Imperial College London

Innovating Climate Mitigation Technologies Post-2012: Integrating Engineering, Science and Policy

UN Climate Change Conference COP18/CMP8
Thursday 29th November 2012

Grantham Institute for Climate Change

CEP CENTRE FOR ENVIRONMENTAL POLICY

energy futures lab

Presentations and Panel Discussion

- **Moderator:**

  Dr Iain Macdonald,

  Imperial College London
- **Technology Challenges:**

  Professor Geoffrey Maitland

  Imperial College London
- **Economic and Policy Issues:**

  Professor Michael Grubb

  Cambridge Centre for Climate Change Mitigation Research
- **Technology-Policy Case Study**

  Tim Dixon, DECC, UK
- **Sahara Forest Project, Qatar**

  Joakim Hauge, CEO Sahara Forest Project

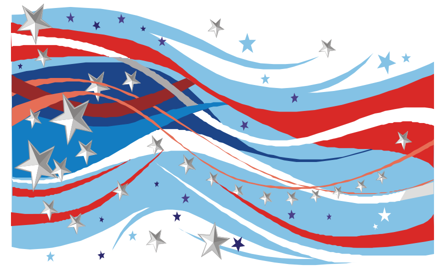
Technical challenges facing alternative energy supplies to meet 2050 Climate Change Targets

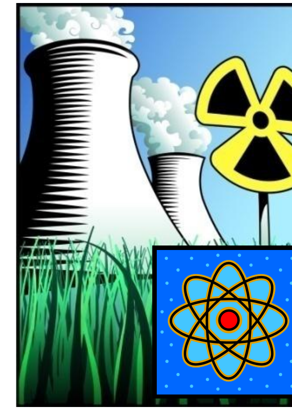
Geoffrey Maitland FREng
Professor of Energy Engineering
Department of Chemical Engineering
Imperial College London

The Energy Landscape

Current world consumption 15 TW

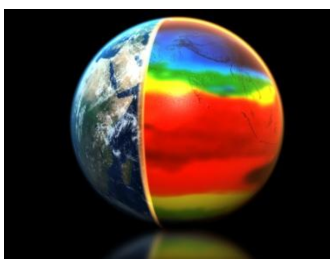
Hydroelectric: 4.6 TW gross, 1.6 TW feasible technically, 0.6 TW installed capacity



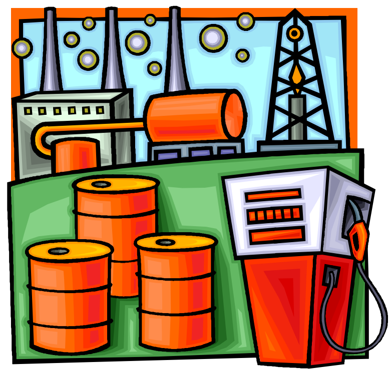


Tidal/Wave/Ocean Currents: 2 TW gross

Nuclear: Current 1TW

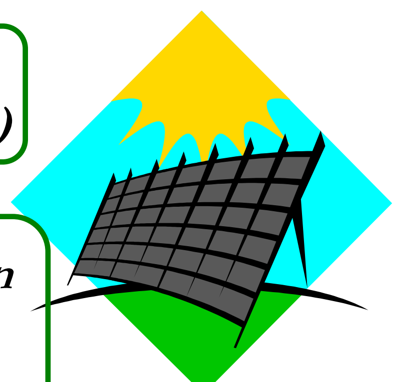


Fossil Fuels: Current 12.5 TW Potential 25 TW



Geothermal: 9.7 TW gross (small % technically feasible)

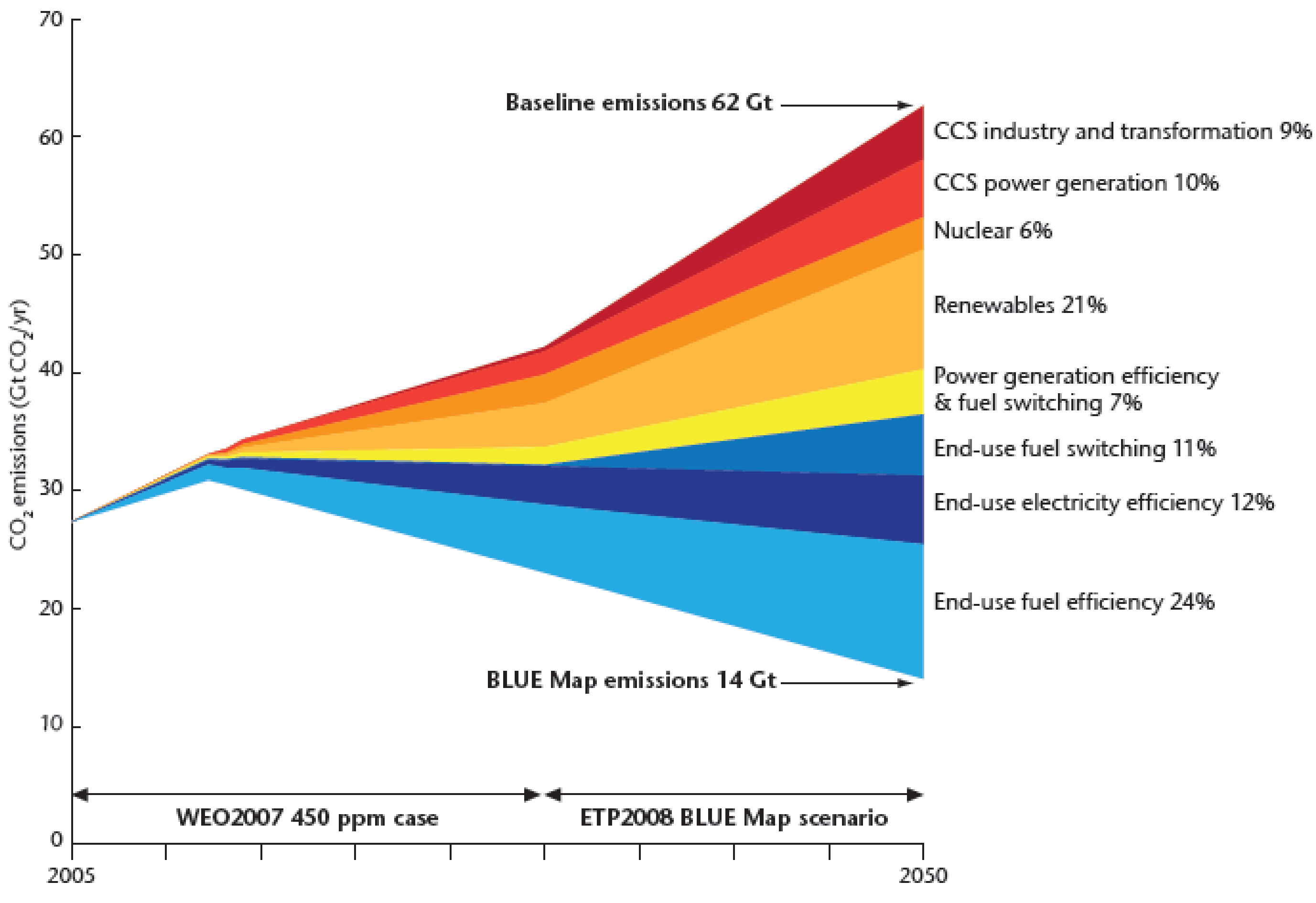
Wind 2-4 TW extractable



Solar: 1.2 x 10^5 TW on earth's surface, 36,000 TW on land

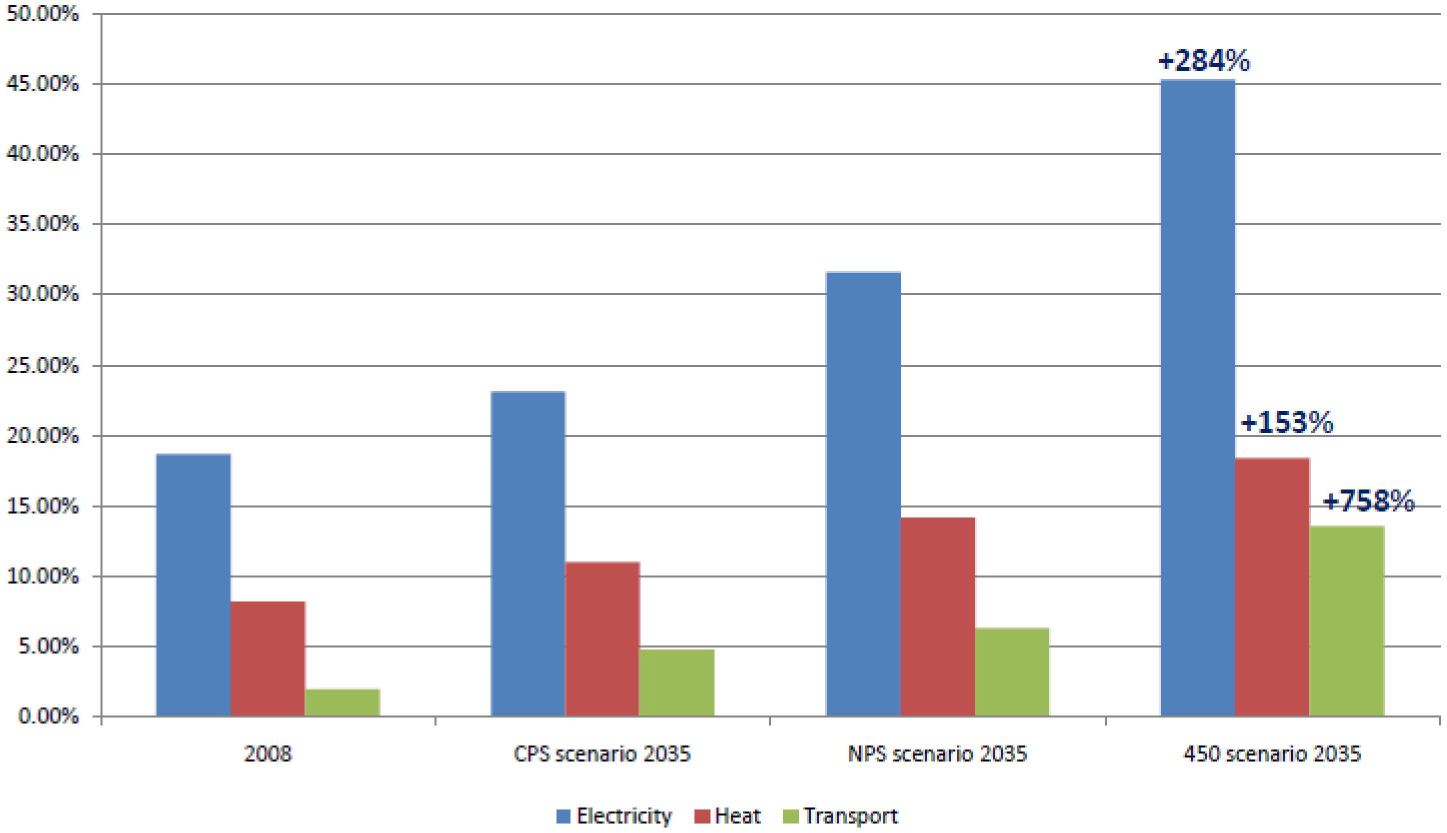
Biomass/fuels: 5-7 TW, 0.3% efficiency for non-food cultivatable land

World abatement of energy-related CO_2 emissions in the 450 ppm Scenario



Source: IEA, *Energy Technology Perspectives* (2008a).

