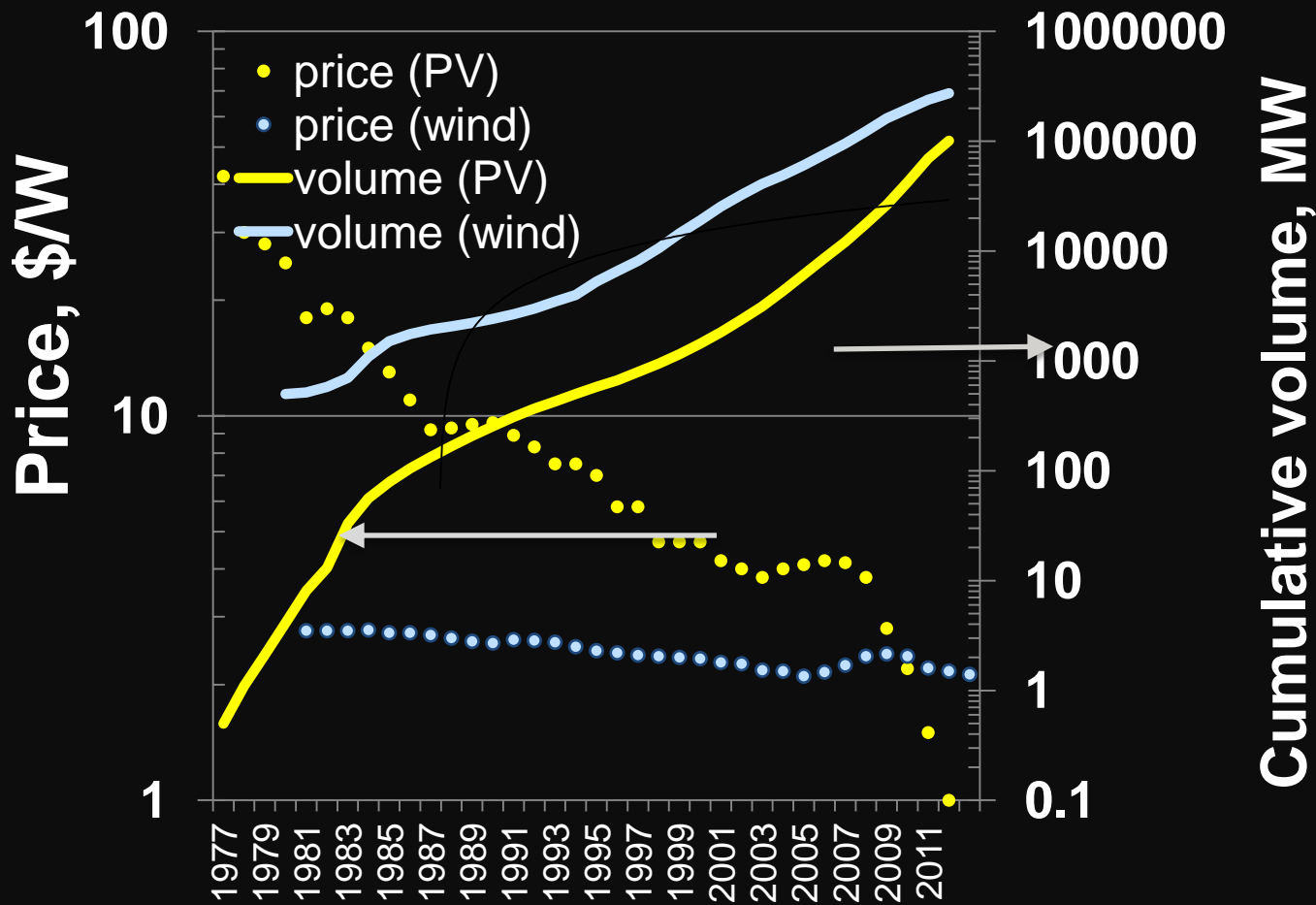
(b) Generation mix in 2050 for the exploratory scenarios

Source: NREL: Exploration of High-Penetration Renewable Electricity Futures, 2012

# Trends in new energy

- growing markets and falling prices

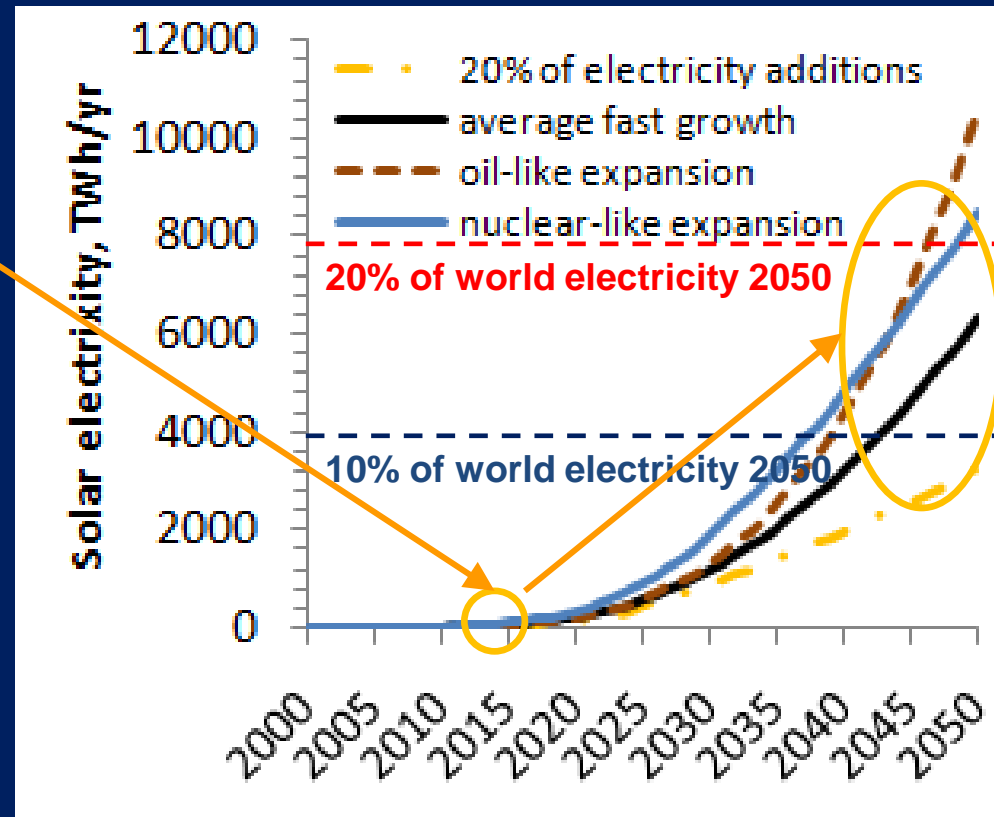
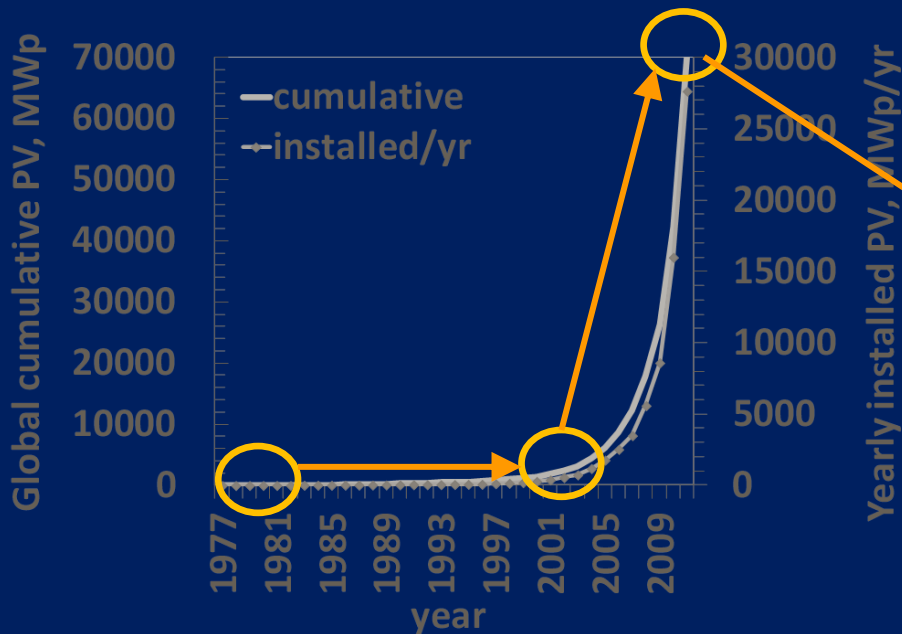
Progress in solar PV and wind power





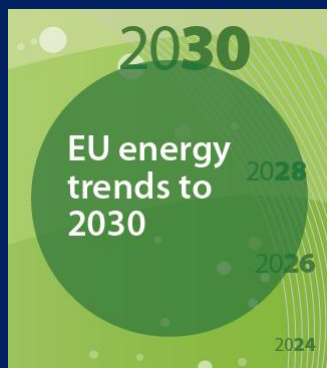
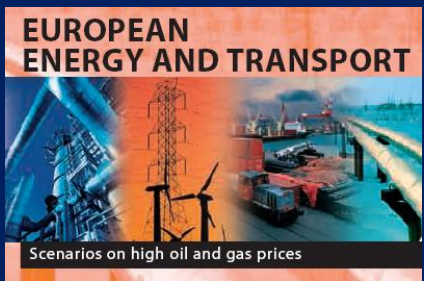
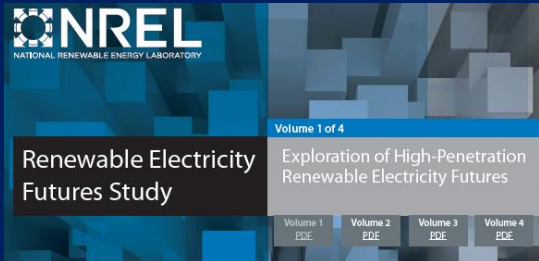
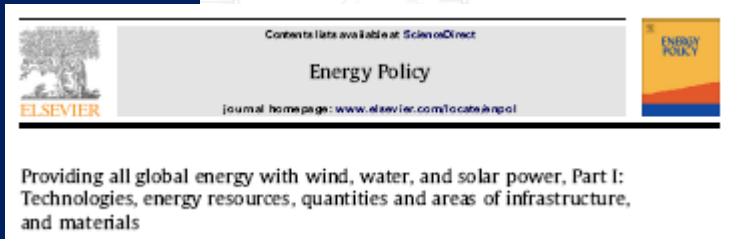
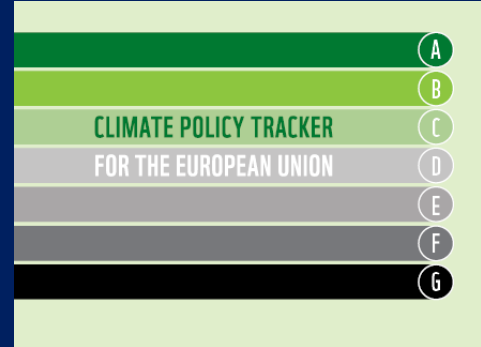
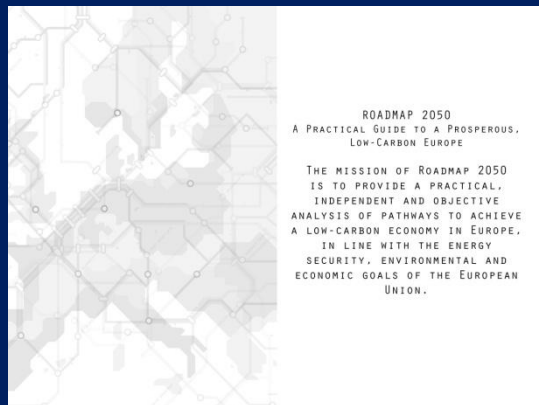
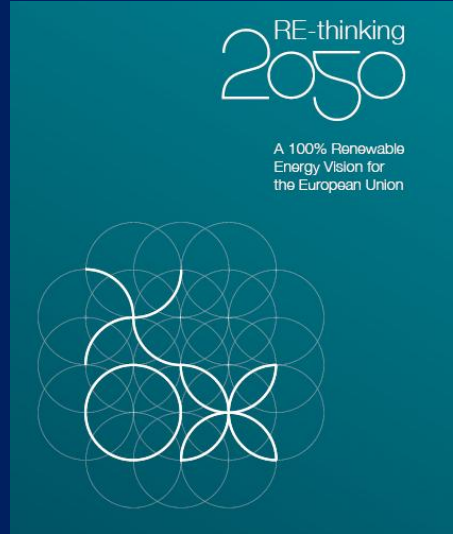
# Take-off of Solar PV?

- PV share of world electricity 2013 < 1%; By 2050: 5% (slowing progress)... 25% (fast-track)



# Shifting to sustainable energy

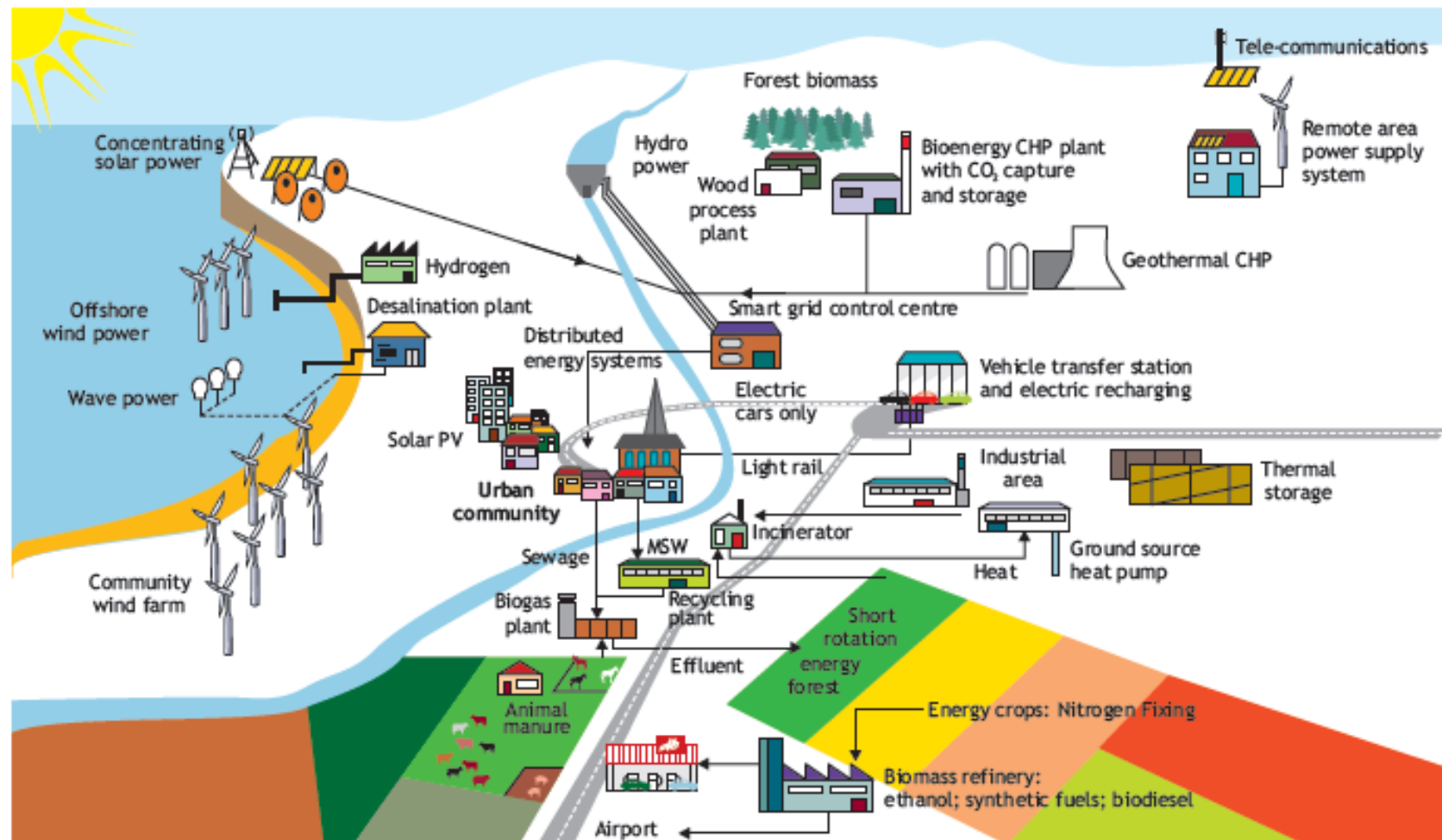
- Several studies and scenarios indicate high future market shares of renewable energy and electricity