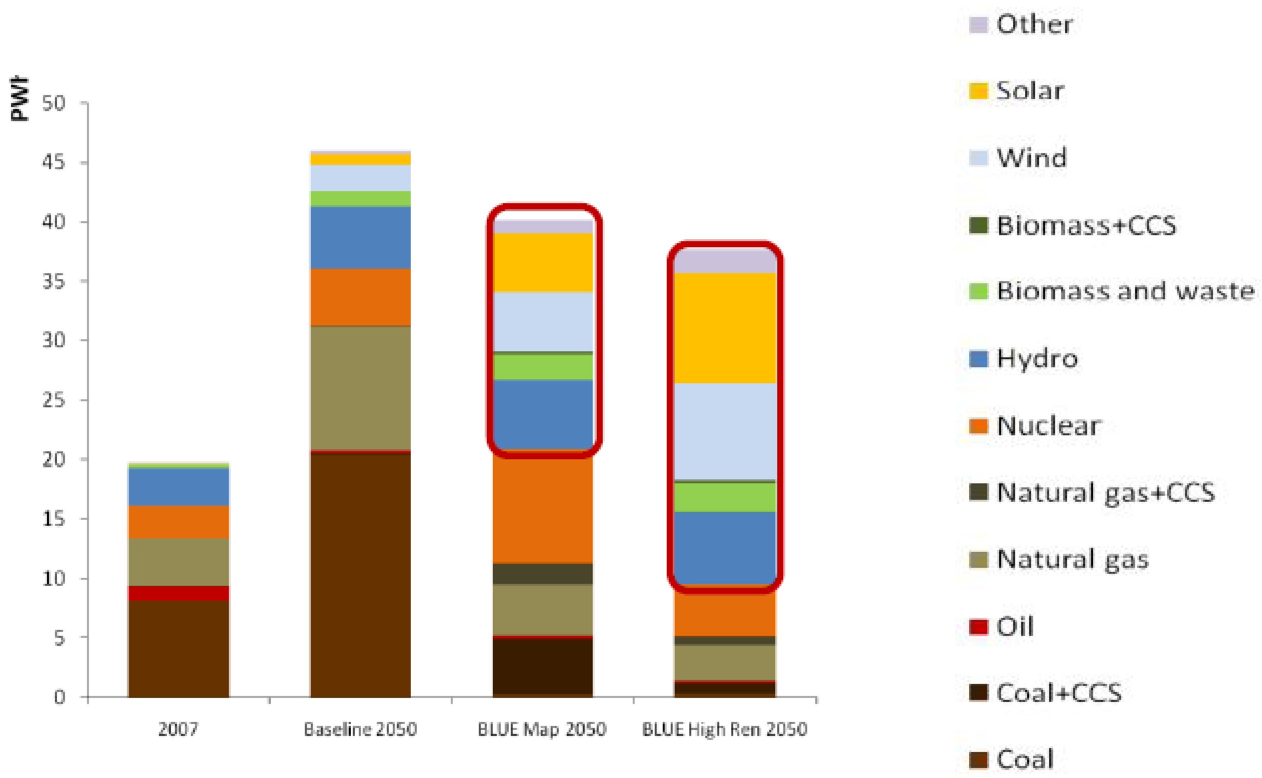
Steady Growth of Renewables



All scenarios point out a large growth of renewables

IEA Energy Technology Perspectives 2010

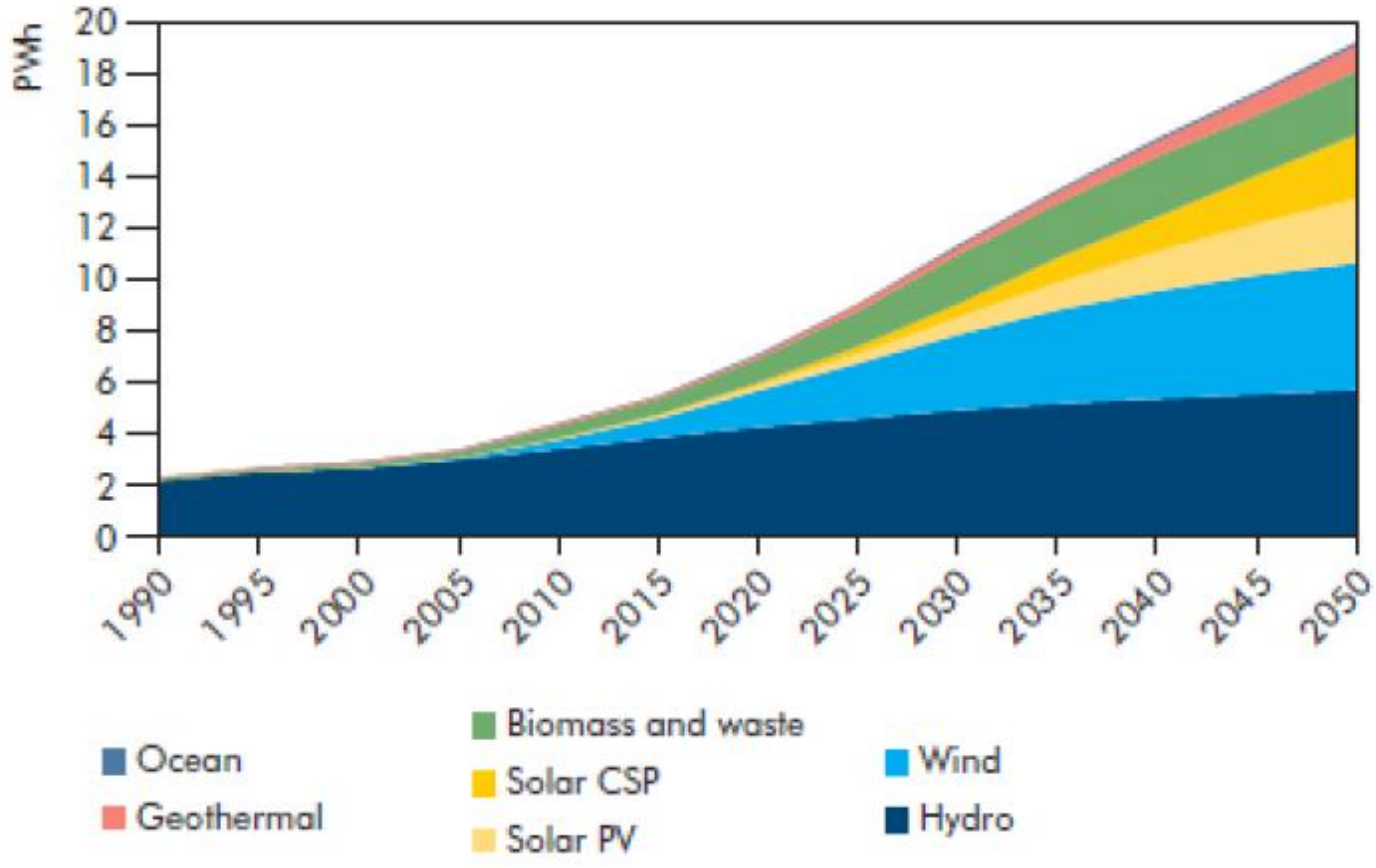
Renewables 50-75% by 2050



Renewables provide from almost half to three quarters of the global electricity mix in 2050

IEA Energy Technology Perspectives 2010

Growth of Renewables in IEA Blue Scenario



IEA Energy Technology Perspectives 2010

Imperial's Flagship Institutes for Energy and Climate Change

www.imperial.ac.uk/energyfutureslab

cep
CENTRE FOR ENVIRONMENTAL POLICY

www.imperial.ac.uk/environmentalpolicy

energy
futures
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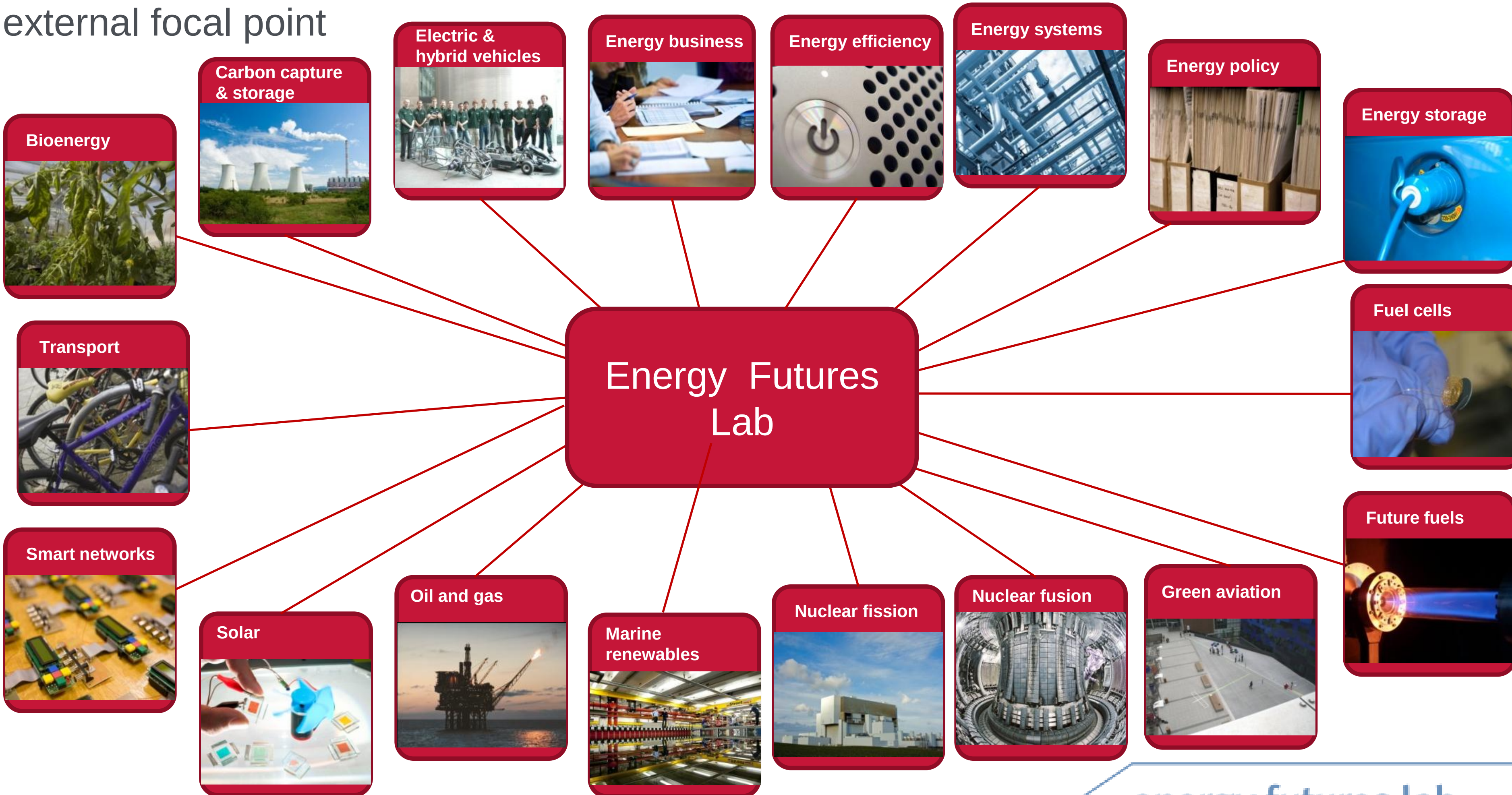
Research networks

18 research networks to enable internal cross-departmental communication and provide external focal point