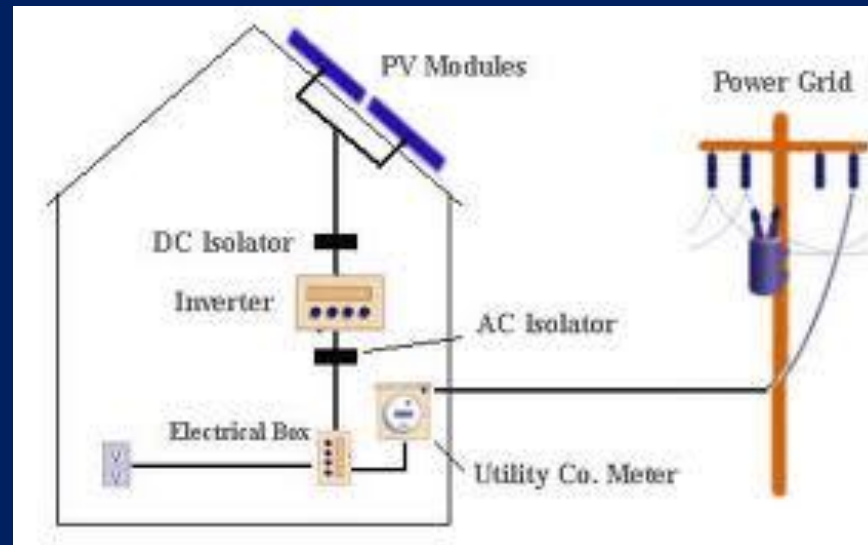
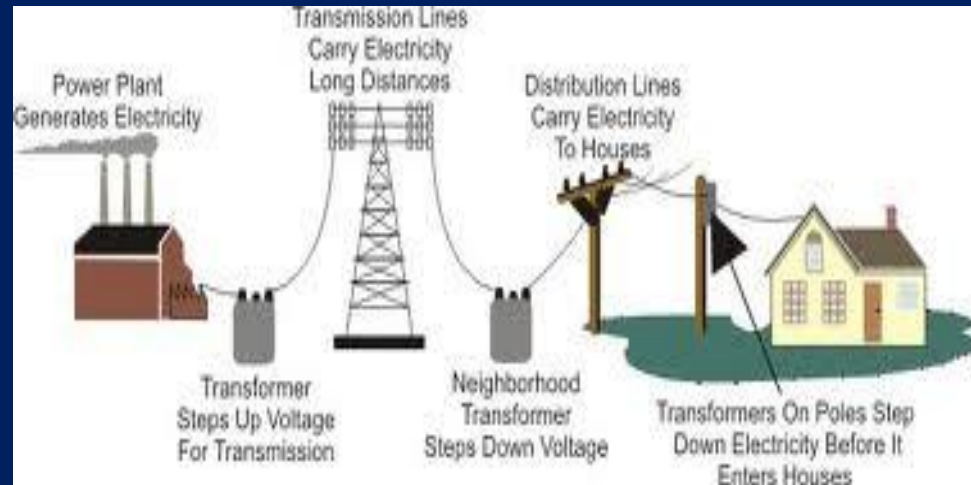
**Die Energiewende**  
Zukunft made in Germany

# Distributed and renewable energy generation technologies

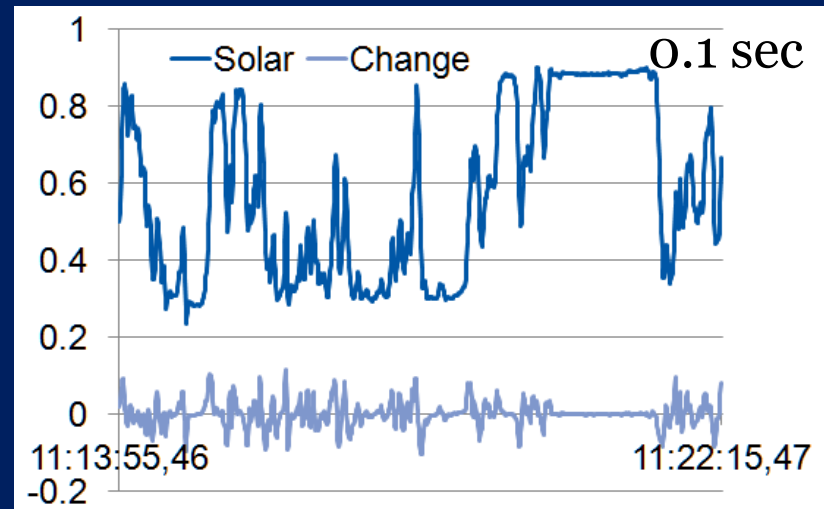
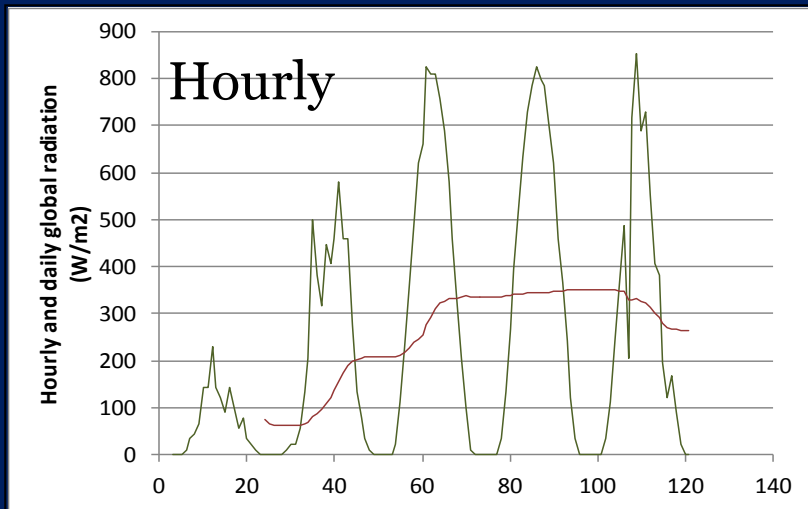
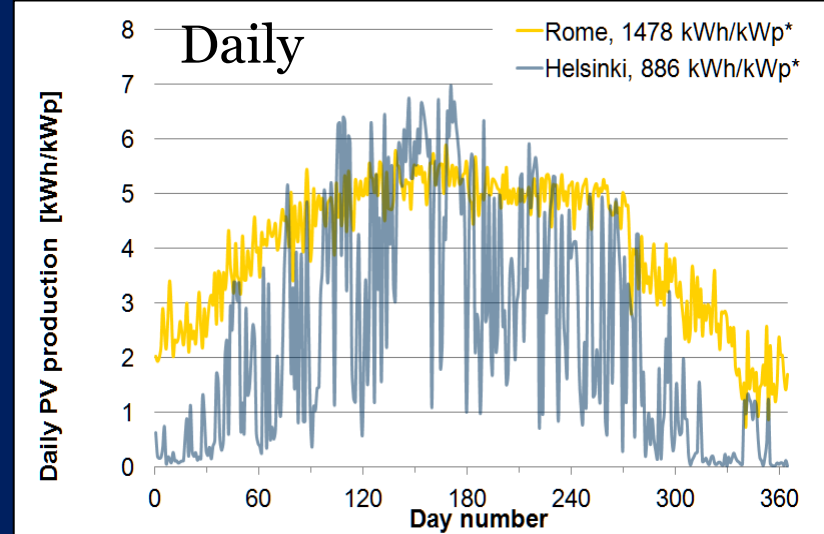
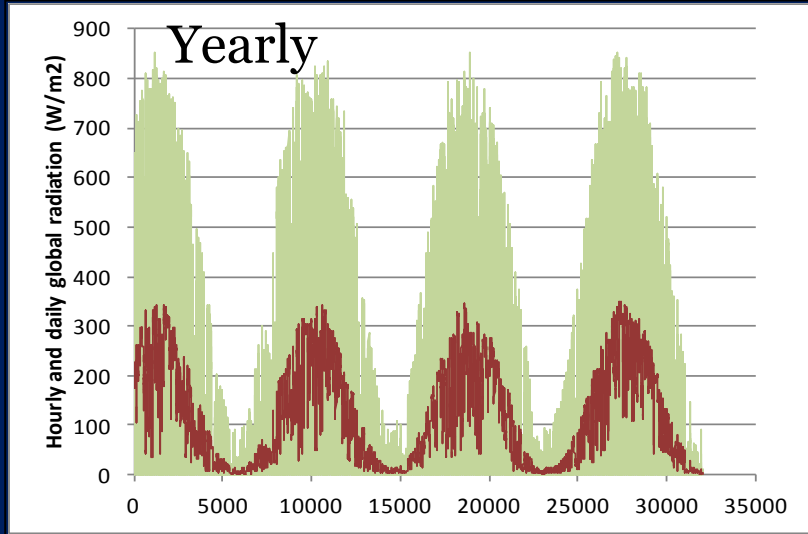
Figure 3 • Producing significant shares of heat, power and biofuels from locally available resources including solar, wind, ocean, geothermal, energy crops and biomass from wastes, could be a future option for a municipality



# Distributed power topology



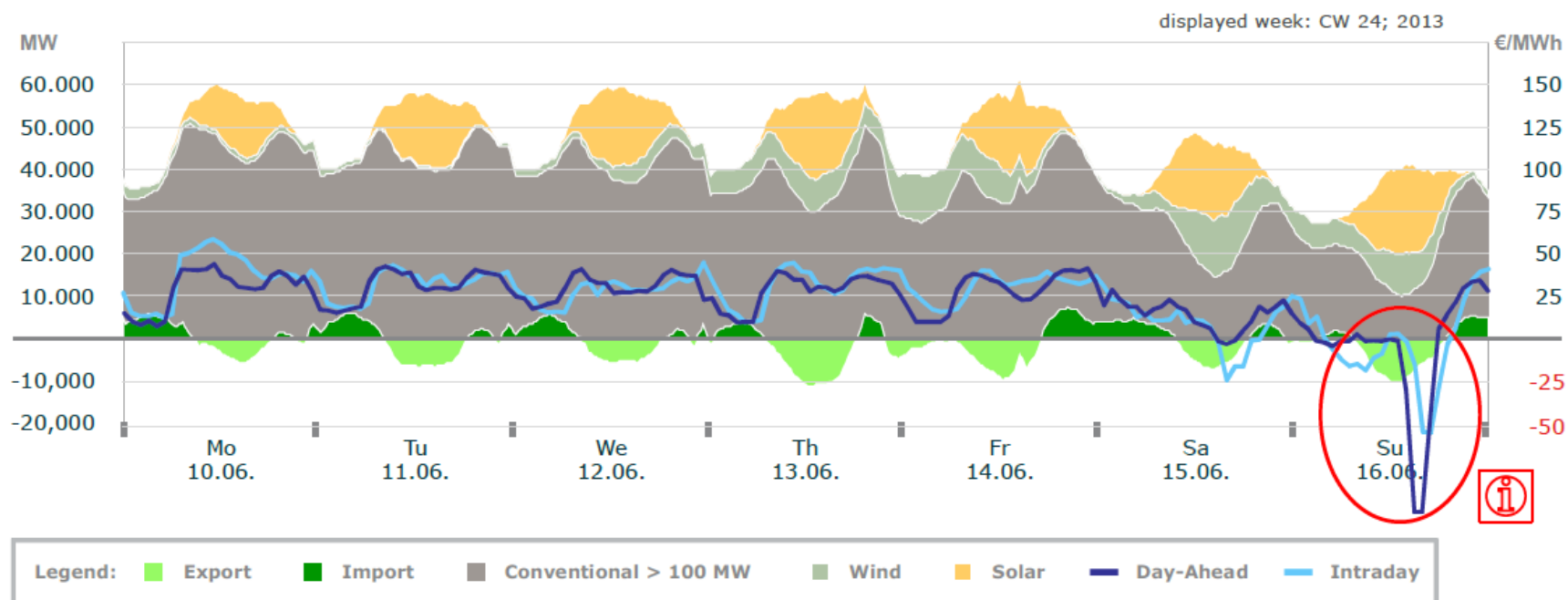
# RE (PV) resource variability on different time scales





# Temporal market effects from large-scale RE (Germany)

## Electricity Production and Spot-Prices: CW 24 2013



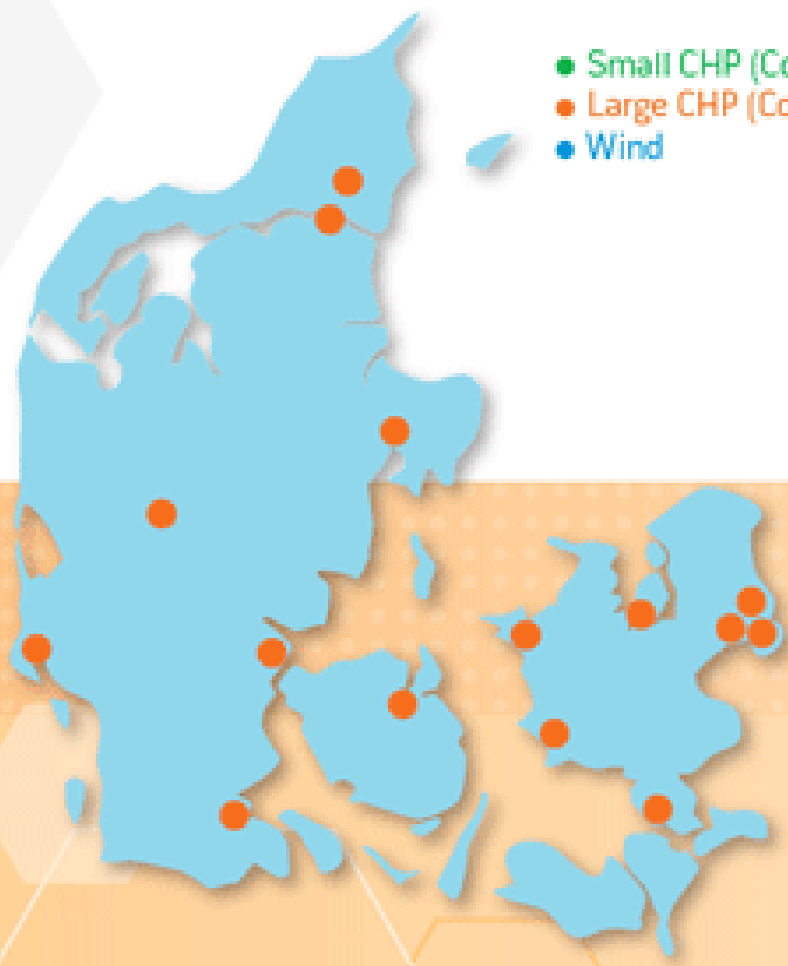
€/ MWh	Period Mean	Period Min	Period Max	Std Deviation
<b>Day-Ahead</b>	<b>23.28</b>	<b>- 100.00</b>	<b>45.00</b>	<b>19.72</b>
<b>Intraday</b>	<b>26.95</b>	<b>- 53.50</b>	<b>59.50</b>	<b>18.99</b>