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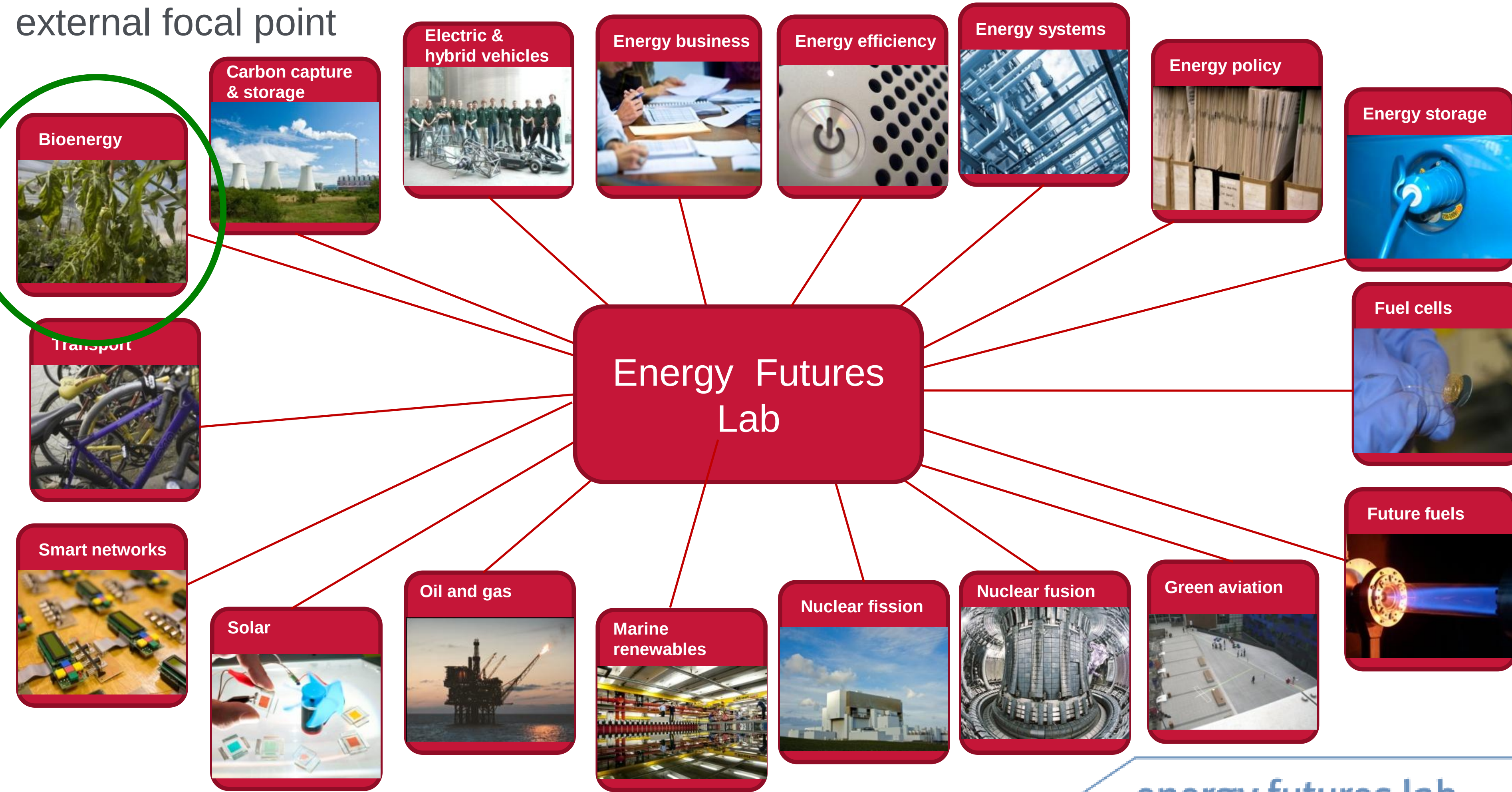
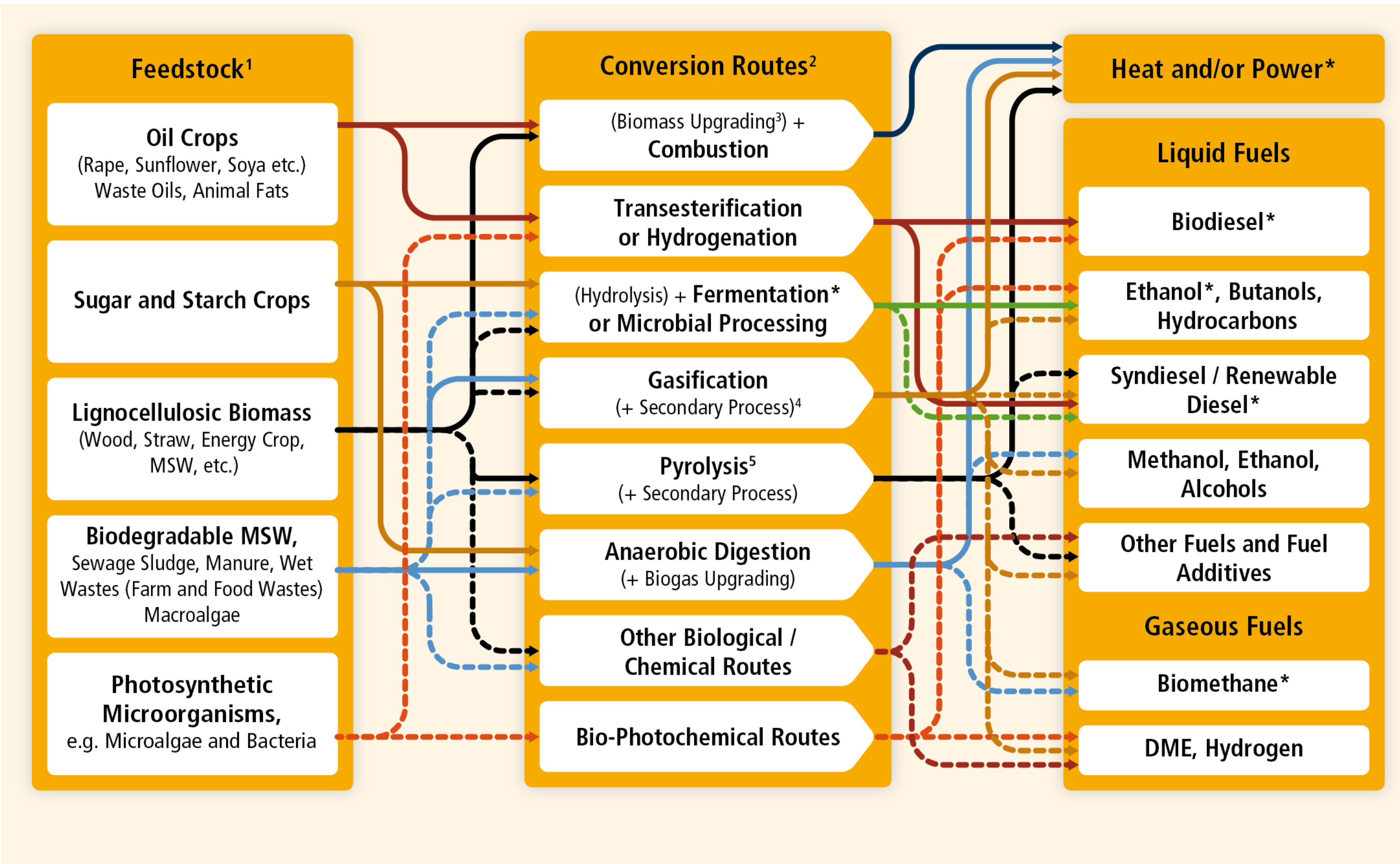
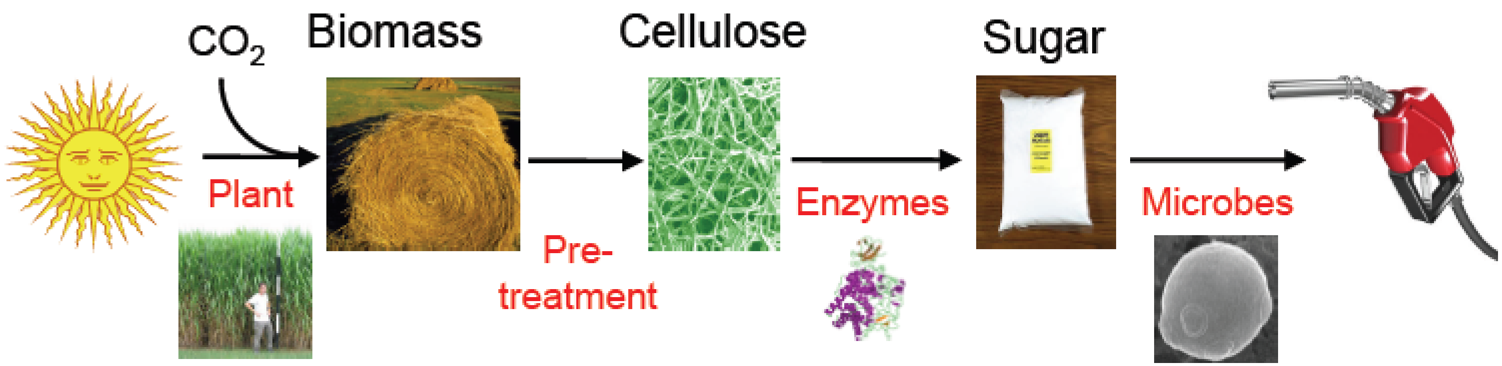


The Complexity of Biomass Conversion



IPCC Report on Renewable Energy Solutions and Climate Change Mitigation, 2011

Biofuels



Low cost and rapidly deployable alternative for transportation fuels
Modest power efficiency – land use issues
Current advanced biofuel development
Use of regionally appropriate waste streams
can address land-use concerns

Biomass + CCS can lead to negative carbon emissions

Source: Paul Alivisatos, Lawrence Berkeley National Lab

Biofuels – The Four Generations

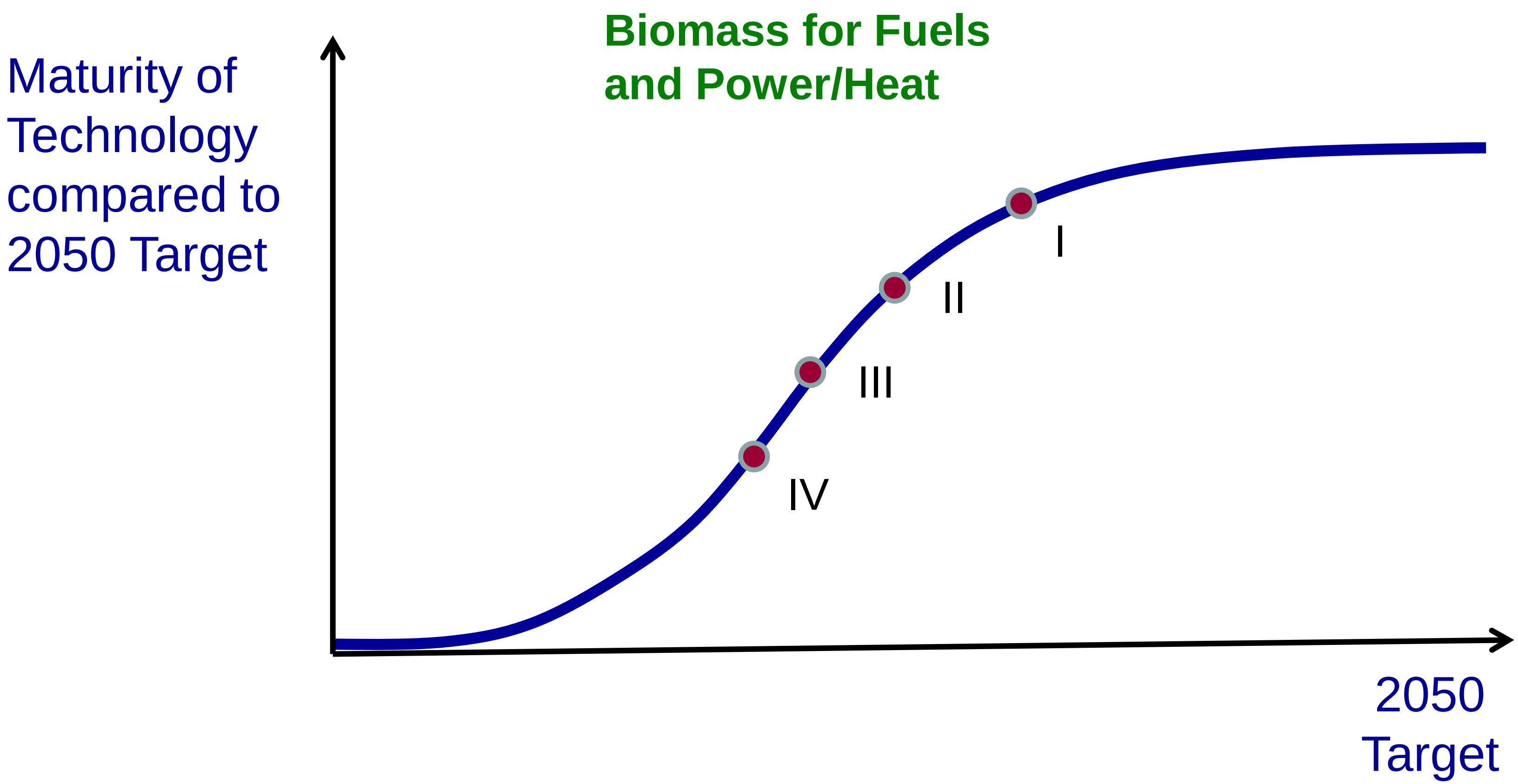
- First Generation
  - Fermentation of sugars and starches
  - Alcohols from wheat, corn, sugar beet…
  - Biodiesel from oils and fats by transesterification

- Second Generation
  - Non-food crop cellulosic feedstocks
    - Waste, stalks, corn, wood, energy crops (eg Miscanthus)
  - Biomass-to-liquids using Fischer-Tropsch etc
    - FT diesel, biomethanol, DME, biohydrogen
  - Cellulosic ethanol and myco-diesel using *Gliocladium Roseum* fungus

Biofuels – The Four Generations

- Third Generation
  - Biofuel from algae – oilgae
    - Up to 30x more energy per acre than land crops
    - Only 15,000 sq miles (1/7th corn land) to replace all US petroleum fuels
    - Ethanol direct production from algae (Algenol)
- Fourth Generation
  - Thermochemical – pyrolysis
  - Solar-to-fuel: photosynthetic algae + flue gases
  - Genetic manipulation of microorganisms to secrete hydrocarbons

Maturity of Renewable Energy Technologies



Biomass Conversion –The Challenges

- Increase land productivity for energy and food crops
- Multi-functional land and water use – integration of bioenergy with agriculture and forestry
- Improved product diversification from lignocellulosics, particularly for high energy density air transport fuels
  - Do not compete directly with food production
  - Can be bred specifically for energy purposes with high land utilisation
  - Can be harvested as residues from crop production
  - Allow the integration of waste management, local symbiosis

Biomass Conversion –The Challenges

- Algal lipids for diesel, jet fuels + other high value products from CO_2, H_2O and sunlight → lower land use
  - Grow in brackish water, land unsuited to cultivation, industrial waste water
  - Operate in dark, metabolise sugars
  - Tune to specific products
- Gasification to syngas and fuels (alcohols, syndiesel) +CCS
- Lower cost H_2, CH_4 and SNG from biomass
- Cost reduction from $10-30/GJ to $12-15/GJ by 2035
- Improvements in efficiency of IGCC biomass power plants *cf* traditional steam turbines + add CCS

Biomass Conversion –The Challenges

- Pyrolysis and hydrothermal oils as low-cost transportable oils for heating or CHP or feedstock for upgrading
- Optimise biogas production by anaerobic digestion from waste streams and upgrading to biomethane for transport, heat and power – ability to combine waste streams including agriculture – improved upgrading + reduced costs required
- Coupling fermentation with concentrated CO_2 streams or IGCC with CCS for CO_2 neutral or negative fuels. Requires optimisation of biomass selection, feedstock supply system, conversion to a second energy carrier and integration of this carrier into future energy systems.
- Improving modest power efficiency
- Efficient and integrated use of waste

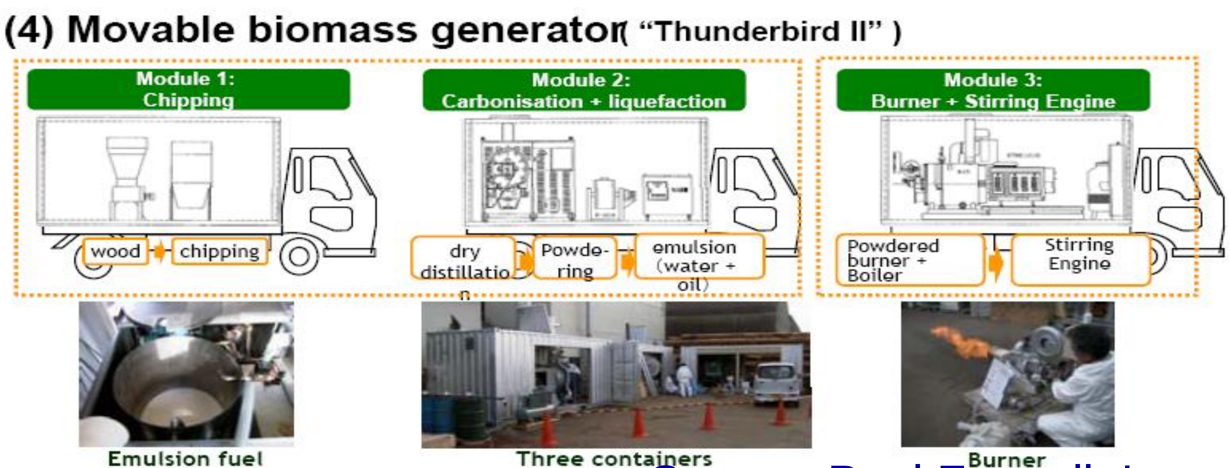
Pyrolysis

- Pyrolysis is the rapid heating of fuels such as wood or coal in an inert atmosphere
- The main aim of pyrolysis is to produce pyrolitic oil (Bio oil)– a liquid mixture of hydrocarbons
- Energy conversion efficiency ~75%; could get to 80%
- Other products include gases and char
- An interesting area of research is the use of wastes (plastics, waste wood, crop residues) to produce fuels

Source: Paul Fennell, Imperial College London

Why Produce Bio-oil from Residues / Wastes?

- Bulk density of many biomasses between 200 and 700 kg / m^3 and only **2 – 7 MJ / dm^3** (many approx **5**).
- Heating value of bio-oil ~ 17 MJ / kg ~ **20 MJ / dm^3**
- Heating value still low in comparison with standard diesel (~ **40 MJ / dm^3)**
- A significant issue in the use of biomasses is transport and logistics – getting the biomass from the field to the point of use
- Potential (after upgrading) to mix with hydrocarbon-based fuels – Current global demand 4,200 Million tonnes / year[1].



Tokyo University Institute of Industrial Science modular demonstration plant

Source: Paul Fennell, Imperial College London

US Energy Information Adminstration (2011): Available from http://www.eia.doe.gov/emeu/steo/pub/gifs/Fig6.gif.

Decentralised Use of Bio-Oil

- For large scale biomass / waste processing, the first step is to convert biomass into a transportable product…
- The pyrolysis plants can be located anywhere, because they can be economically built on a reasonably small scale.
- A stand-alone central gasifier could then be used.

Source: Paul Fennell, Imperial College London

Biomass Conversion –The Challenges

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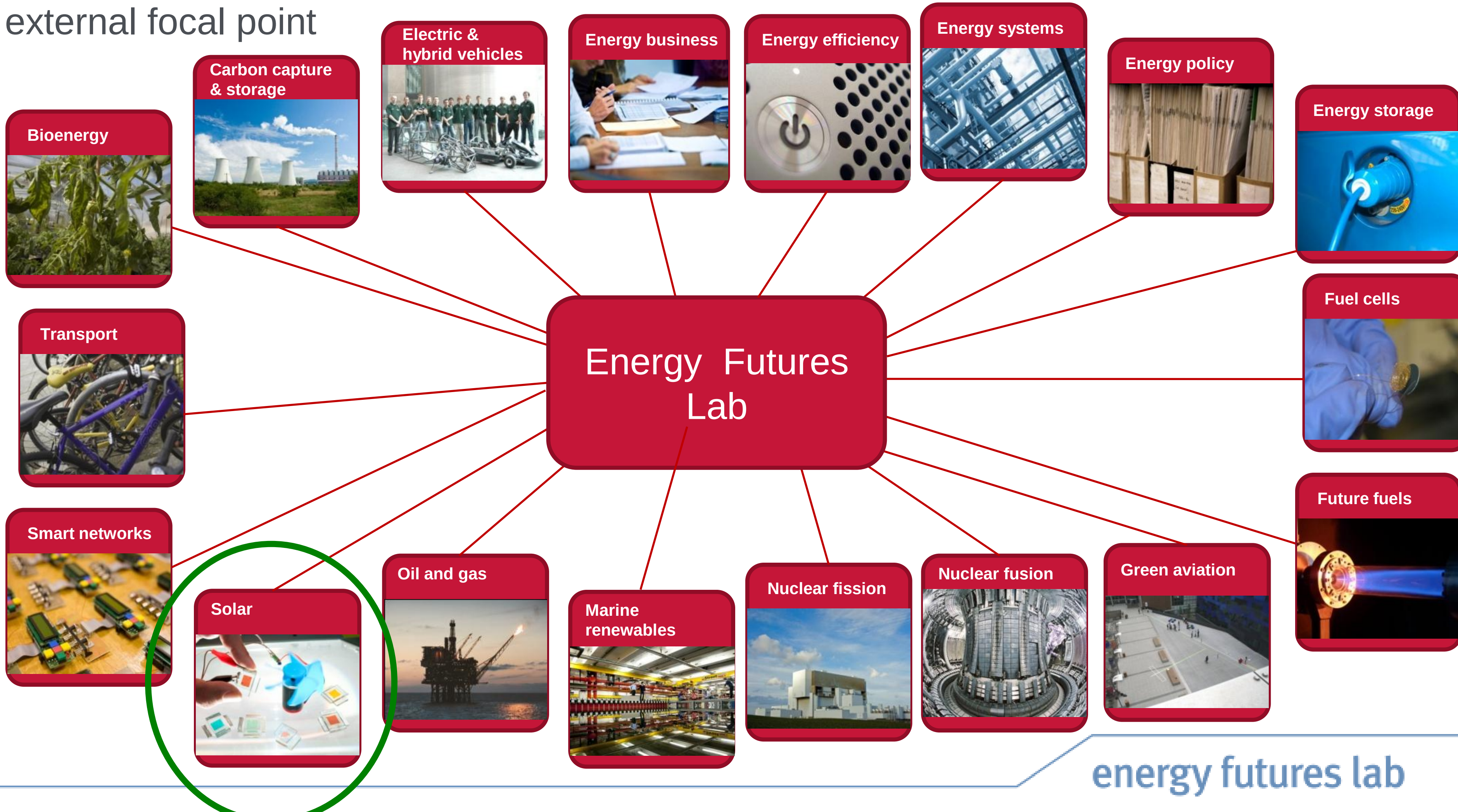

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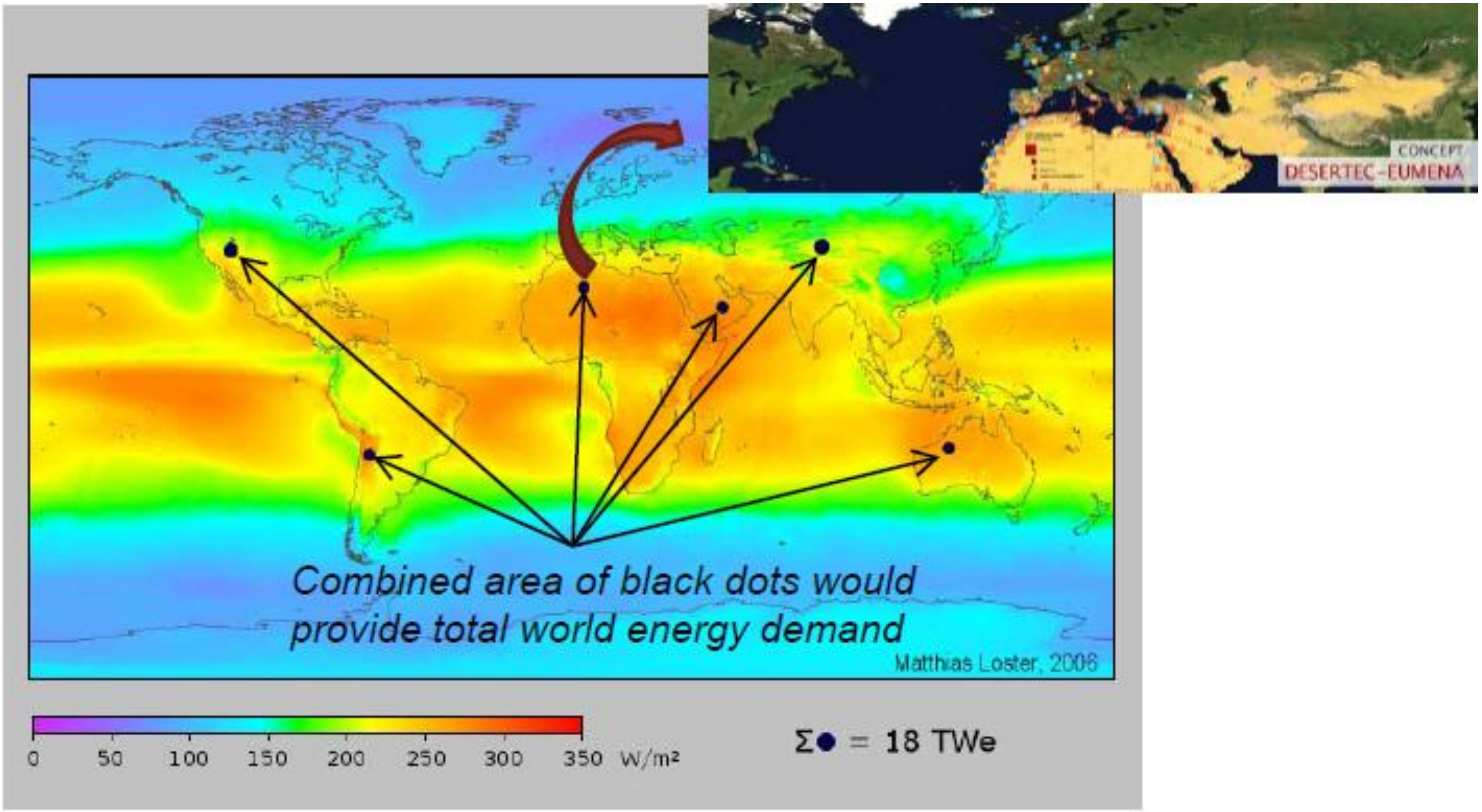
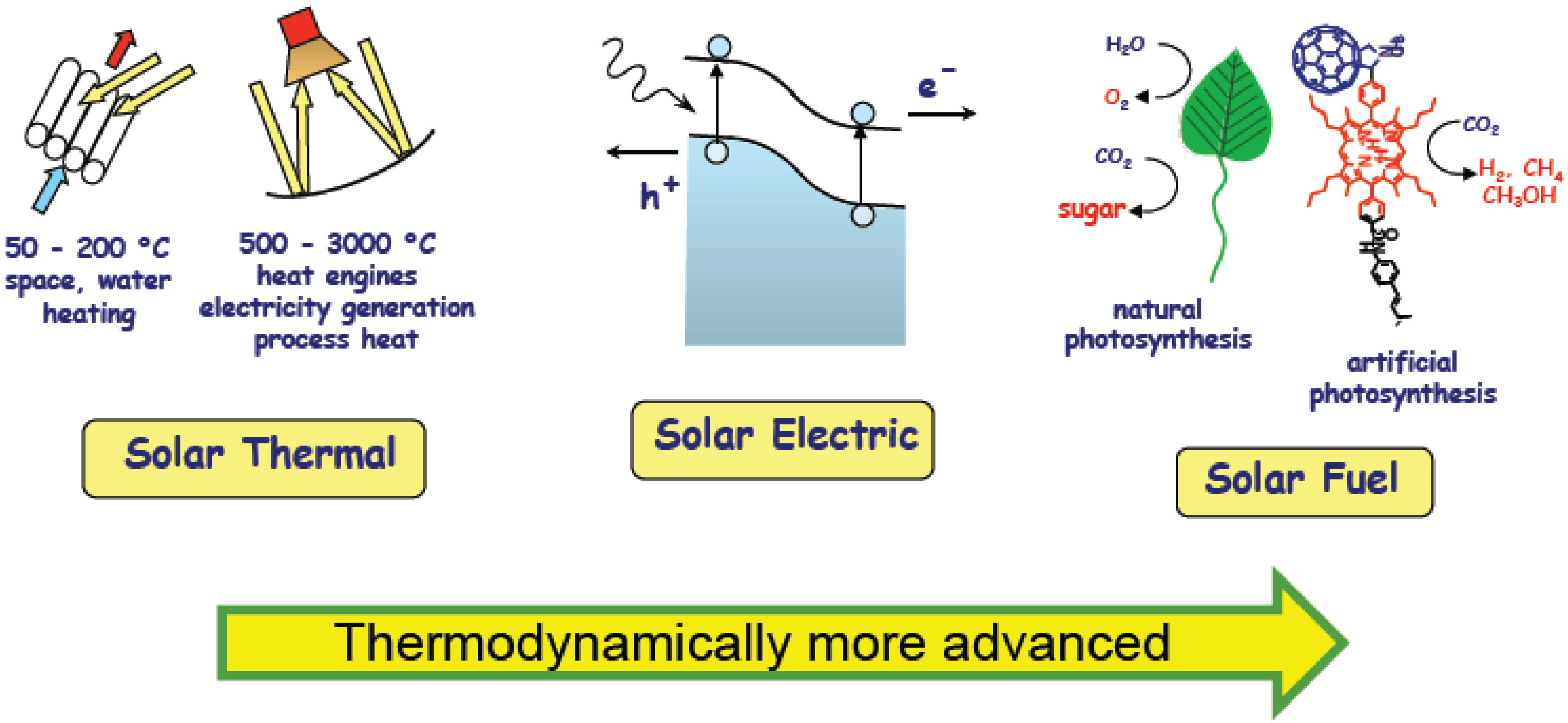
Solar – the long-term energy solution



Solar
36,000 TW on land (world)