# Spatial effects from RE schemes

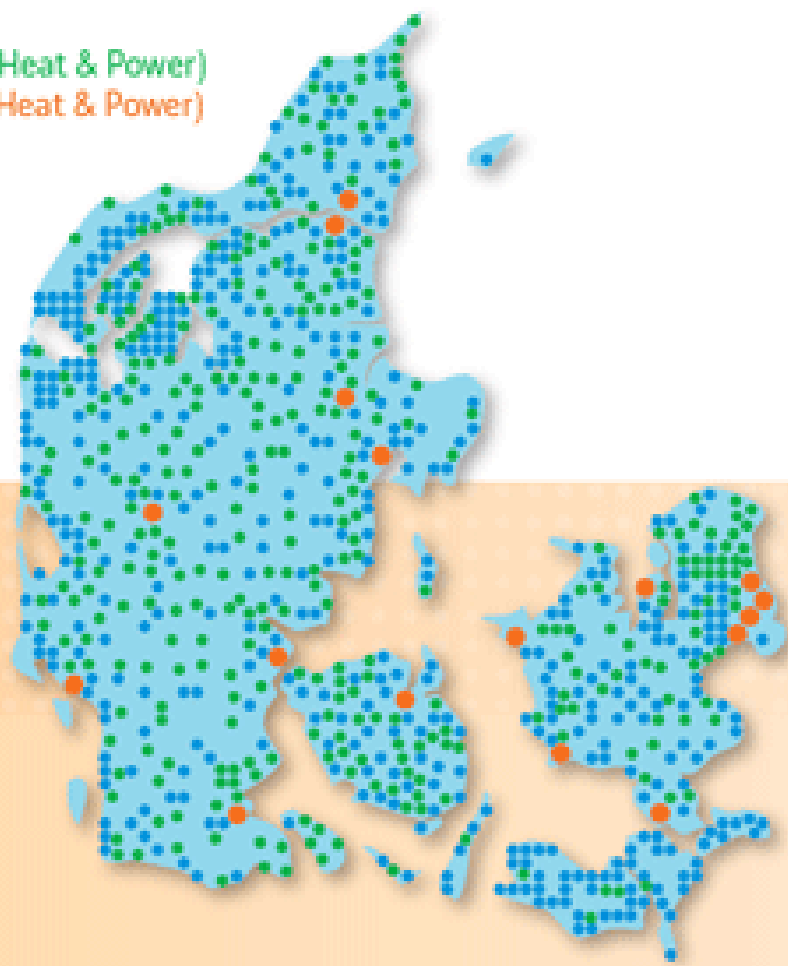


# DENMARK'S PROGRESS OVER THE PAST TWO DECADES

- Small CHP (Combined Heat & Power)
- Large CHP (Combined Heat & Power)
- Wind



Centralized System of the mid 1980's



More Decentralized System of Today



# Large-scale RE schemes require systemic bridging innovations

Old 100%



- Multi-energy networks
- Flexible demand
- EV, ICT

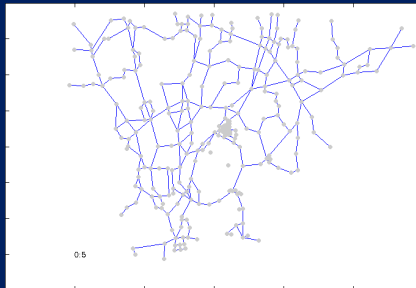
New 100%



**How does the energy system work with much renewable energy?**



- Storage
- E2T, V2G, E2Gas



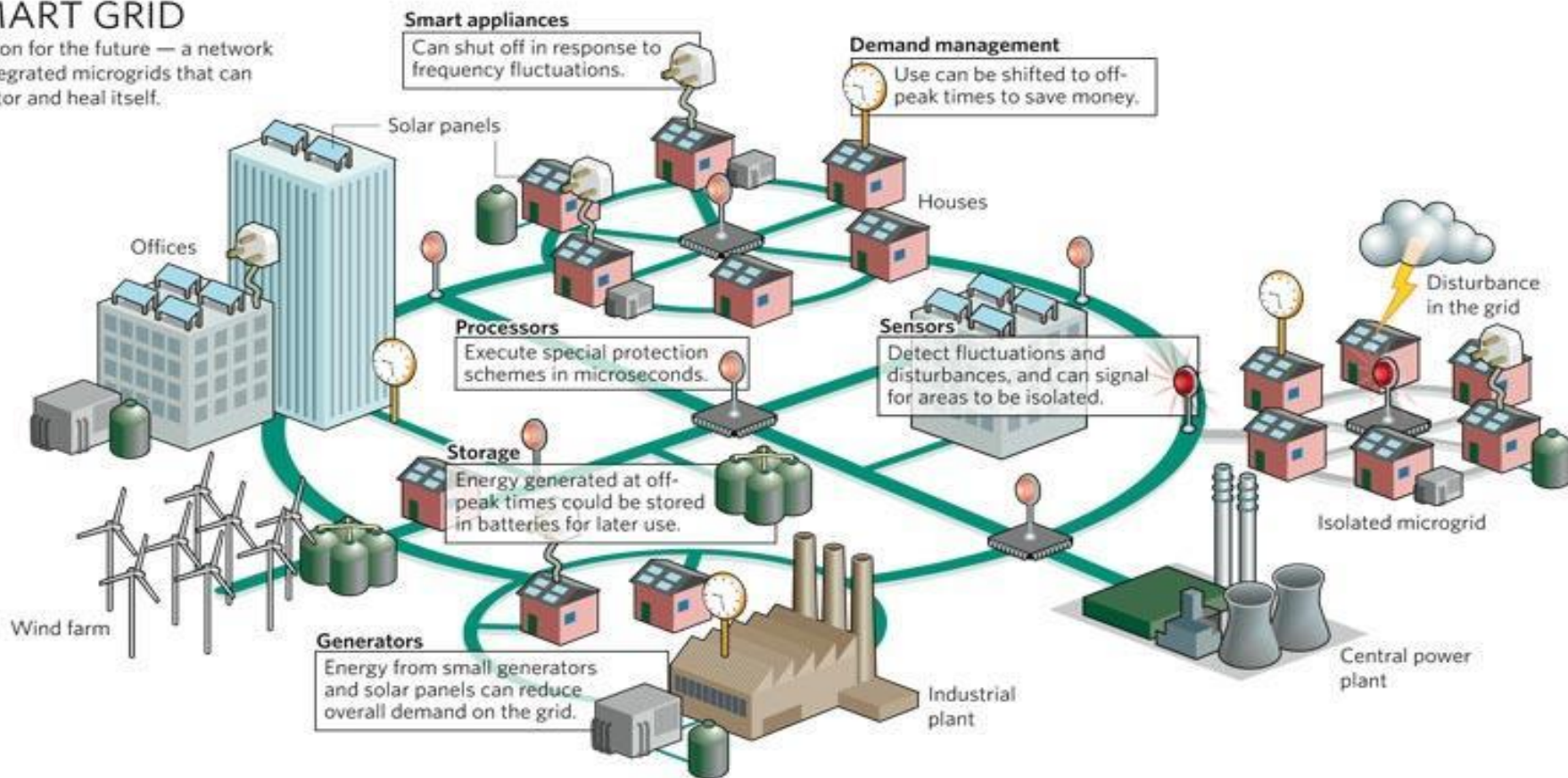
New 0%

Old 0%

# Smart infrastructures provide spatiotemporal flexibility

## SMART GRID

A vision for the future — a network of integrated microgrids that can monitor and heal itself.





# Smart built environment provide spatiotemporal flexibility



## The Smart House

Xcel Energy's Smart Grid Consumer is imagining a future that would allow you to communicate your energy choices to the power grid and automatically receive electricity based on your personal needs.

### The potential benefits:

- Lower cost of power
- Cleaner power
- A more efficient and resilient grid
- Improved system reliability
- Increased conservation and energy efficiency

### Plug-in Hybrid Electric Car

Xcel Energy is studying how plug-in electric vehicles can store energy, act as backup generators for homes and supplement the grid during peak hours.

### Smart Meter

Real-time pricing signals create increased options for consumers.

### Smart Appliances

Smart appliances contain on-board intelligence that "talks" to the grid, senses grid conditions and automatically turns devices on and off as needed.

### Smart Thermostat

Customers can opt to use a smart thermostat, which can communicate with the grid and adjust device settings to help optimize load management. Other "smart devices" could control your air conditioner or pool pump.

### High-Speed Connections

Advanced sensors distributed throughout the grid and a high speed communications network to the entire system together.

### Customer Choice

Customers may be offered an opportunity to choose the type and amount of energy they'd like to receive with just the click of a mouse on their computers. 100 percent green power? A mix of sources? The cheapest priced source? In Smart Grid City, it could be up to you.

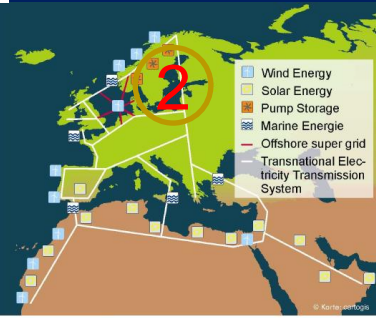
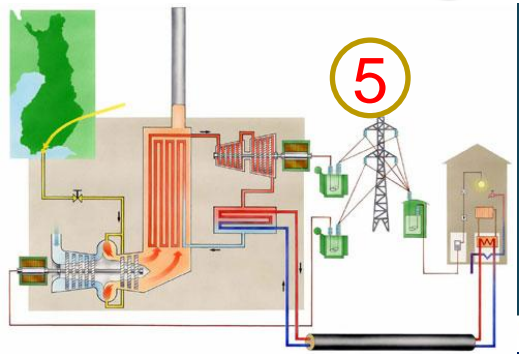
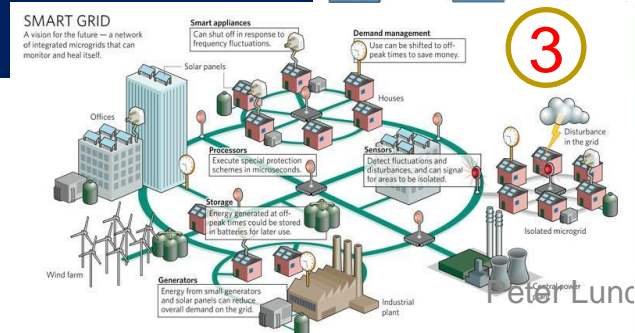
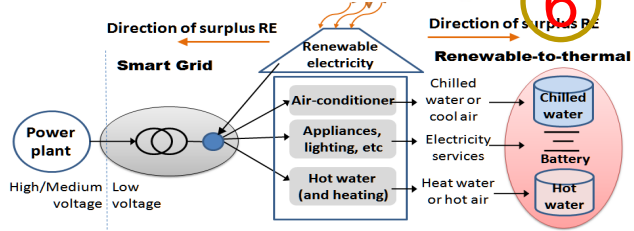
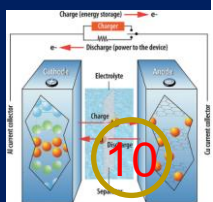
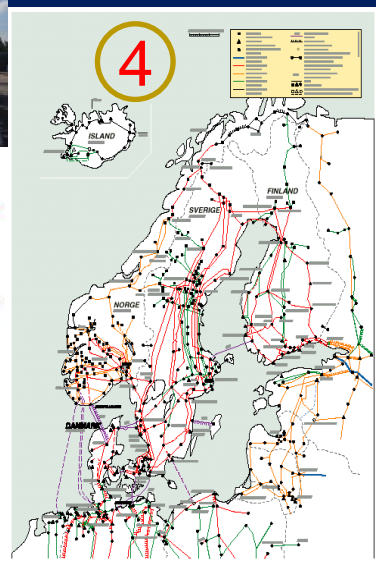


# Energy systems perspective to high-shares of RE power

Q1: matching supply and demand of electricity with RE sources  
 Q2: integrating distributed RE power into the energy system

Examples of solutions:

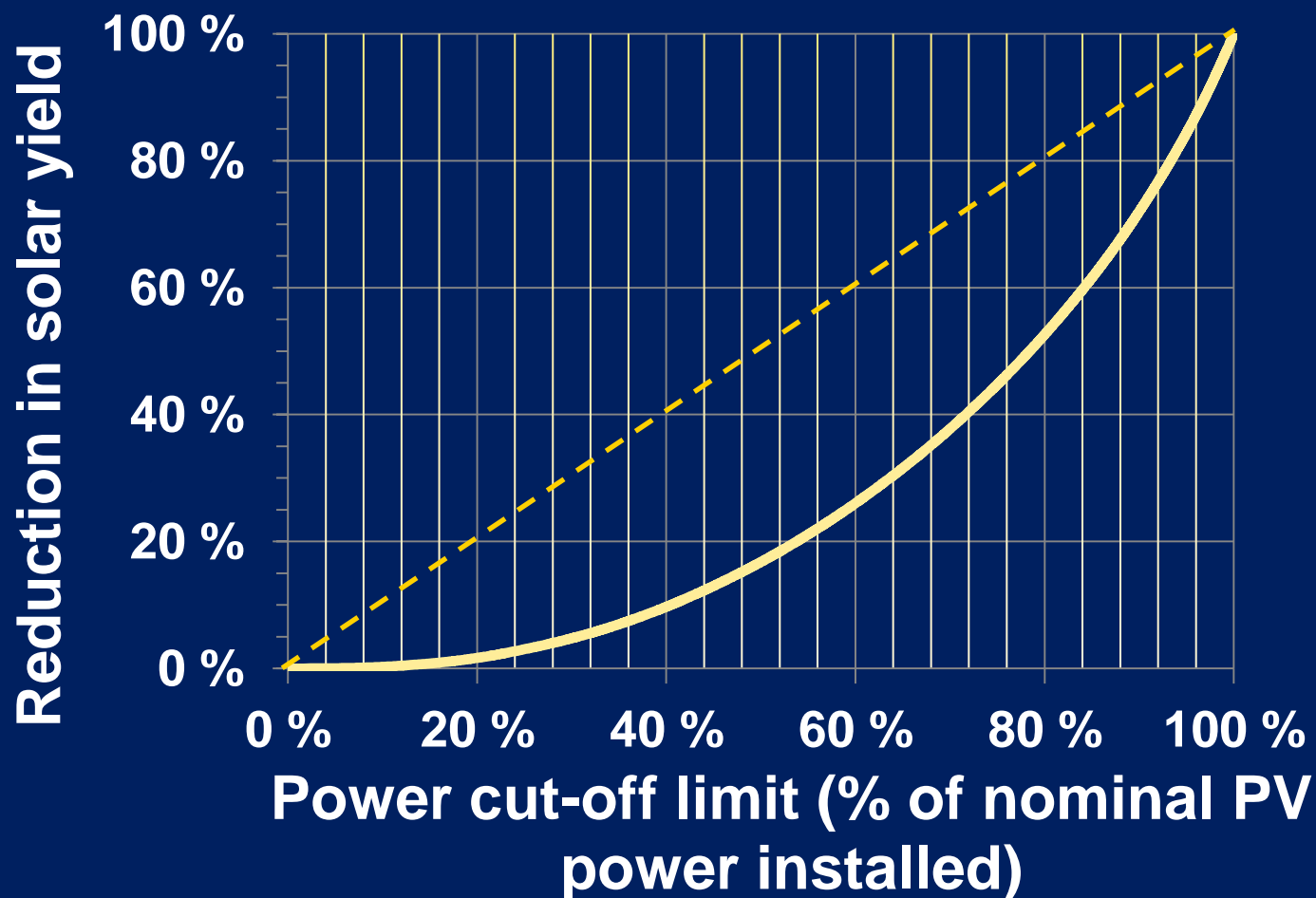
1. RE in urban context
2. Grid infrastructures
3. Smart Grids
4. Electricity markets
5. Co-generation (CHP)
6. RE coupled with end-use
7. Electricity-to-Gas
8. RE+Gas integration
9. Demand flexibility
10. Storage



Potential of green generation for Europe determining the future transmission needs. Source: Fraunhofer-Institut für Windenergie und Energiesystemtechnik (IWES).