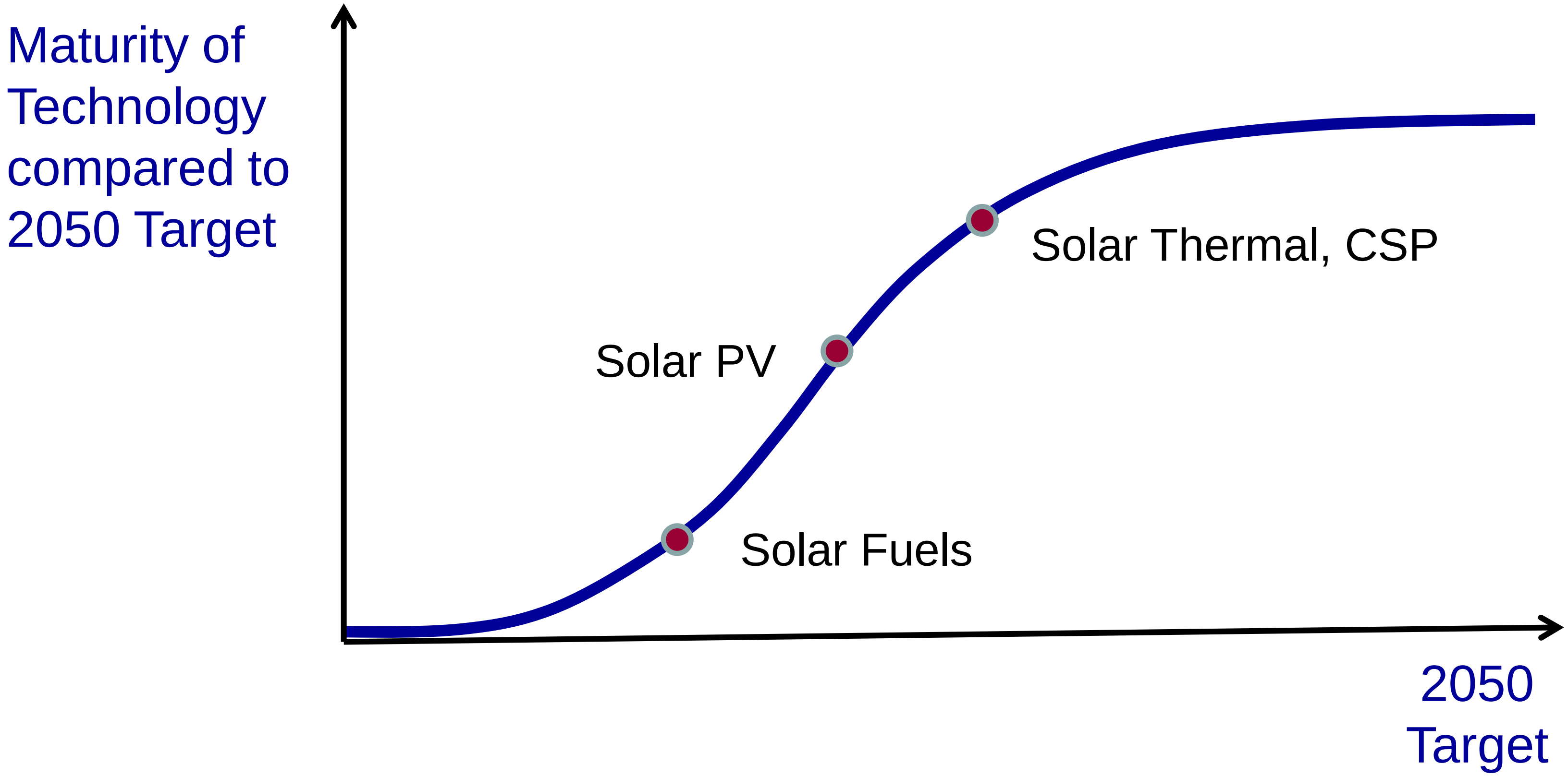
All other renewables
36 TW on land (world)

The evolution of Solar Technology



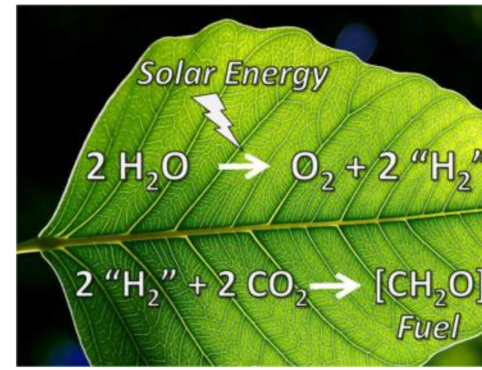
Source: Paul Alivisatos, Lawrence Berkeley National Lab

Maturity of Renewable Energy Technologies



Solar Network

- Largest solar energy research program in UK
- Over 100 research staff and students in 8 departments
- Supported by ~ £5m funding
- Partnerships through EPSRC, TSB & EU funded projects,
  - including 10 projects > £1m each.
- Over 20 industrial partners with over £3m of direct industrial funding

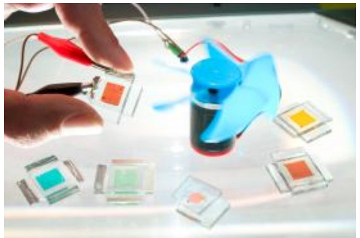


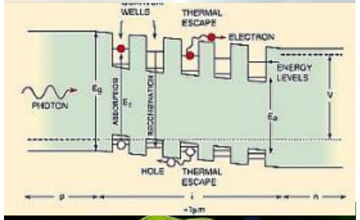
ners include:

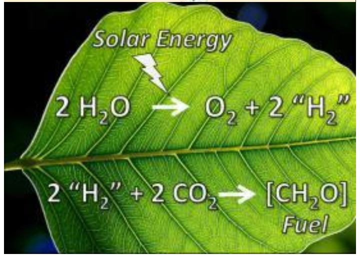
Network Leaders: Prof. James Durrant & Dr Ned Ekins-Daukes
Website: www.imperial.ac.uk/solar

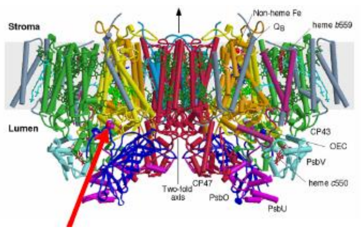
Solar Network: Research Areas

- Photovoltaic Technologies
  - Organic & dye sensitised photovoltaic cells
  - New concepts for high efficiency photovoltaic devices
- Solar Fuels: The Imperial Artificial Leaf initiative
  - Solar hydrogen generation
  - CO_2 reduction
- Molecular Processes of Photosynthesis
- PV systems and environmental analysis



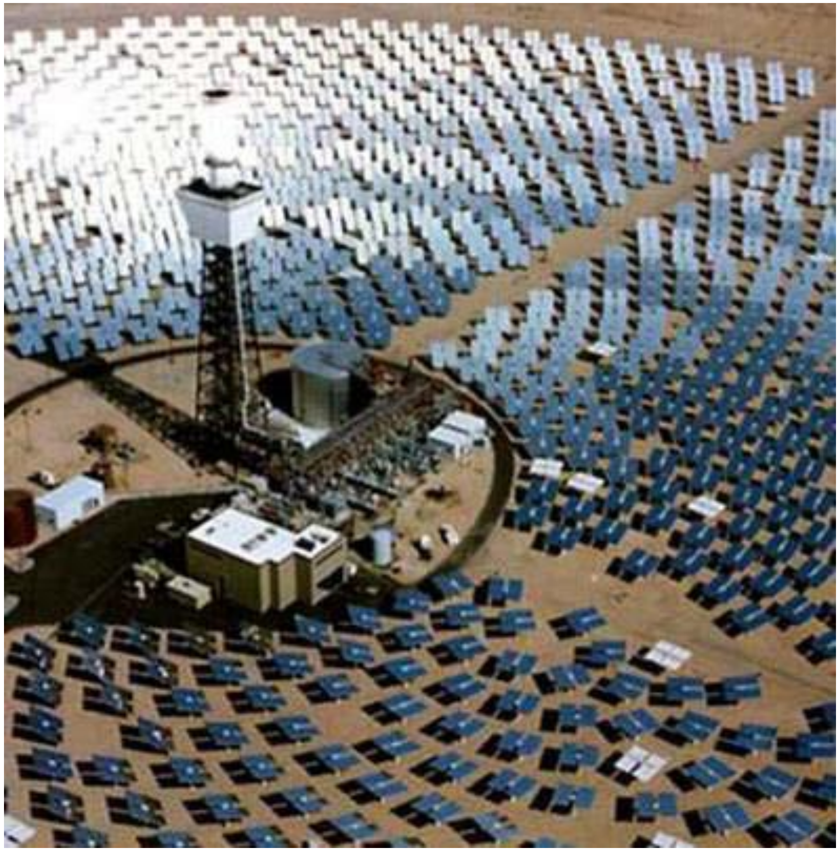






Solar Thermal

- Similar in scope to a Natural Gas Plant
- Issues with water, transmission, intermittency
- Developments in Australia, Qatar, India, Mexico, North Africa, Spain, US
- Challenges:
  - Higher temperatures
  - Dry-cooling of steam cycle?
  - Dust-resistant mirrors



e.g. Desertec – German-led project targets15% of Europe's Energy needs by 2019 start-up

Source: Paul Alivisatos, Lawrence Berkeley National Lab

Solar Thermal Opportunities

- **Active Solar Buildings** – thermal collectors + PVs or hybrids built into all components of roof and facades...covers all energy demands for water heating and space conditioning
- **Heating demanding climates**: combined evacuated glazing and solar units for heating and improved insulation
- **Cooling demanding climates**: cool (white) roofs, heat-dissipation by ground and water heat sinks, solar control to allow penetration of lighting but not thermal components.
- **Improved thermal storage** in building materials
- **Improved distribution** of absorbed solar heat around buildings

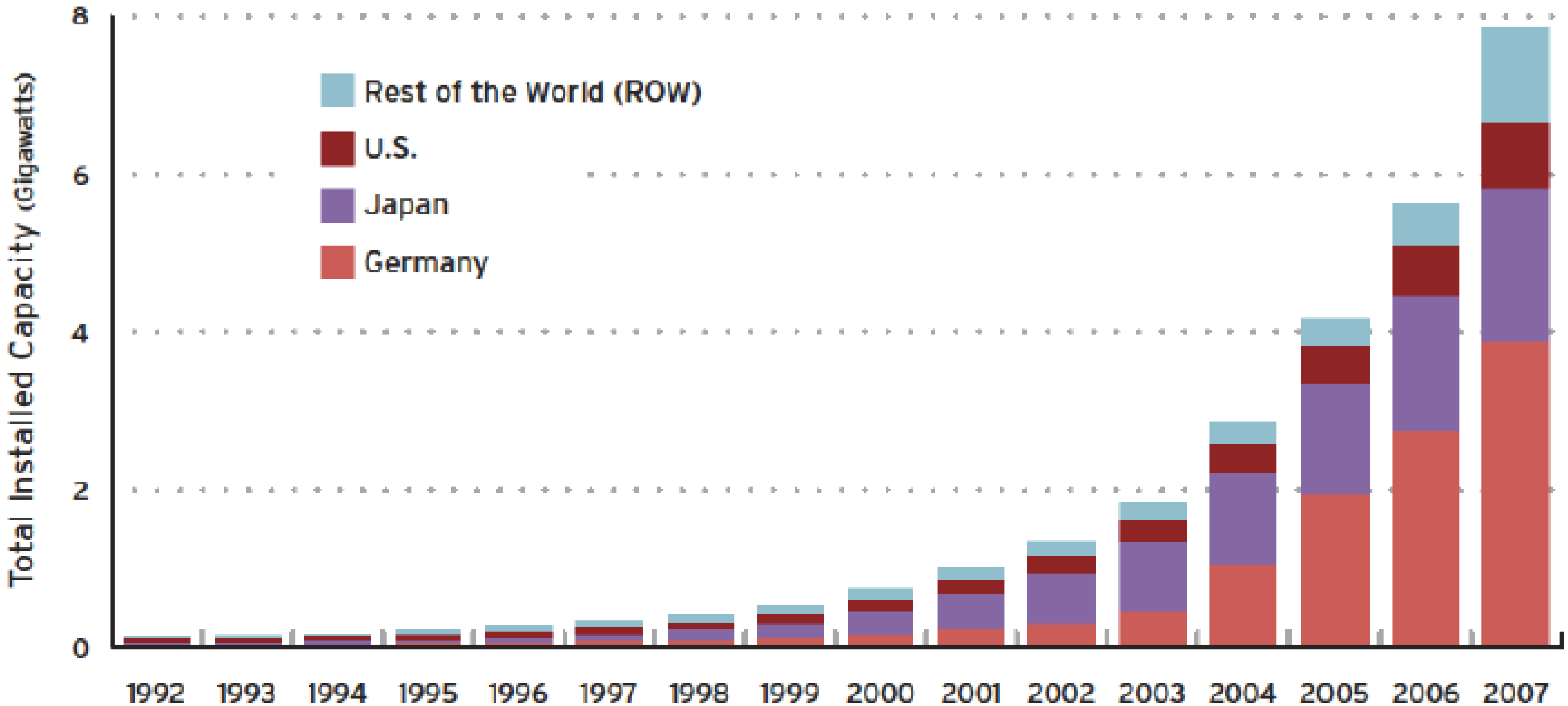
Solar Thermal Challenges

- **Electricity production without intermediate thermodynamic cycle**
  - Thermoelectric
  - Thermoionic
  - Magnetohydrodynamic
  - Alkali-metal methods

CSP Challenges

- Proven at utility scale but still advances required
- Cost reductions through mass production and economies of scale
- Improved solar-to-electricity efficiency
  - Higher collector temperatures
  - So alternatives to oil as heat transfer fluid (water or molten salts)
- Higher efficiencies for central-receiver systems
- Peak efficiencies targeted to double to say 35%
- Improved trough technologies
  - Solar-selective surfaces
  - Improved receiver/absorber designs which increase solar intensity at focus
- Space solar power
  - beamed via microwaves to receiving antennae