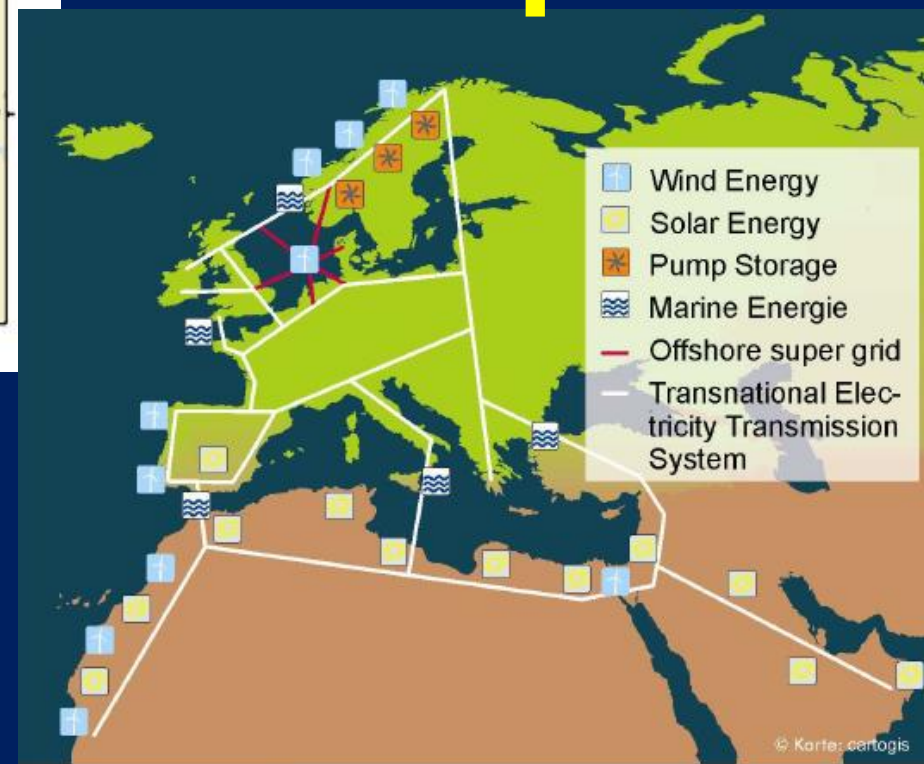
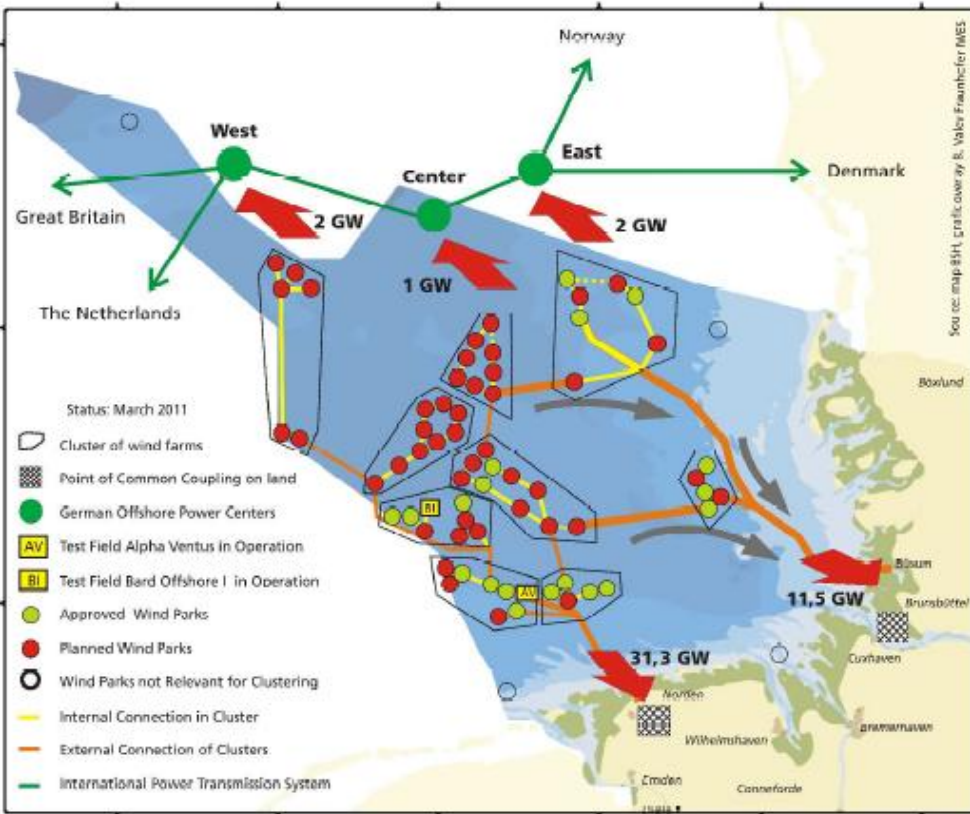
# Simple control of large-amounts of RE:

Ex. Curtailing PV power





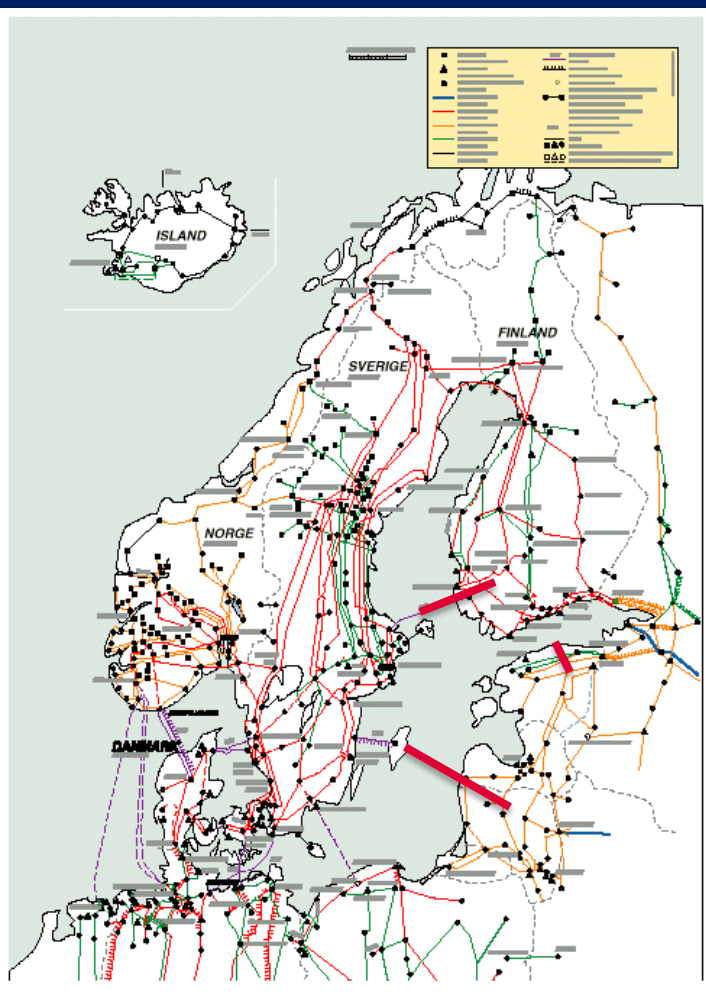
# Examples of grid extension plans in Europe



Potential of green generation for Europe determining the future transmission needs. Source: Fraunhofer-Institut für Windenergie und Energiesystemtechnik (IWES).

# Integrated electricity market

– a Nordic system innovation for large-scale use variable renewables

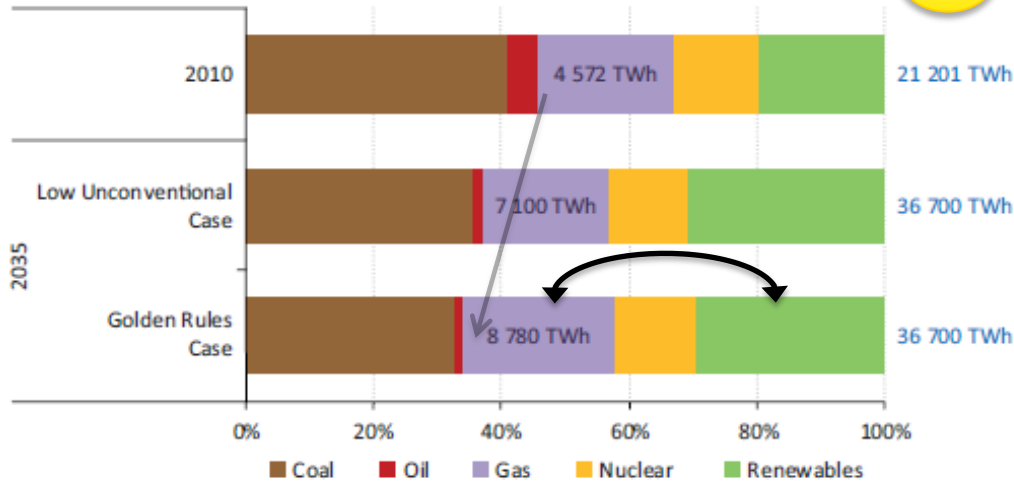


- Nordic electricity market has a common power reserve which can be accessed through the power exchange
- How much wind power is possible without major reserve power increase?
  - **If wind 10% of all electricity → extra cost for reserve power is 1 €/MWh**
  - **If 20% → 1-7 €/MWh** (source: H.Holttinen, VTT)
- Vision: 20-25 % of all Nordic electricity wind power by 2030; Norwegian hydropower buffers



# RE&Gas: better power plant flexibility

Figure 2.15 ▷ World power generation mix by case

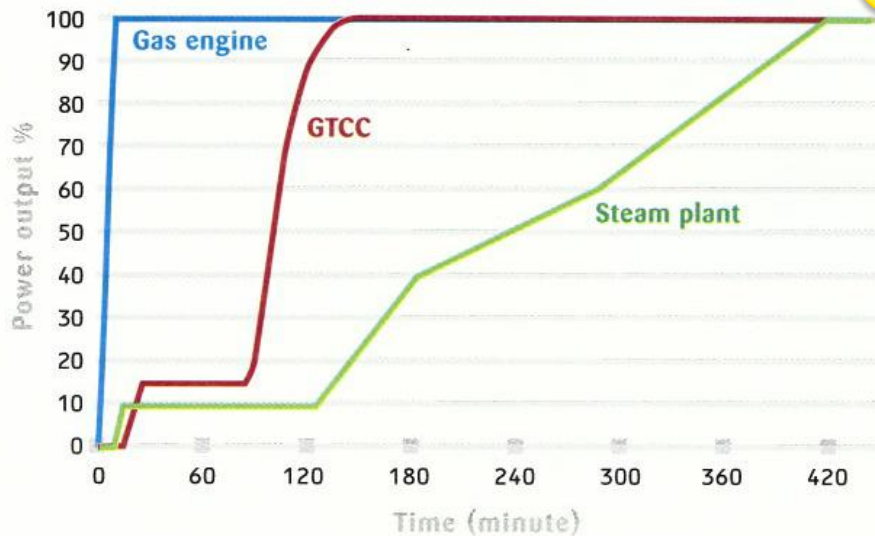


A

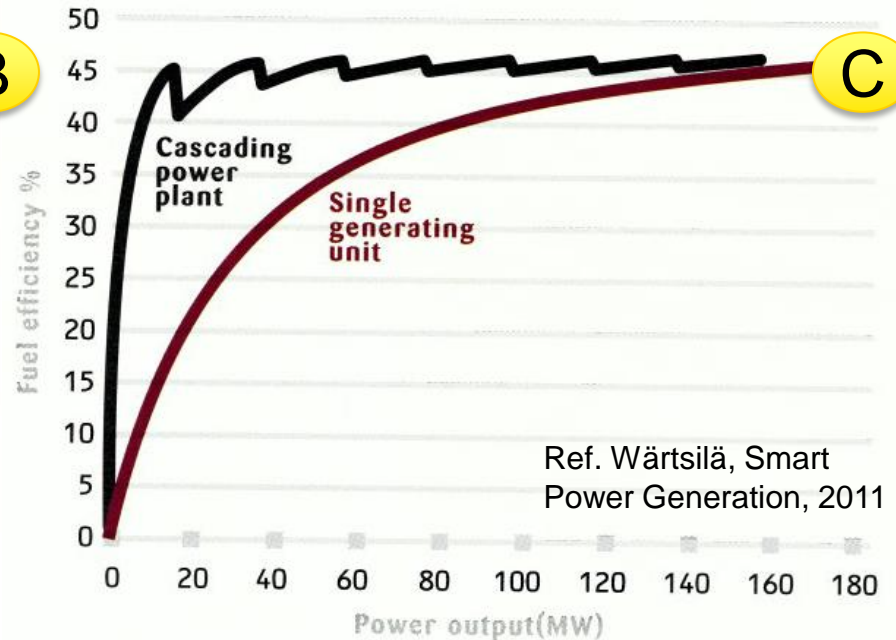
Note: TWh = terawatt-hours.