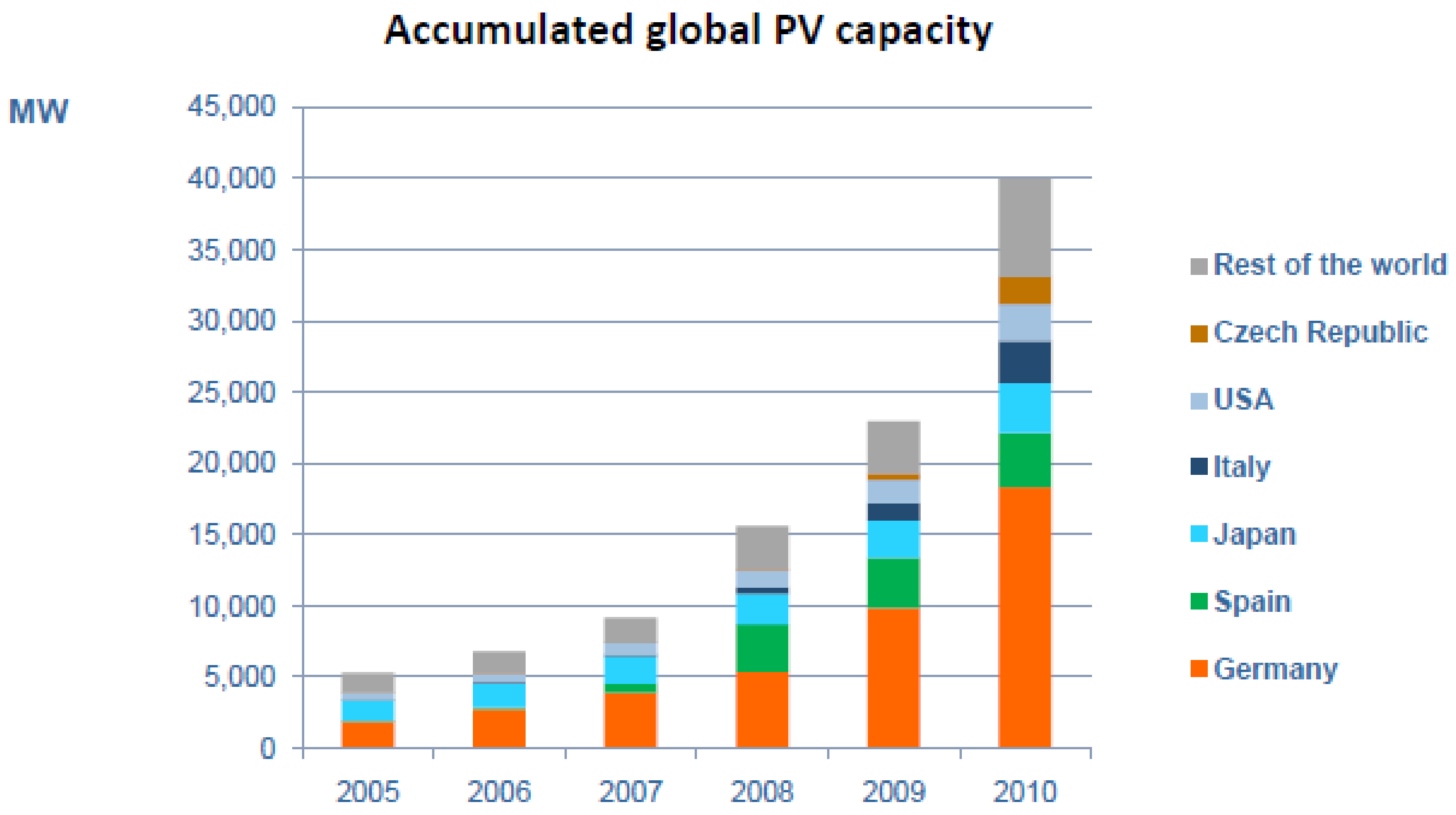
Solar PV



- 2010 global installation >40 GW
- Module costs falling steadily
- 2010: Thin film $0.75/W, Si $1.25/W
- US DoE target for installed cost is $1/W
- Rapid technology developments
- Monocrystalline Si (Sunpower) 12.5% efficiency
- Spectrolab triple junction PV world record 41.6%

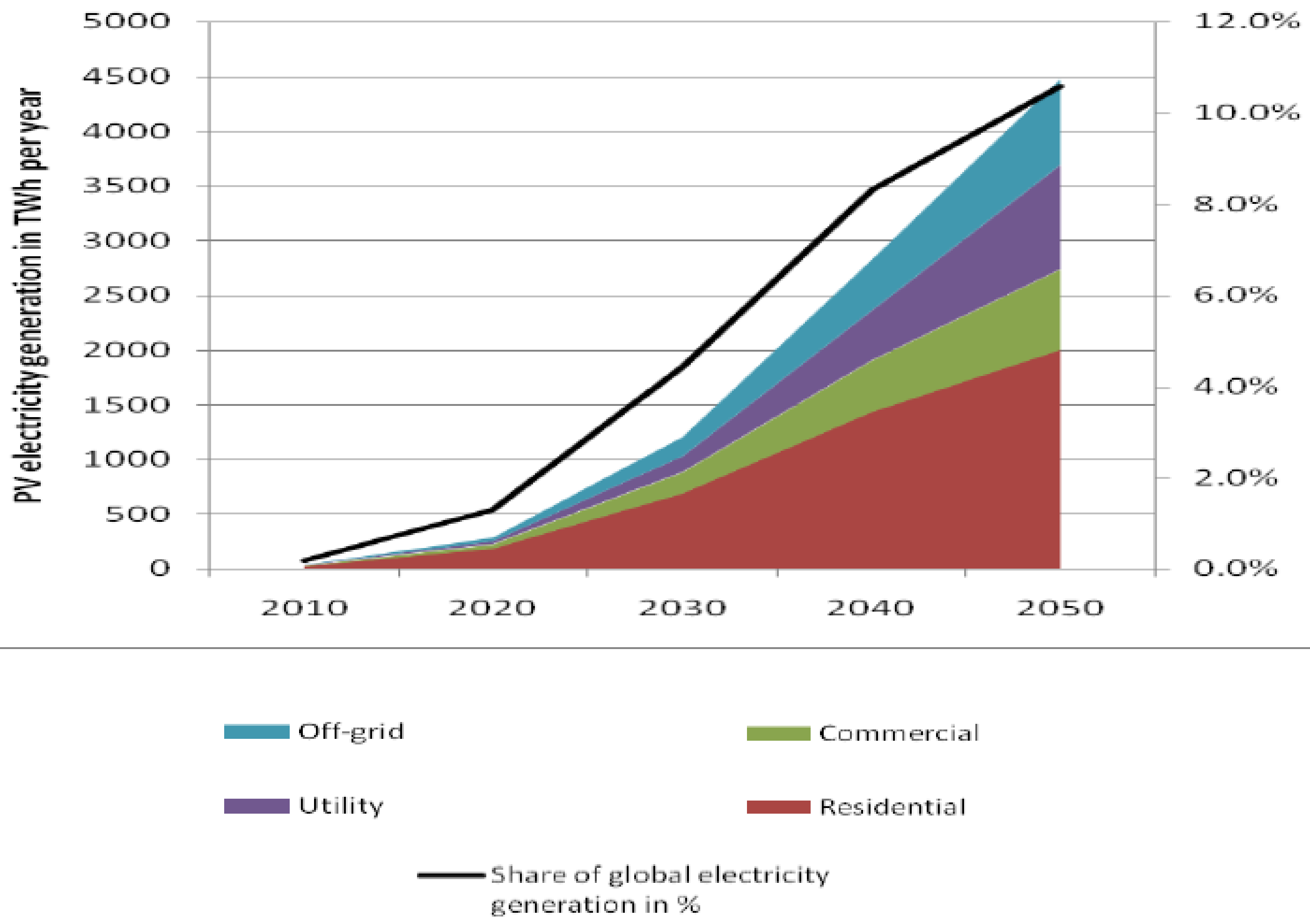
Source: Paul Alivisatos, Lawrence Berkeley National Lab

Recent Boom in PV Growth



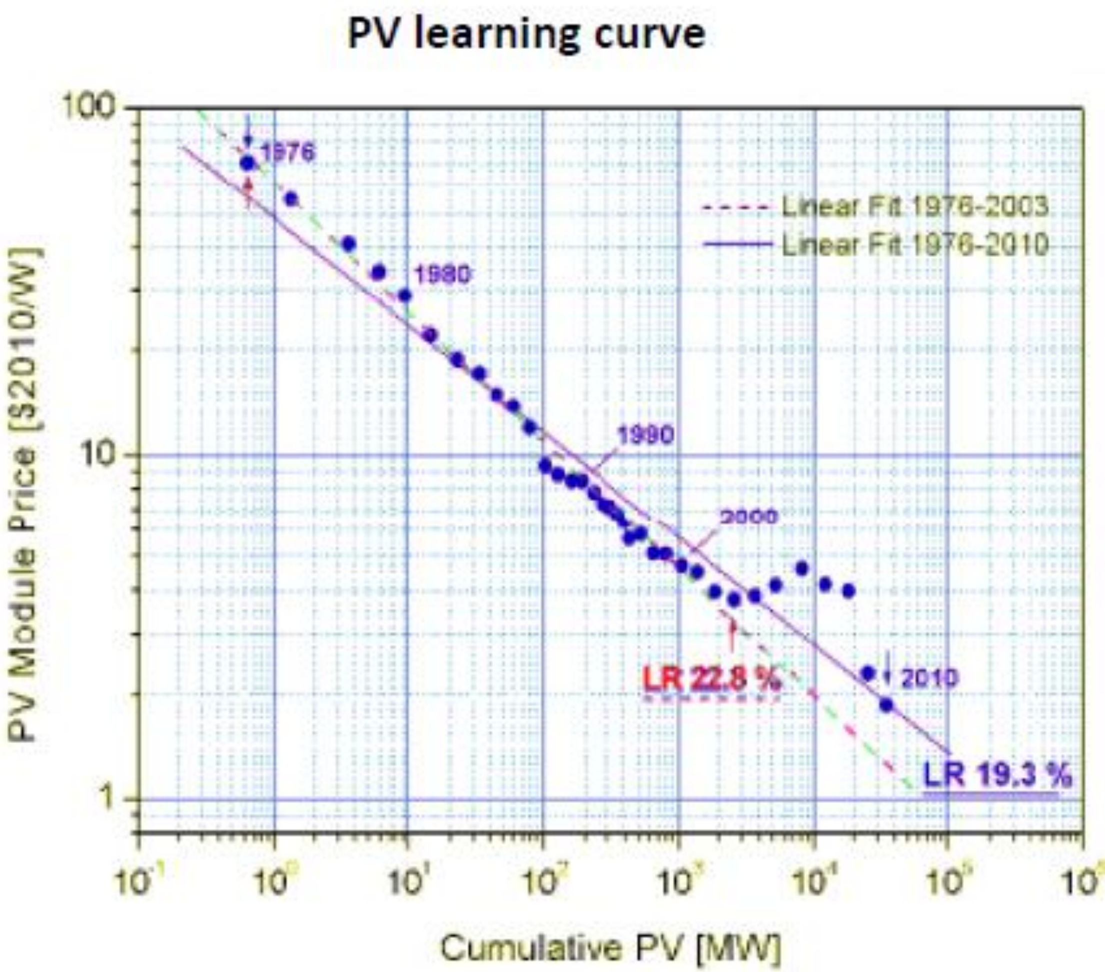
Sources: IEA PVPS, BP Statistical Report, BNEF

Solar PV Roadmap Targets



If sound policies are put in place, PV can provide 5% of global electricity generation in 2030, 11% in 2050

PV Learning/Cost Curve



Source: Breyer and Gerlach, 2010

PV Challenges

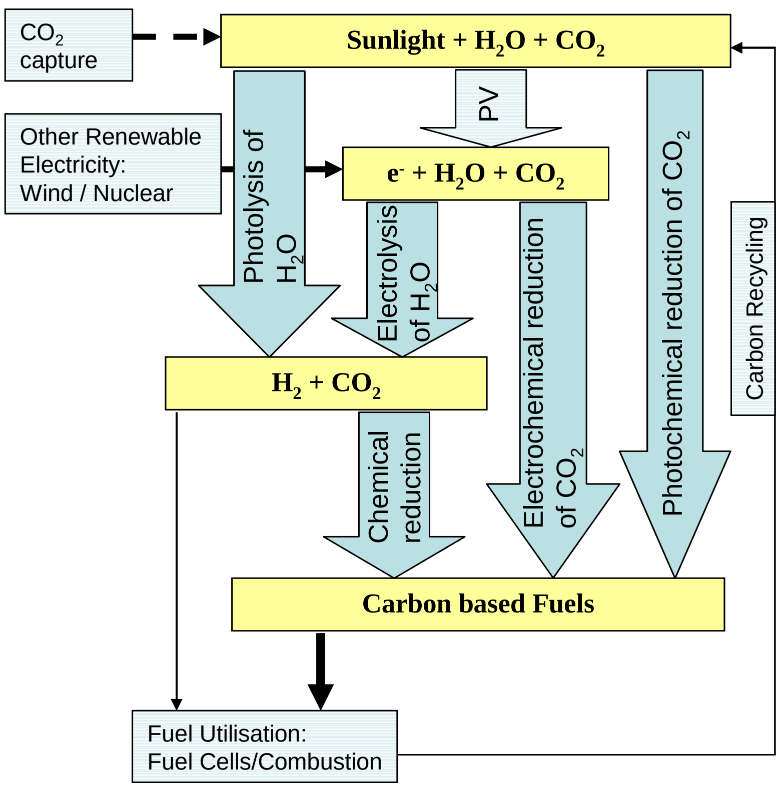
- Continuation of rapid improvements in performance and decreases in cost
- Improvements in
  - Cell efficiency, stability and lifetime
  - Module productivity and manufacturing
  - Environmental sustainability
  - Applicability, standardisation and harmonisation
- Emerging cells for 2030 and beyond
  - Multiple junction
  - Polycrystalline thin films
  - Crystalline silicon < 100 μm

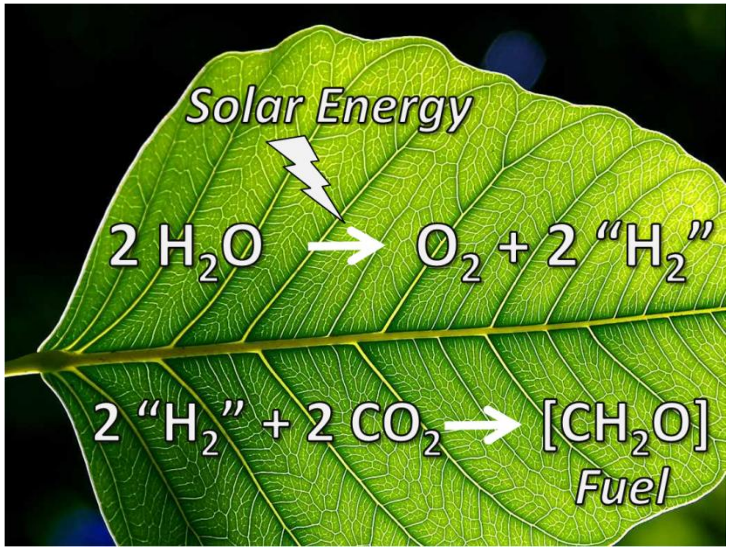
PV Challenges

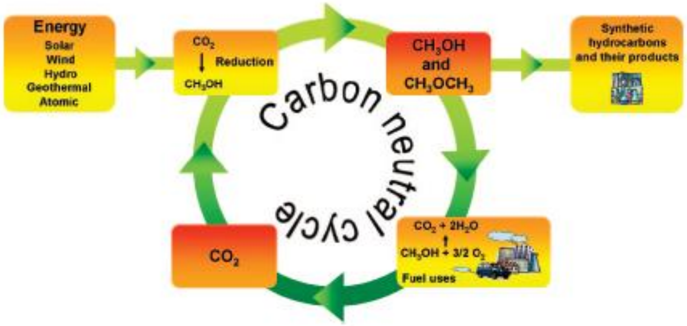
- High Risk Cells – potential to increase max efficiency substantially
  - Organic solar cells
  - Biomimetic devices
  - Quantum dot designs
- Balance of Systems
  - Inverters
  - Storage
  - Charge Controllers
  - System Structures
  - Energy Network

Solar to Fuels

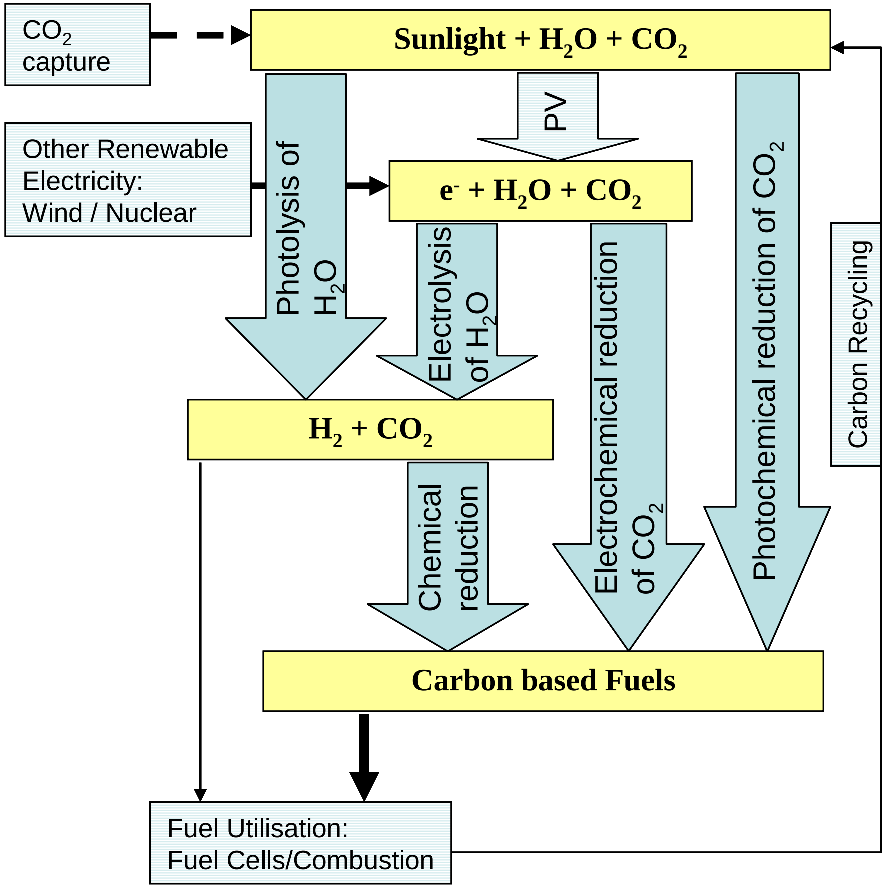
- Renewable fuel synthesis
- Storage of solar energy







The Imperial Artificial Leaf Project



Crossing Cutting Themes:

- Nanostructured Materials
- Molecular and Heterogeneous Catalysis
- Biomimetic Systems
- Photochemistry & Electrochemistry
- Photoreaction Engineering
- Environmental & Economic Analyses

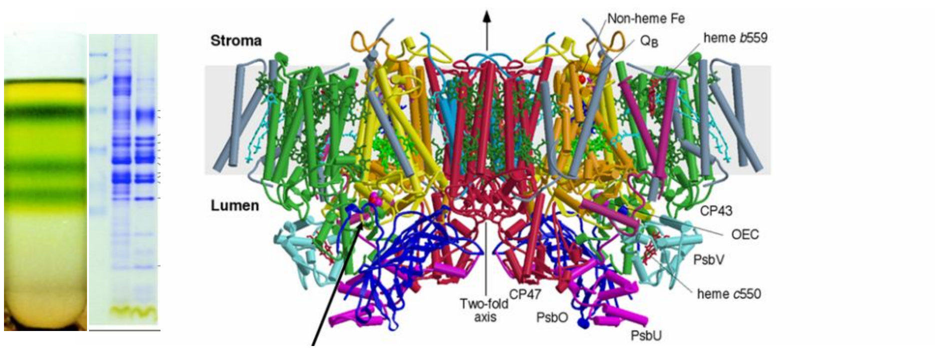
Now funded by 3 large UK EPSRC programmes (> £8 m funding)

- Solar Hydrogen Generation
- CO_2 reduction
- Nanostructured Materials
- ~ 20 research staff and students in 5 departments
- 2 new senior academic appointments
- Support from several companies:

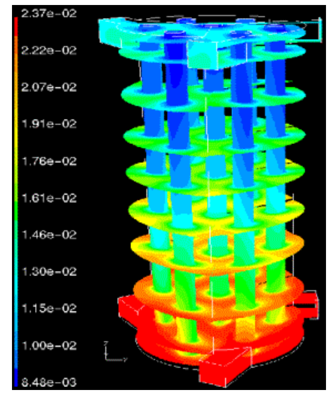
Johnson Matthey · Cristal Global · Cemex · e.on

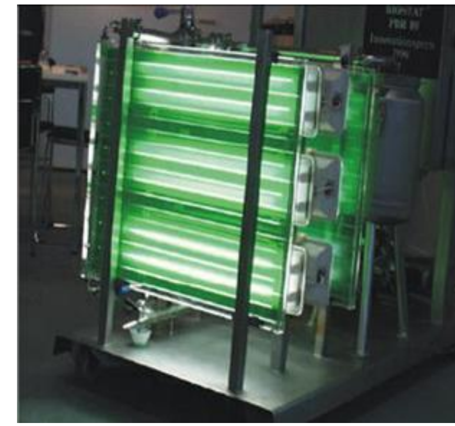
http://www3.imperial.ac.uk/energyfutureslab/research/grandchallenges/artificialleaf

Imperial's Solar to Hydrogen Programme



Biochemistry and Molecular Biology



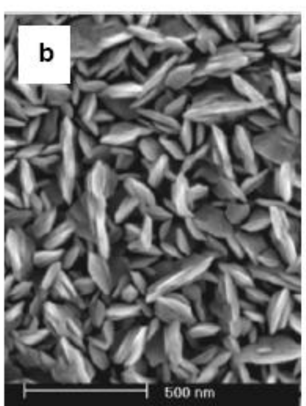


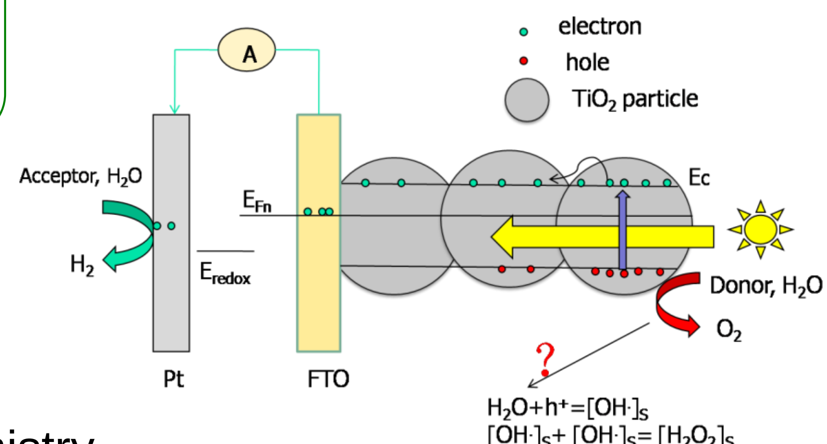
Reactor and Electrochemical Engineering

Nanostructured Photoelectrodes

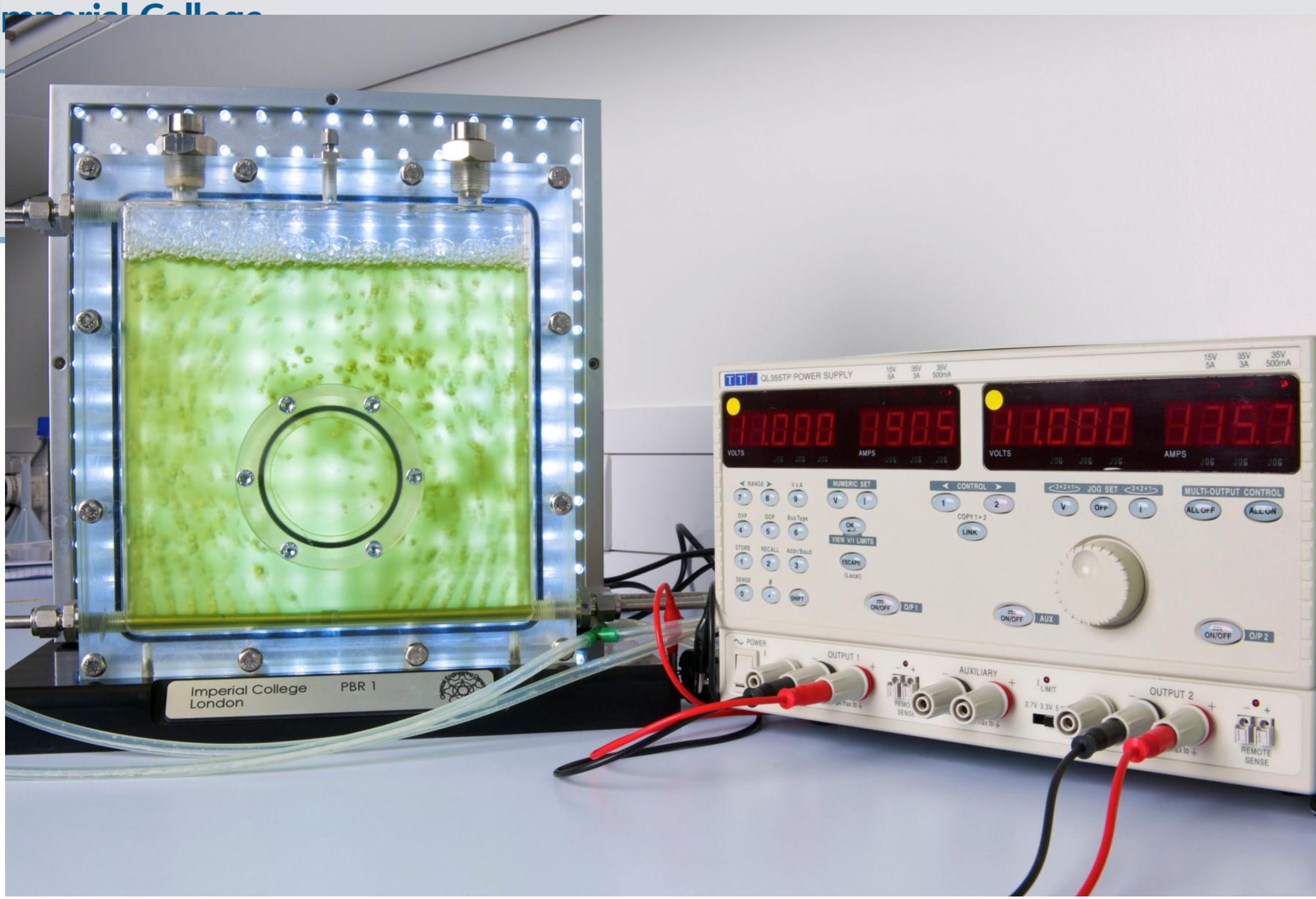
DOE 2015 Targets:

- Biophotolytic H_2: \$10/kg
- Photoelectrolytic H_2: \$5/kg





Photochemistry & Photoelectrochemistry



This strange machine is a bioreactor. Scientists at Imperial College London created it to make hydrogen without burning fossil fuels…

Image: Imperial College London

The green stuff inside is algae, tiny plants that naturally produce small amounts of hydrogen gas.