Ref. IEA, Golden Rules for a Golden Age of Gas

STARTING AND OUTPUT RAMPING UP OF THREE DIFFERENT GENERATING TECHNOLOGIES AFTER A FIVE DAYS STOP



B



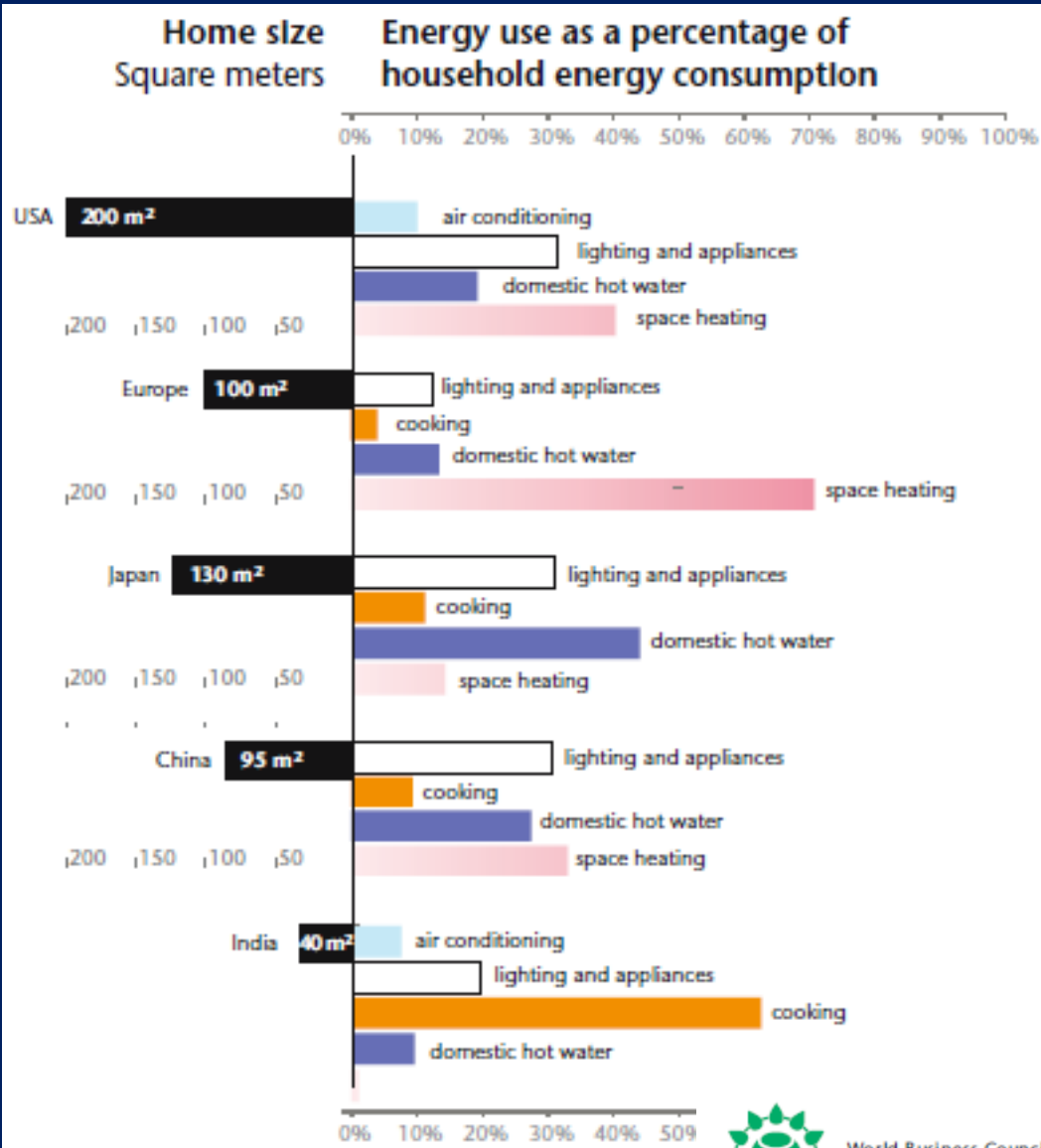
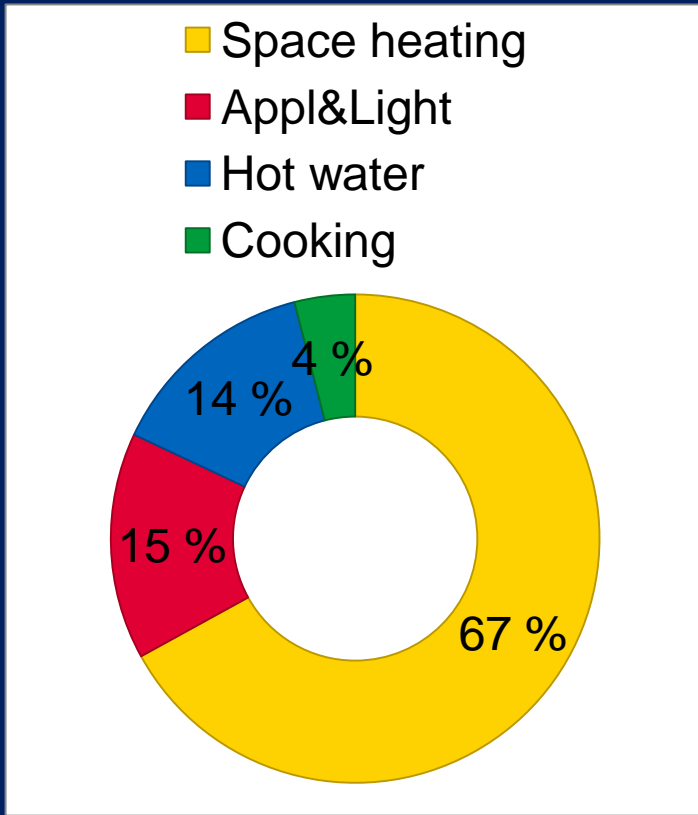
C

Ref. Wärtsilä, Smart Power Generation, 2011

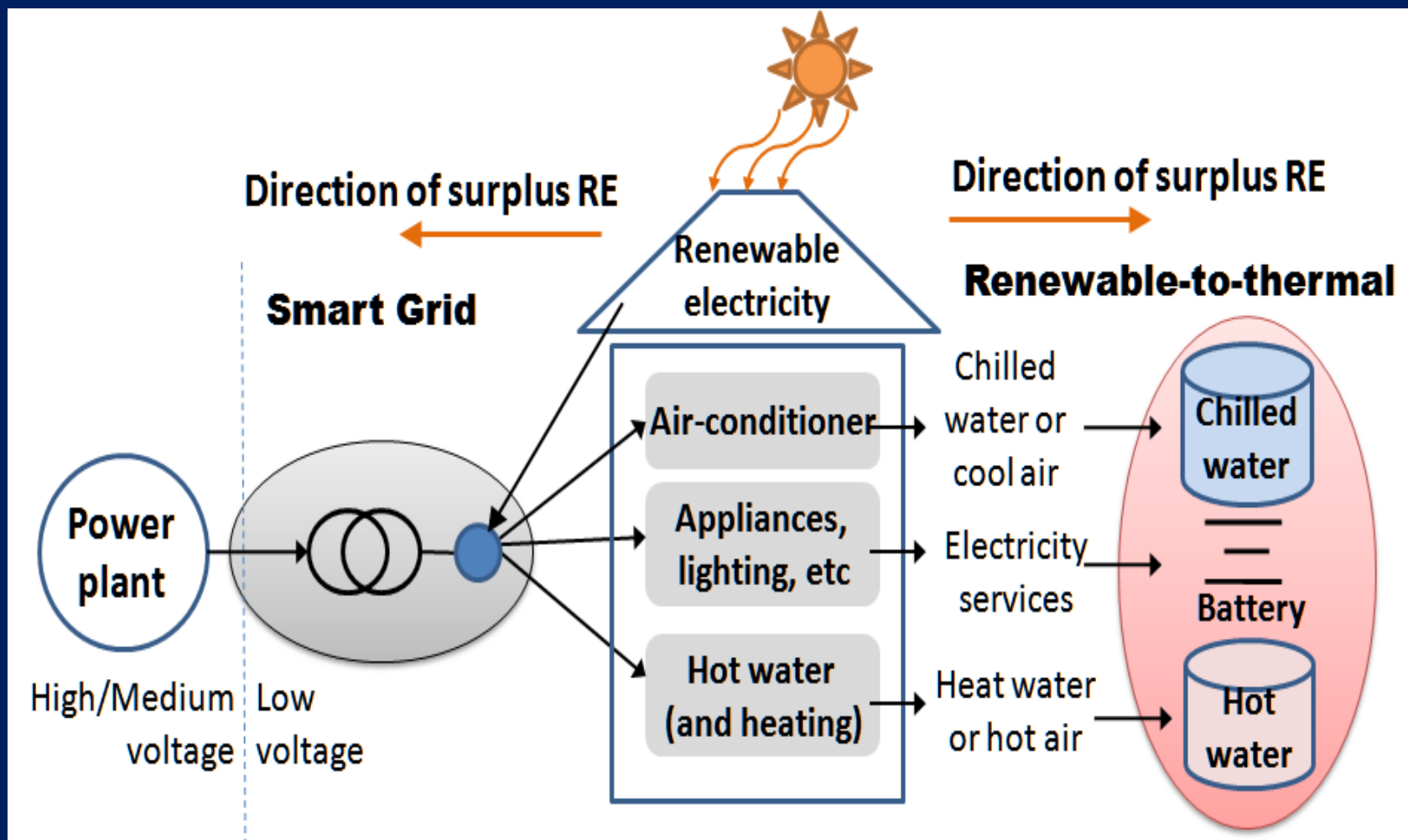
# Final energy in urban environment

## – thermal energy forms dominate end-use side

- Final energy use forms in buildings: heating, cooling, electricity
- EU-27 household energy:



# Electricity-to-thermal conversion of surplus renewable electricity



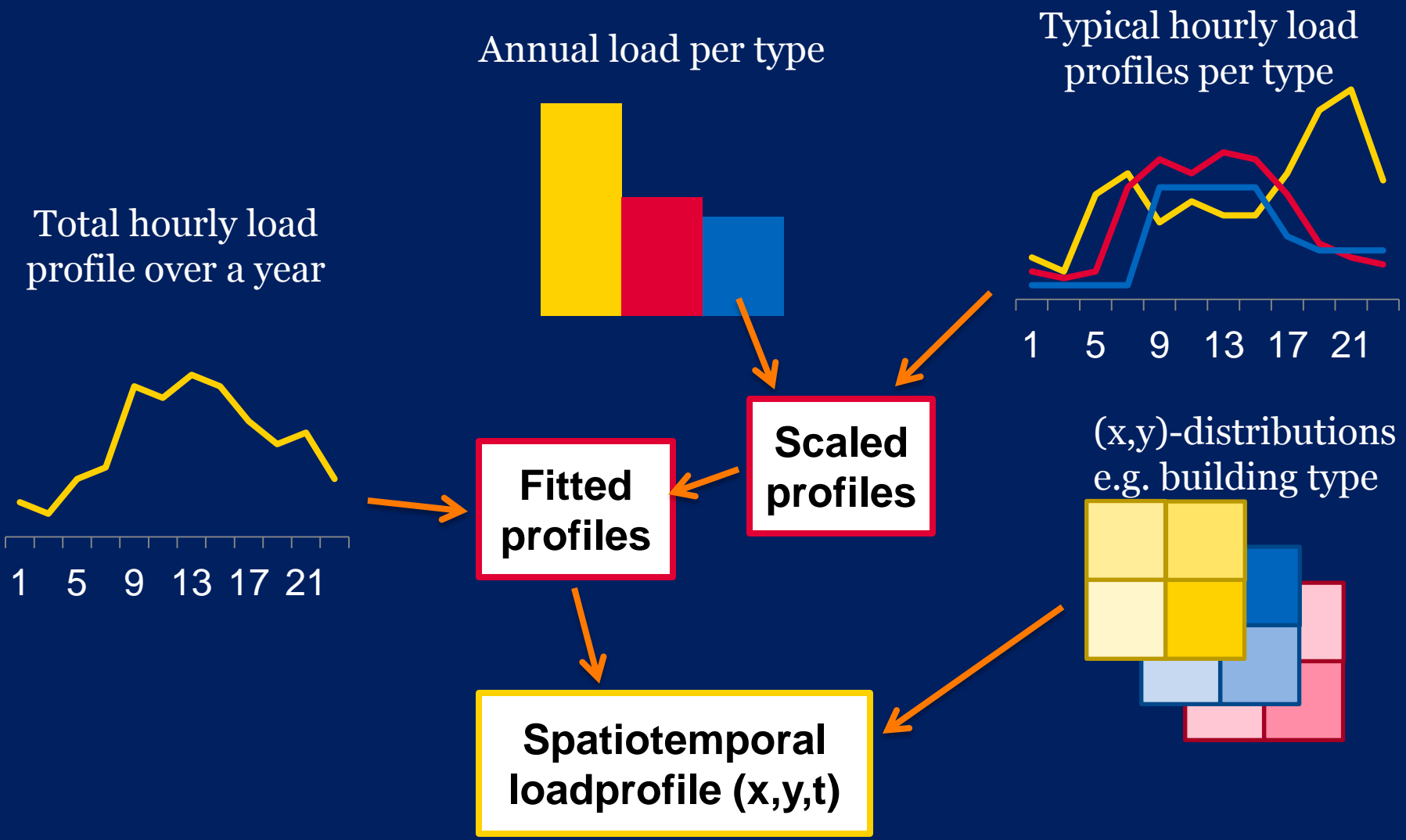


An aerial photograph of Helsinki, Finland, showing a dense urban area with numerous buildings, streets, and green spaces. The city is situated on islands and peninsulas, with a large body of water (the harbor) visible on the left side. The text "How much wind power could be utilized in Helsinki?" is overlaid in large, bold, yellow letters across the center of the image.

# How much wind power could be utilized in Helsinki?

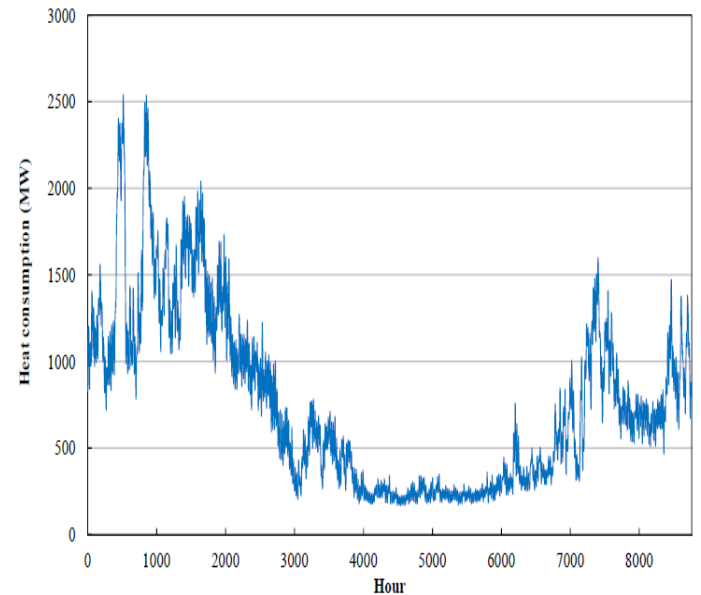
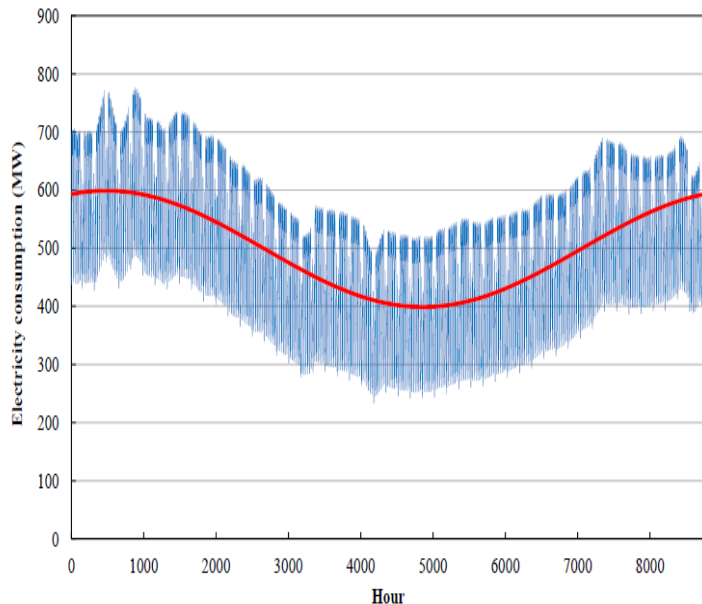
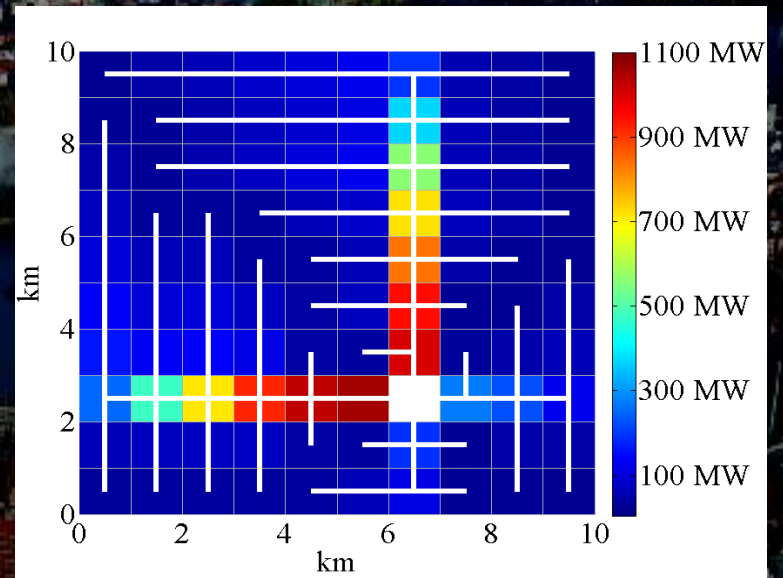
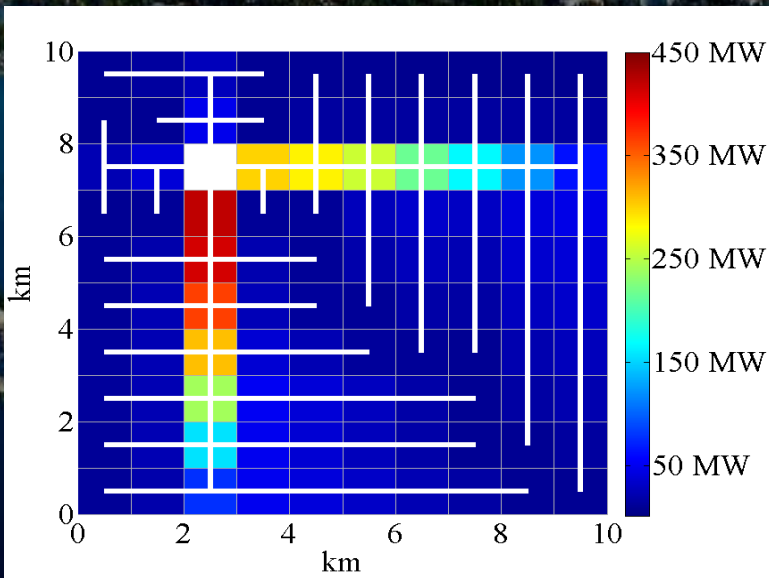
Peter Lund 2013

# Generating spatiotemporal (load) profiles (x,y,t)



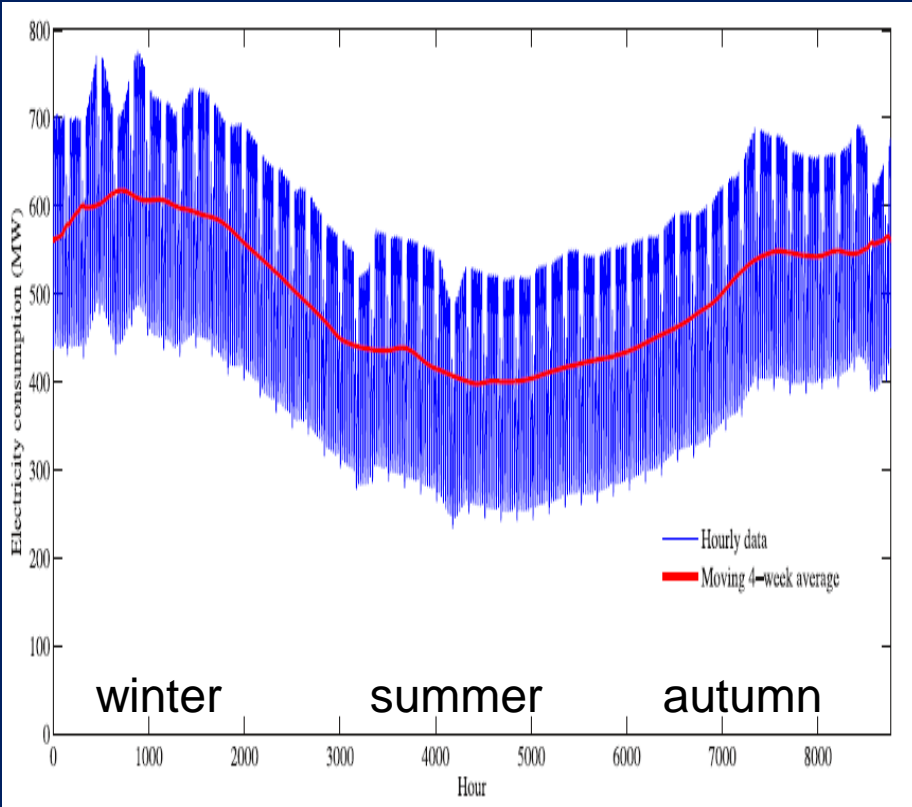


# Electric (left) and District Heating Networks and Loads (right) in Helsinki

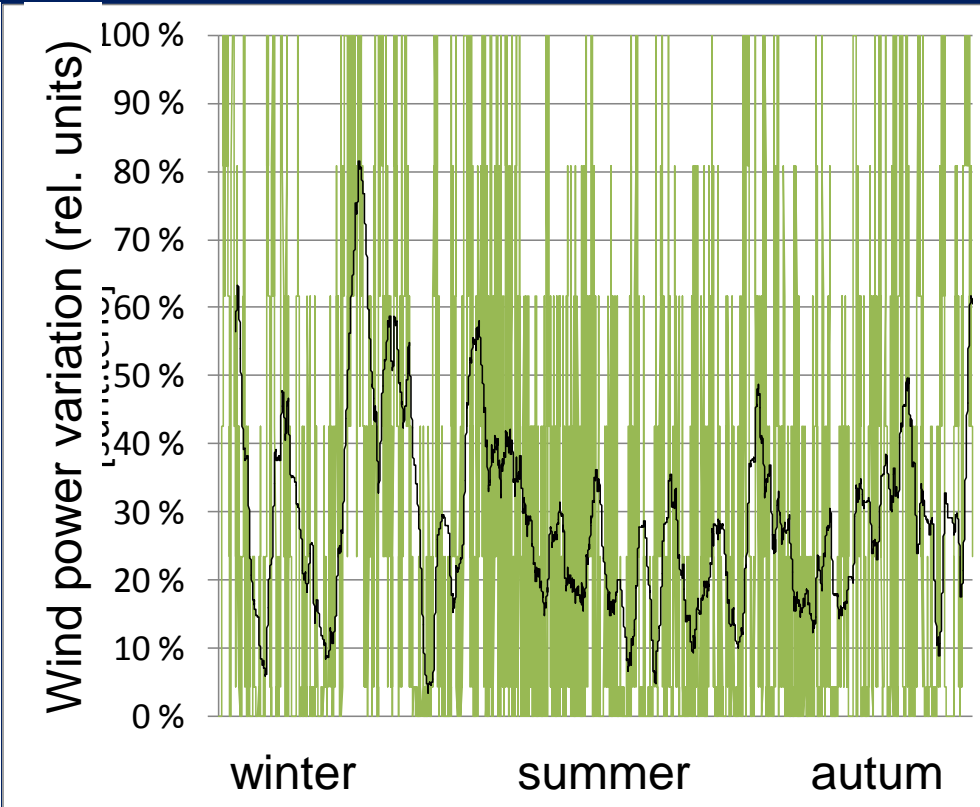


# Matching power demand and supply – each hour of the year!

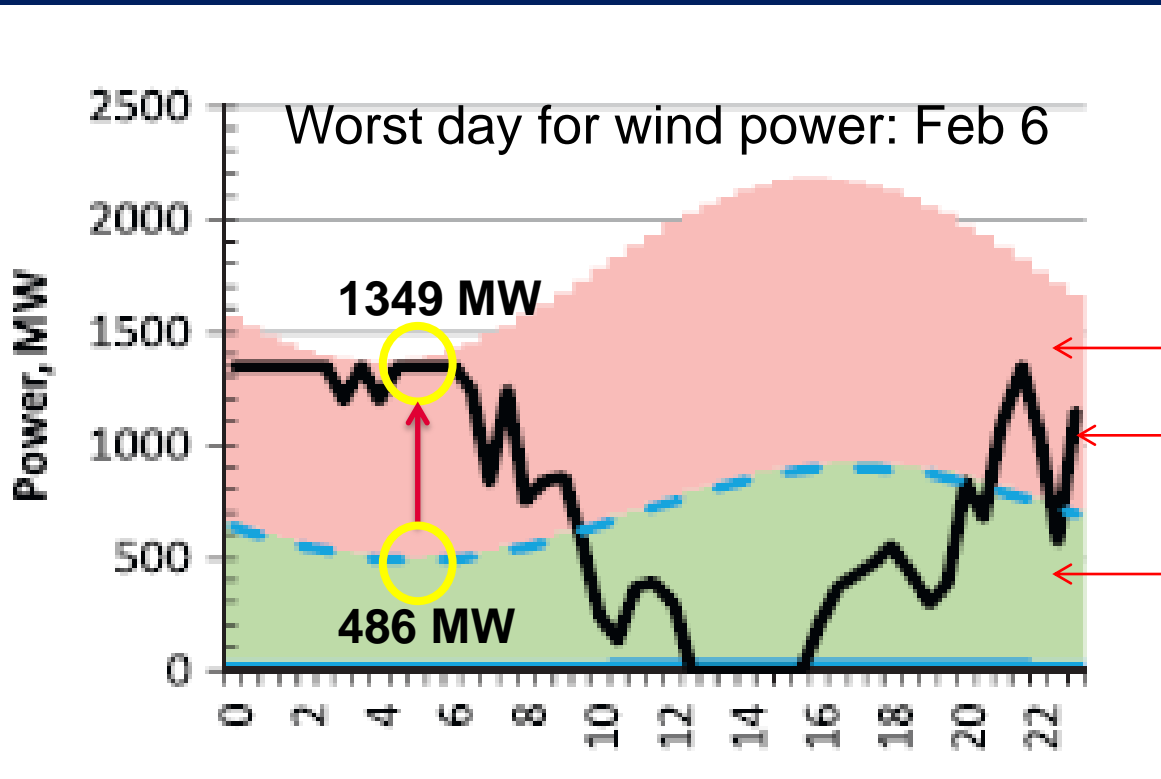
## Helsinki power demand



## Wind power production



# How does wind power match demand?



Heat demand

Wind power supply

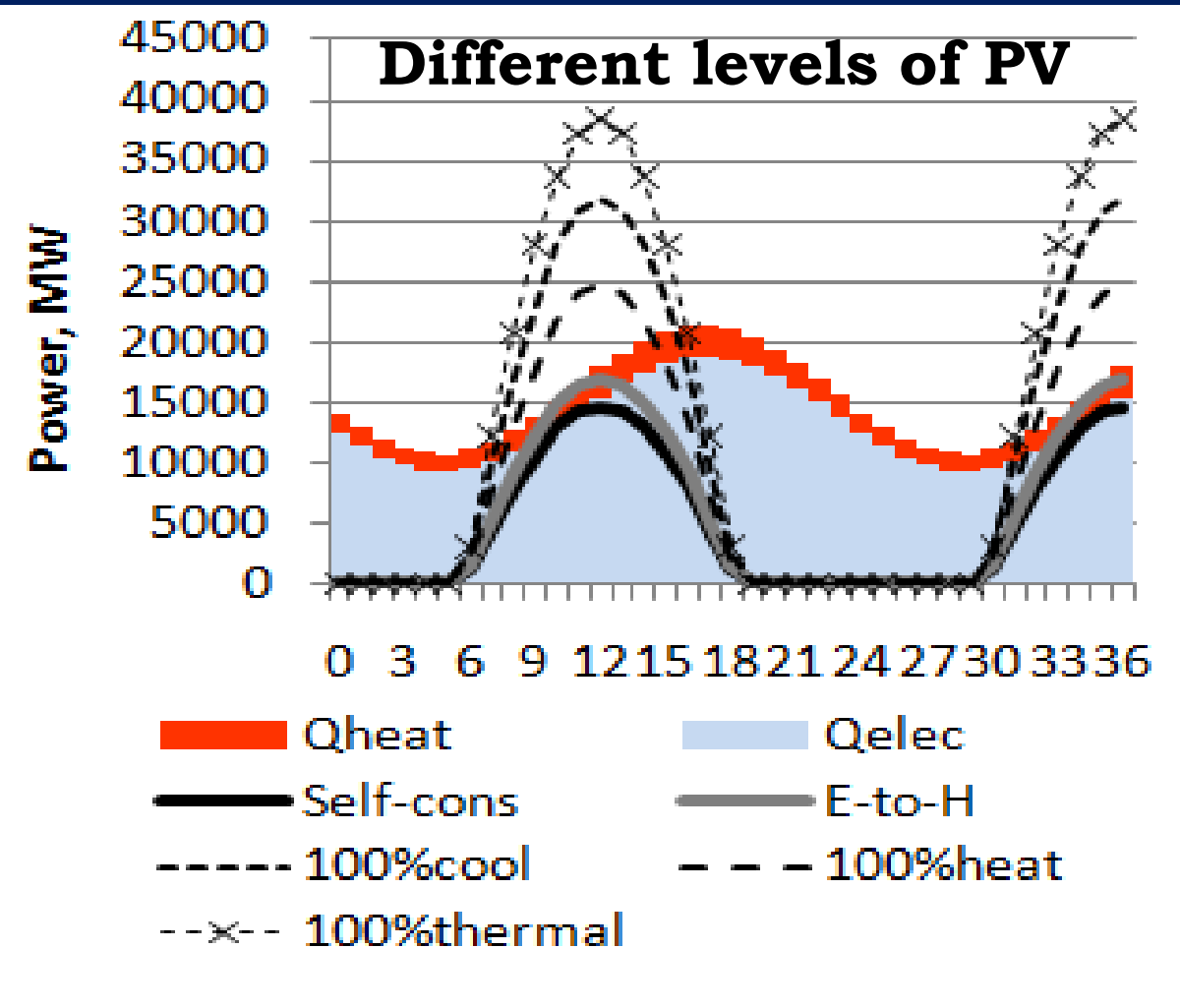
Electricity demand

Wind = power demand → **486 MW** wind power = **25%** of yearly electricity in Helsinki

Wind = power and heat demand → **1349 MW** wind power = **71%** of electricity per year (2% of heat)

Ref: Lund, P. : Large-scale urban renewable electricity schemes - integration and interfacing aspects. Energy Conversion and Management, 2012  
 Ref: R. Niemi, J. Mikkola, P.D. Lund: Urban energy systems with smart multi-carrier energy networks and renewable energy generation. Renewable Energy, 2012.  
 Peter Lund 2013

# Mismatch between PV and electricity demand – case Shanghai



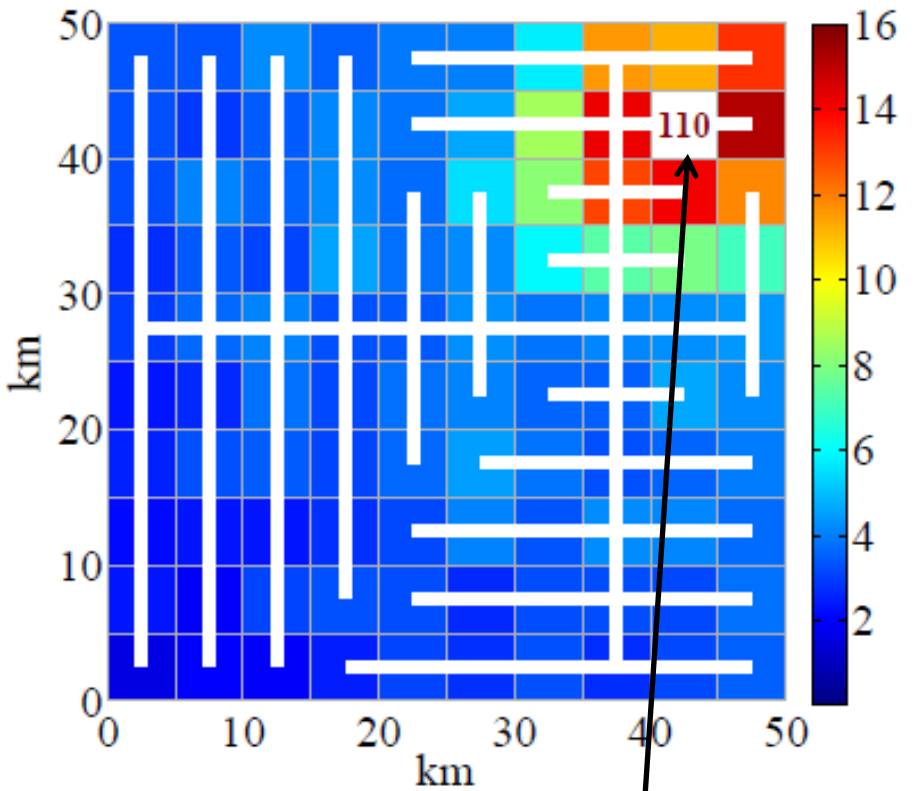
**Smart energy may  
2-3 x feasible PV  
capacity in  
Shanghai**

Base case (PV peak equals to electric load): 31% daily energy share, 25% of yearly electricity share

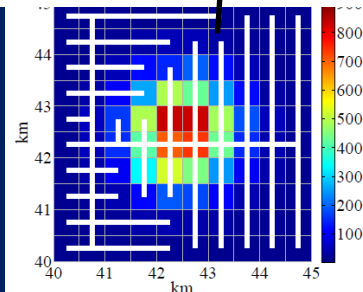
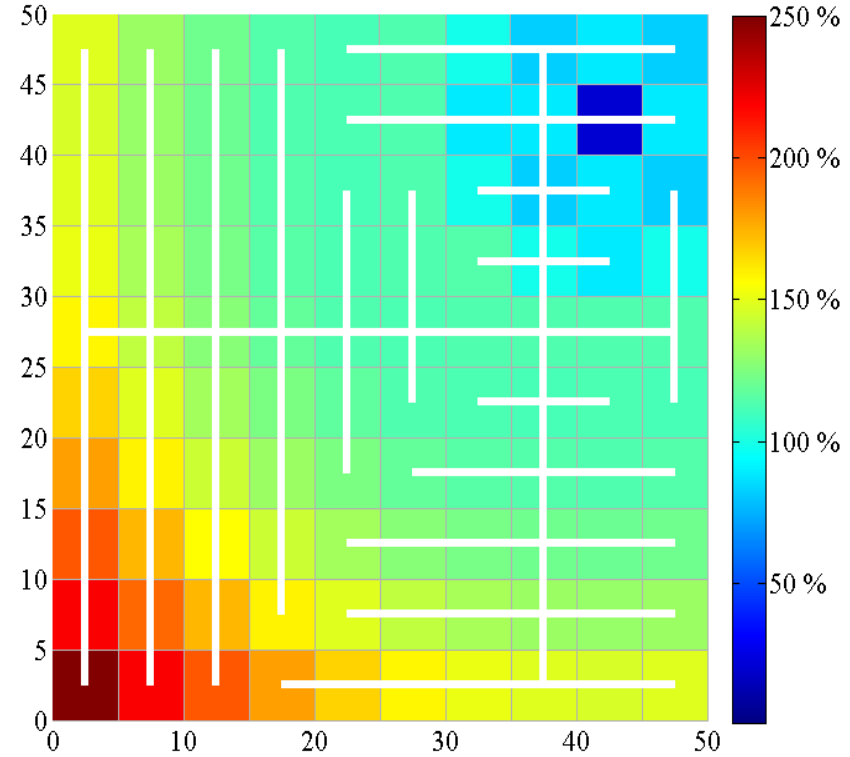
Advanced case (PV peak equals to total load: 50-70% of daily energy demand (40-55% of yearly electricity)

# Example of power distributions with large PV schemes in Shanghai

Peak electricity consumption



Max. PV production / Max. load



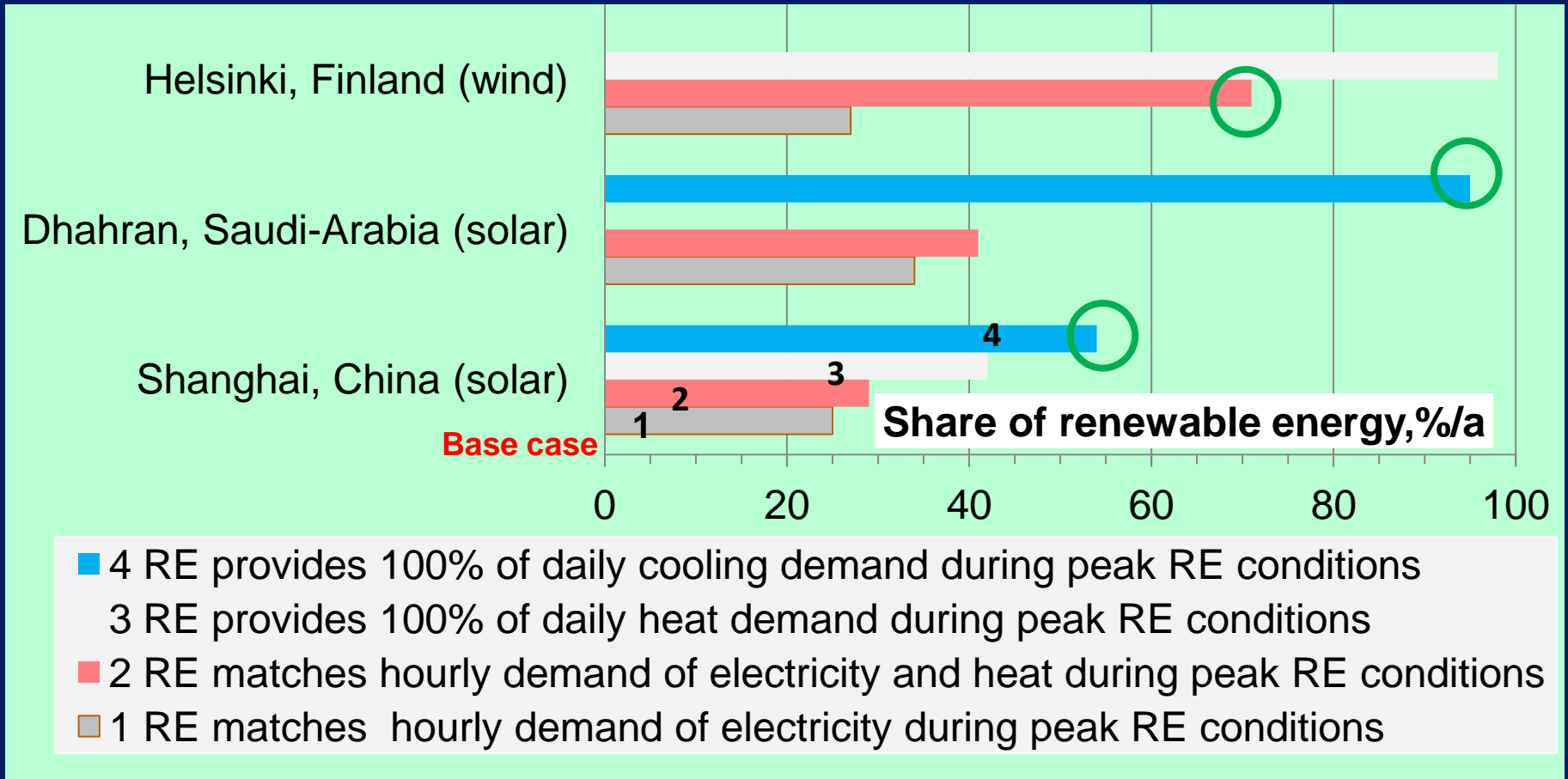
Niemi, R., Mikkola, J., Lund P., Urban energy systems with smart multi-carrier energy networks and renewable energy generation, *Renewable Energy* 48 (2012) 524-536.

Peter Lund 2013



# Pushing the share of RE power 2-3-fold beyond the traditional limit

- Electricity-to-Thermal strategy: RE system is oversized, surplus turned into and stored as thermal energy (heat or cold) ; or curtailed



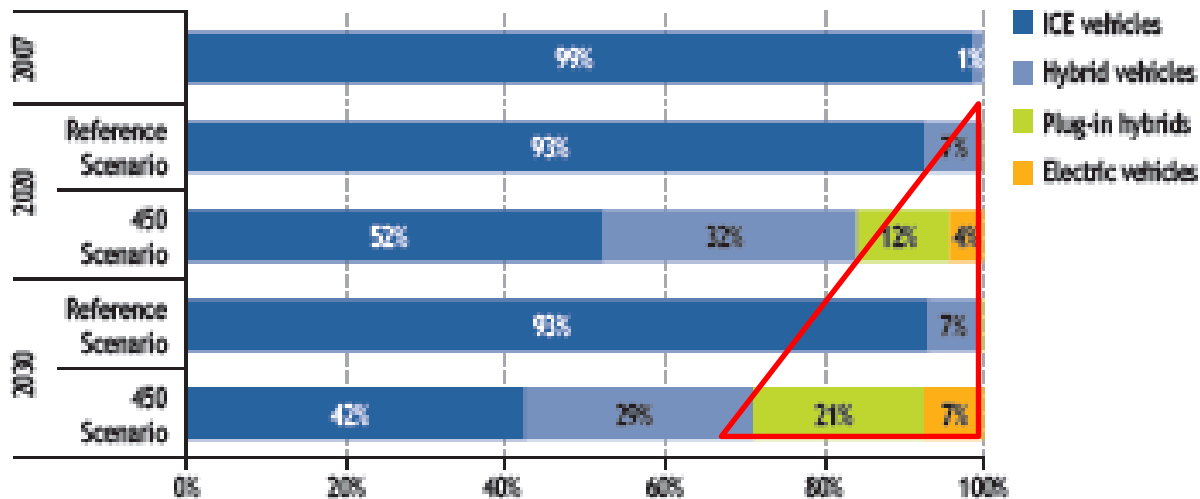
Ref: Lund,P.: Large-scale urban renewable electricity schemes - integration and interfacing aspects. *Energy Conversion and Management*, 2012

# Electrified vehicles providing electricity services (E2V, V2G)



Tesla Motors - Model S lithium-ion battery pack

**Figure 6.10** • Share of global passenger vehicle sales by engine technology and scenario

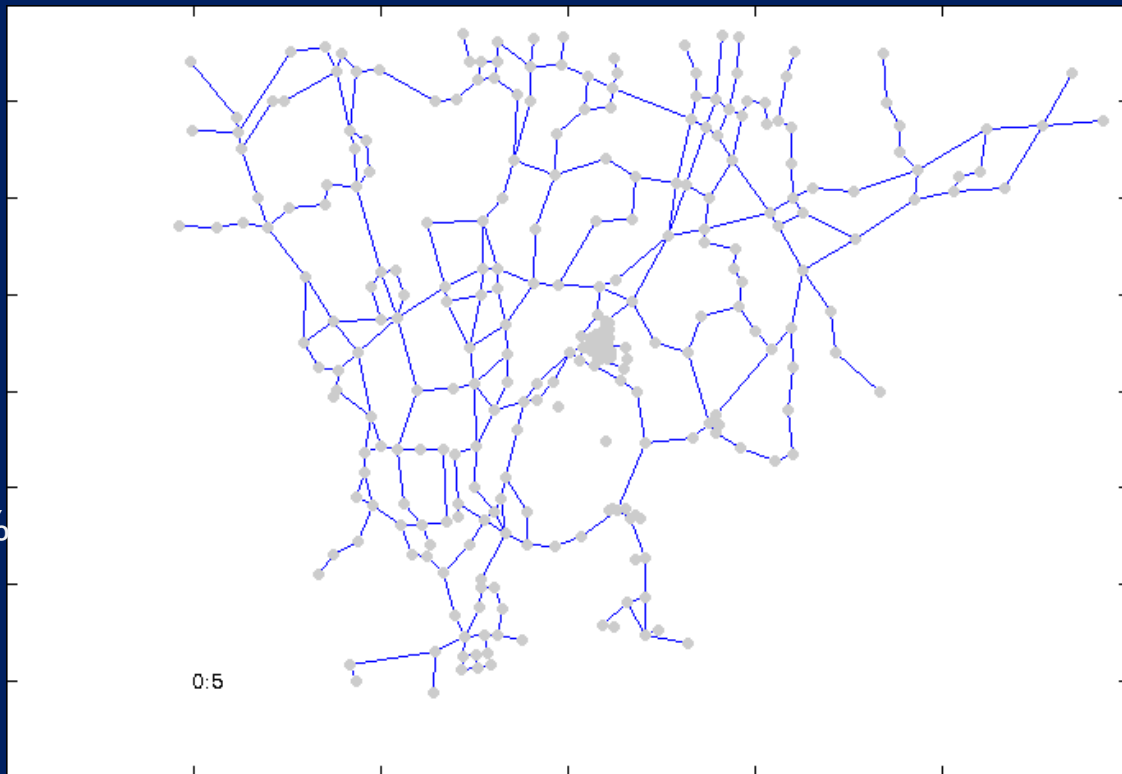


# EV & PV & Grid

- Case Helsinki Metropolitan region Area (1 million people)

## Key parameters for the simulation:

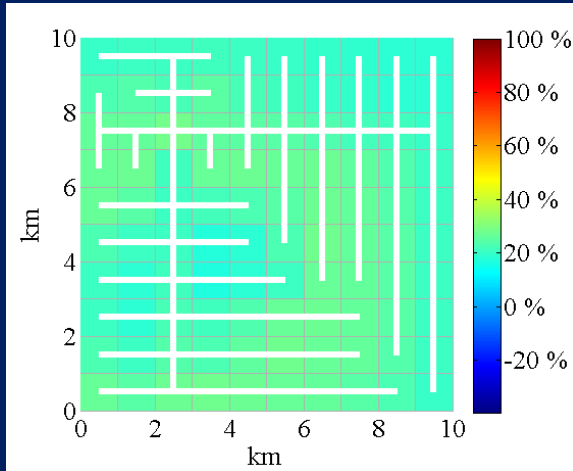
- battery capacity 10 kWh
- electricity consumption 0.2 kWh/km
- charging efficiency 0.9
- power coefficient @ home:  $\infty$  kW
- power coefficient @ work:  $\infty$  kW
- sockets: *plenty* (no queuing)
- socket power limit 7.4 kW
- battery recharge limit: 1-hour 0  $\rightarrow$  100%



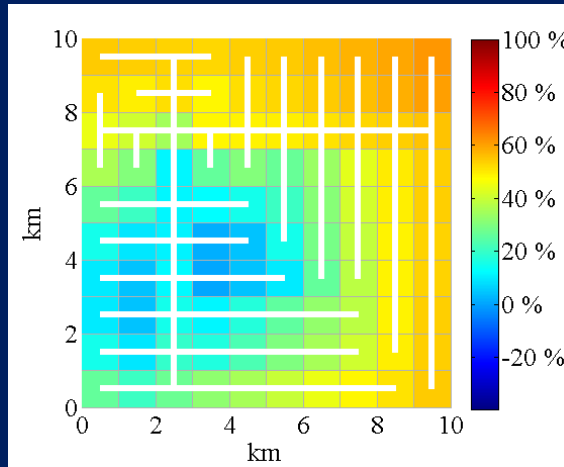
# Large-scale PV+EV case for Helsinki:

2 GWp PV (1/3 of yearly demand, 6x min. summer demand)

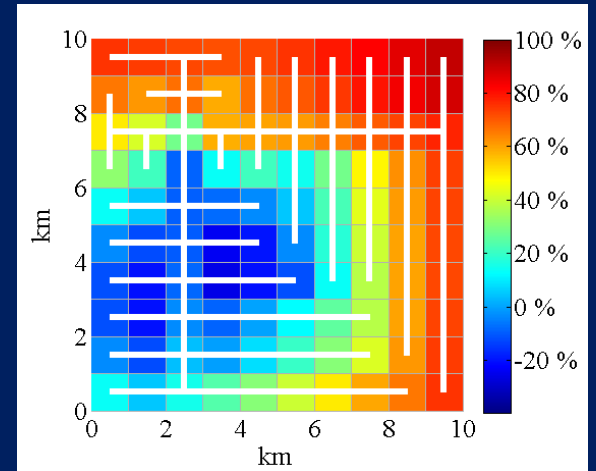
Maximum PV power overflow at peak conditions:



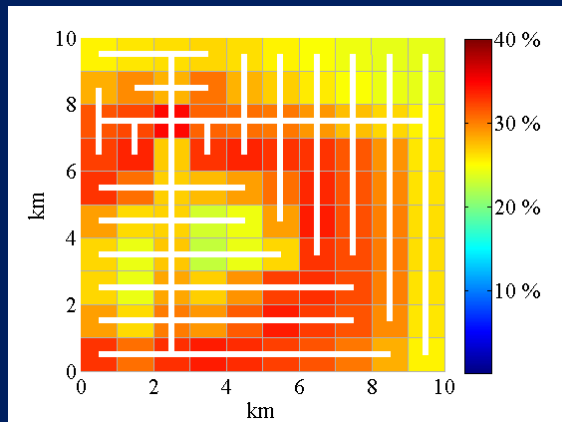
100% of PV placed based on load



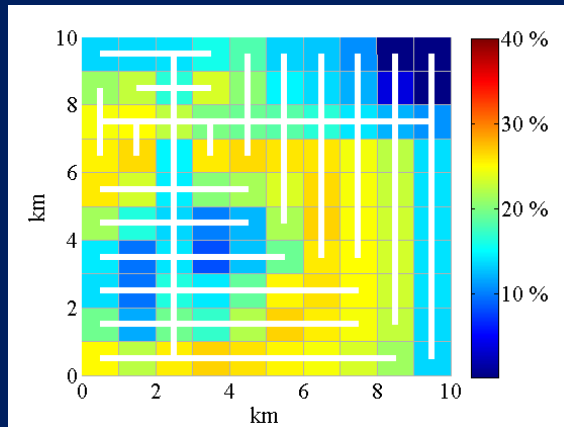
1/2 on consumption and 1/2 evenly



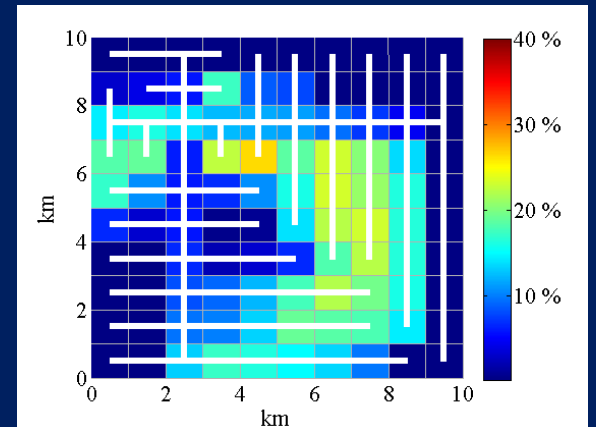
100% of PV evenly placed



0 EVs



50,000 EVs (a' 10kWh)



100,000 EVs

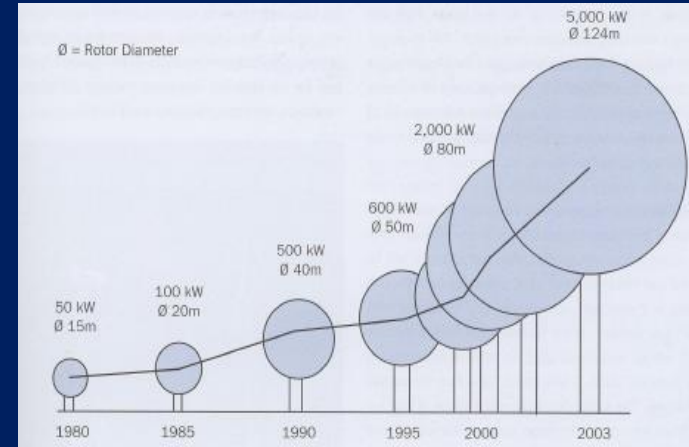


# EXTRA

# How to build your own power plant in "1 minute" ?



# 1 wind turbine = 3-10 GWh electricity (ca 1000-3000 households)



# New energy technologies moving into large scale

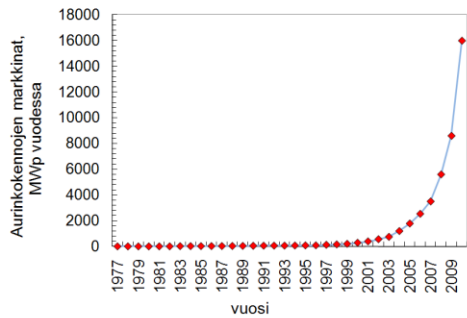
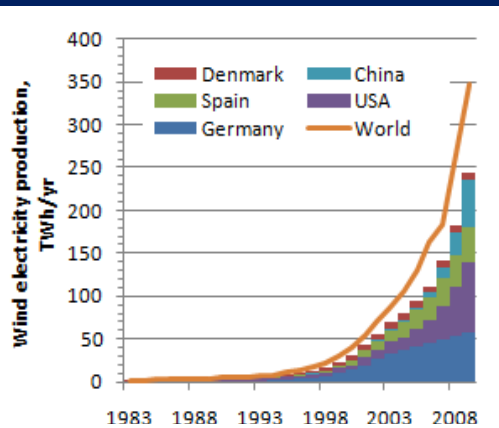
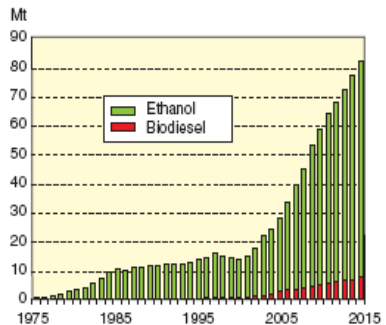


Fig. 1 Trend in world biofuel production

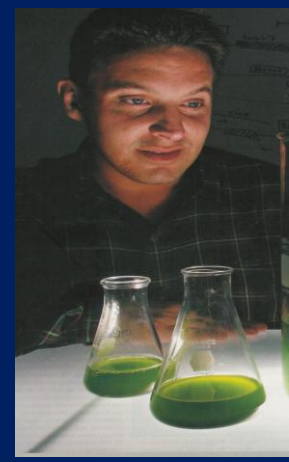


Source: F.O. Licht, Christoph Berg, presentation made at World Biofuels 2006, Seville, May 2006

□ Wind power: now 3 % of world electricity, 25% in 2050 ? Costs may drop by 1/2

□ Solar electricity (PV) : 1/2% of world electricity (\$100 B business), 5-25% in 2050; Price < \$1/Wp, a massproduced commodity?

□ Bioenergy: 4% of EU's energy; energy may set the price but environment limits of use; large potential is 3rd and 4th generation biofuels



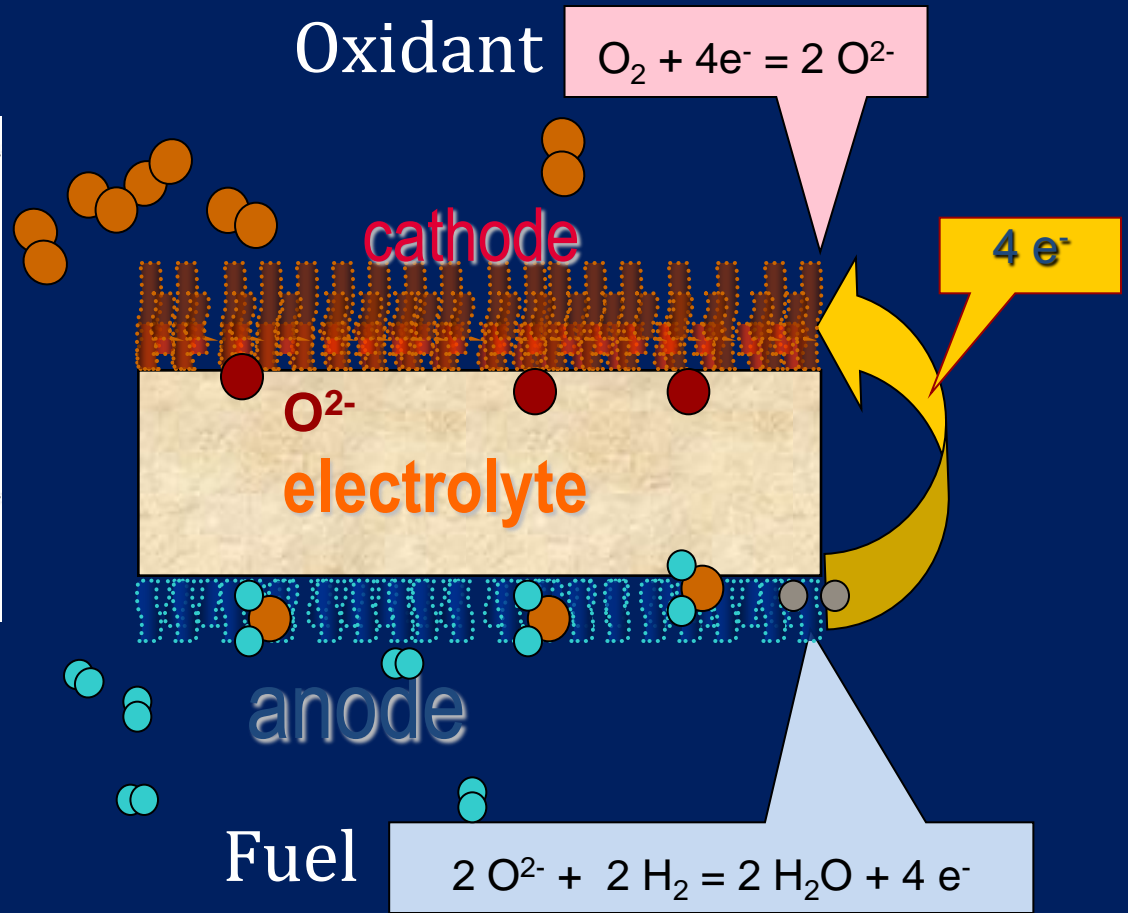
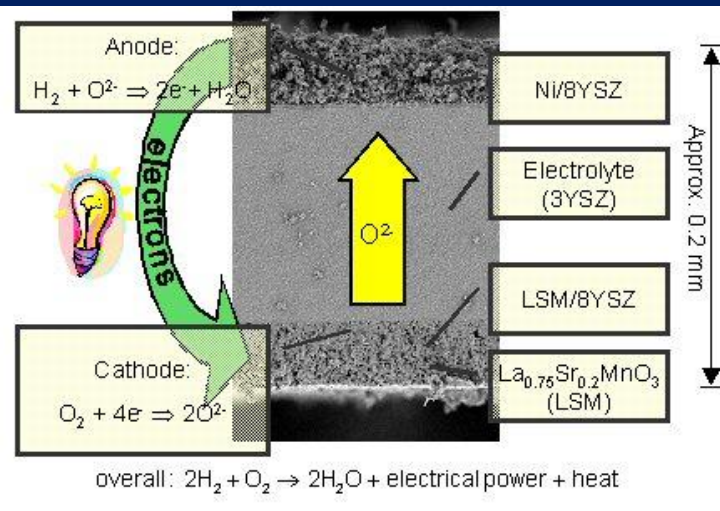


# Mass-production (roll-to-roll) of solar cells



Source: Janne Halme

# Electrochemical conversion of fuel to electricity – Fuel Cell (solid oxide fuel cell)



Courtesy Bin Zhu