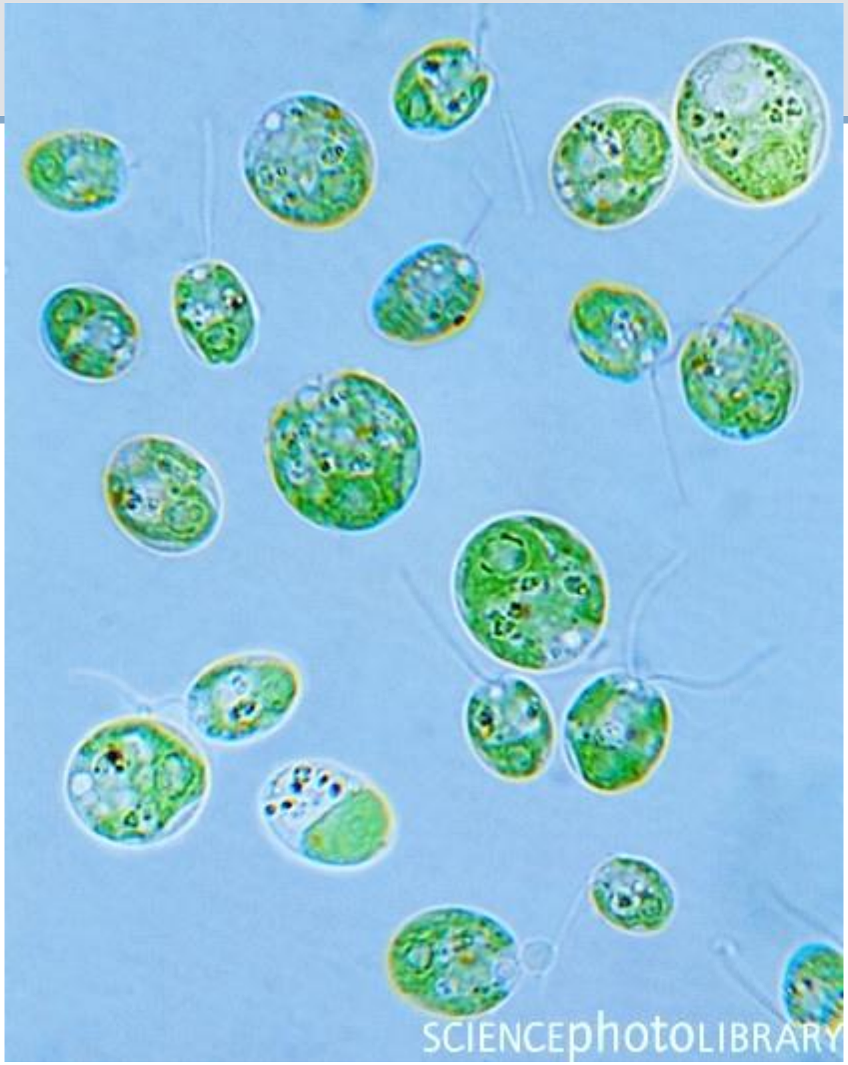


Image: Imperial College London

Imperial College London

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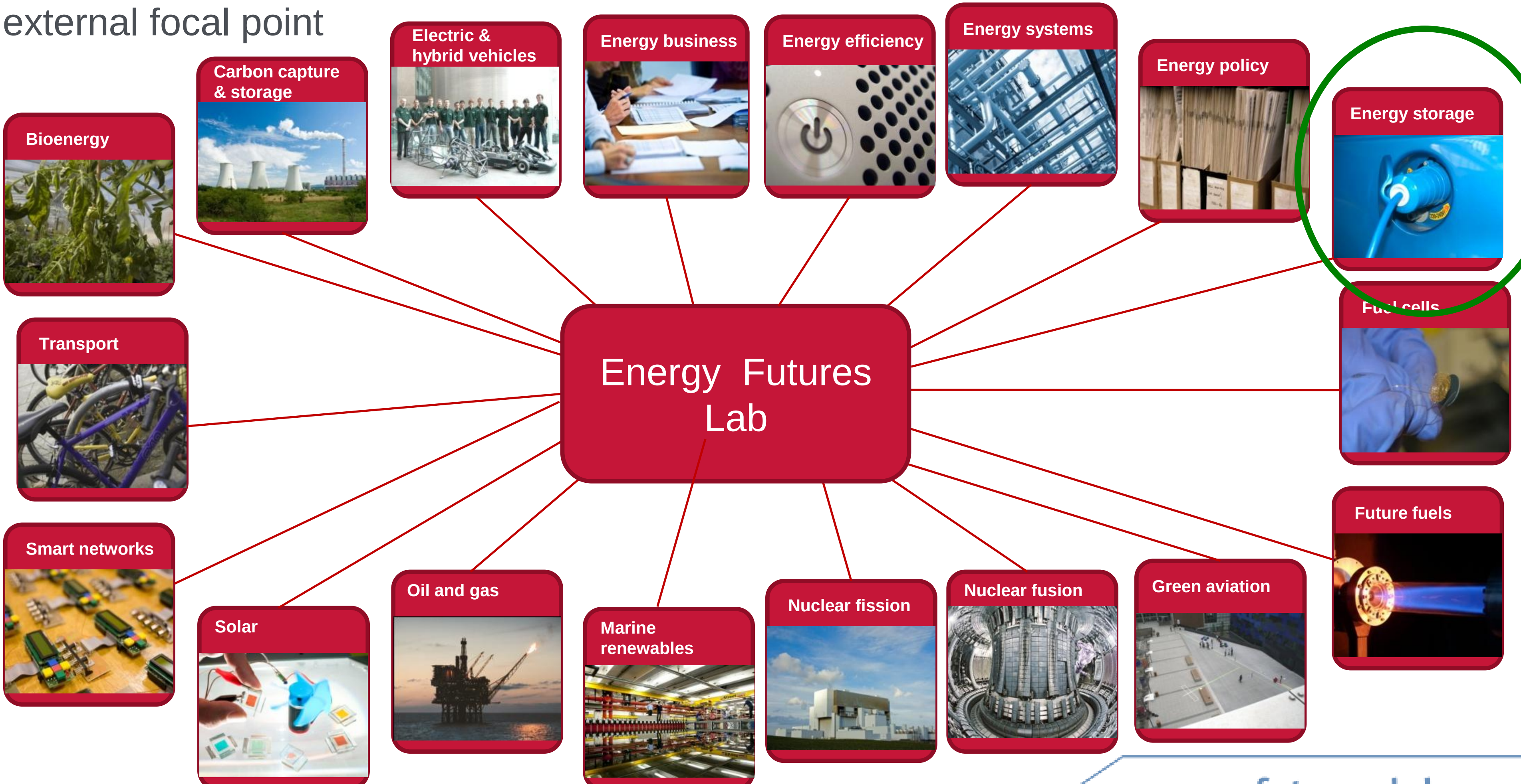
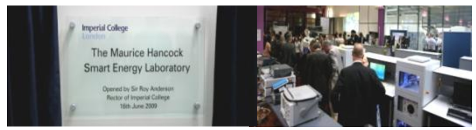


Energy storage

EDF ENERGY

Charging



Integration

DEPARTMENT OF ENERGY & CLIMATE CHANGE

Systems

imperial innovations

Battery control

Battery failure analysis

GM

Redox flow batteries

imperial innovations

Hydrogen & fuel cells

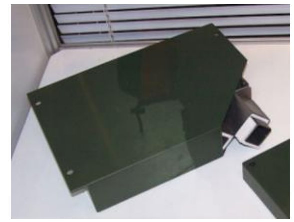
RICARDO

New chemistry & materials

EPSRC Pioneering research and skills

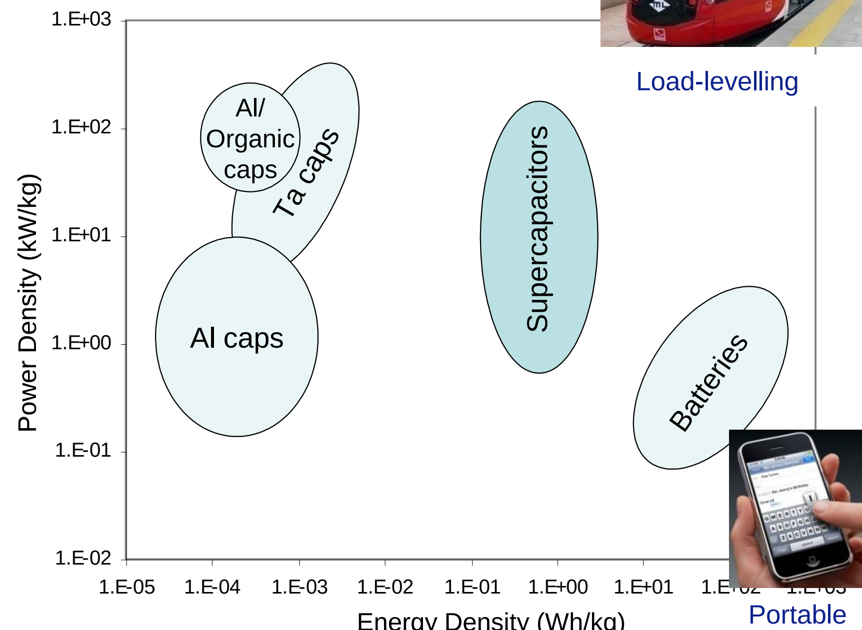
Types of Device

- Generic issues means different devices can be considered throughout research
- ***Batteries**:* high energy density, but low power density
- High resistance at high discharge rates - kinetics of redox process
- ***Capacitors**:* offer a limited energy density with a high power density,
- Energy only stored as charge on electrodes.
- ***Supercapacitors**:* avoid solid state redox reactions & half-way-house between batteries & capacitors
- Energy density 5Wh/kg, Power density 0.2-5 kW/kg
- ***Hybridcapacitors**:* combined batteries and supercapacitors



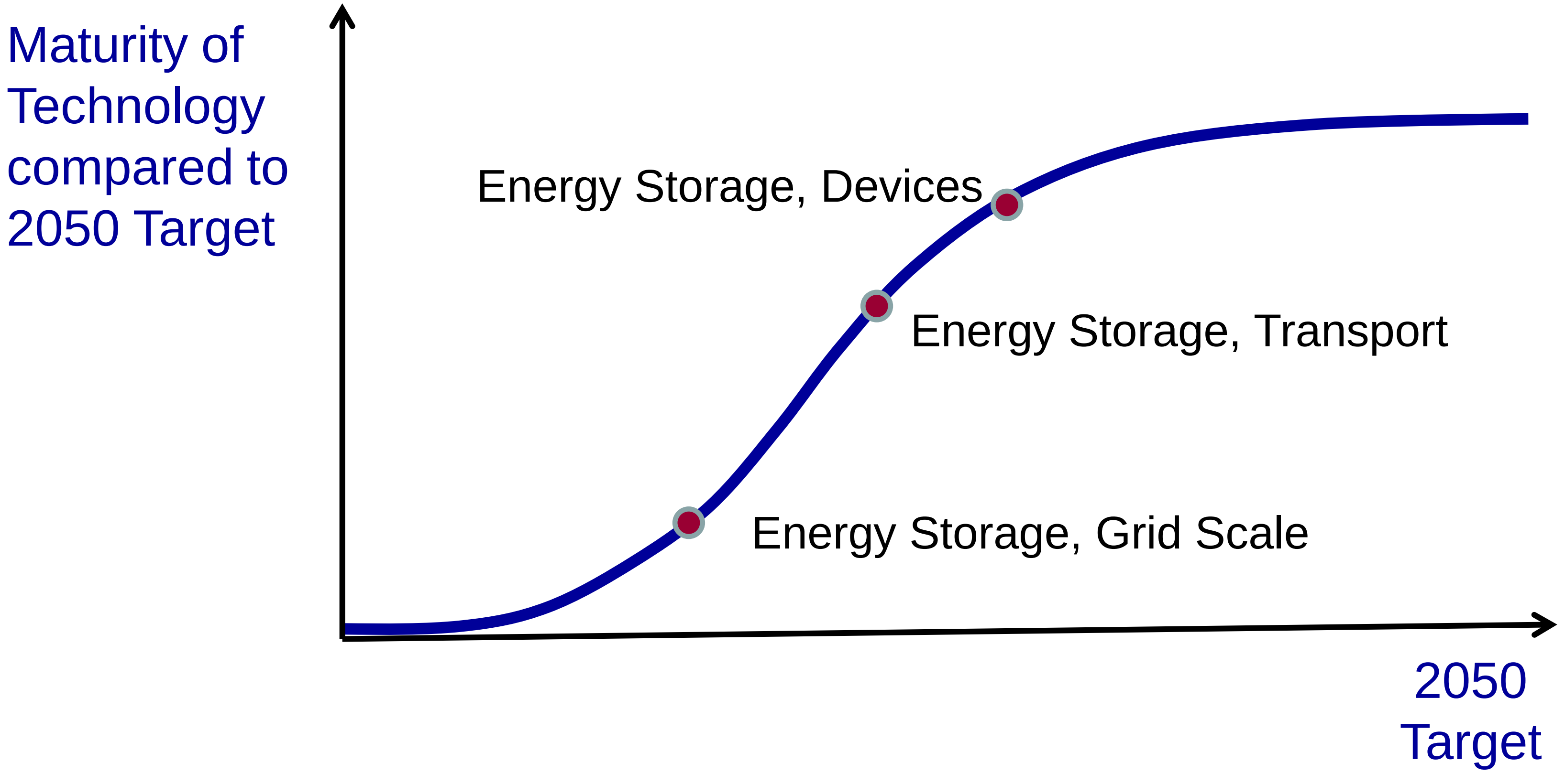
Reactive armour

Load-levelling



Portable electronic s

Maturity of Renewable Energy Technologies



Batteries, Storage and Electric Vehicles

- The options
  - Hybrid Vehicles
    - Multi-fuel: Hydrogen/Ammonia/LPG/Battery
  - Plug-in Hybrids
  - Electric Battery Vehicles
  - Fuel Cell Vehicles

SRZero – Imperial electric sports car

Energy Usage = 150 Wh/km cf efficient ICE vehicle @ 50mph = 550 Wh/km

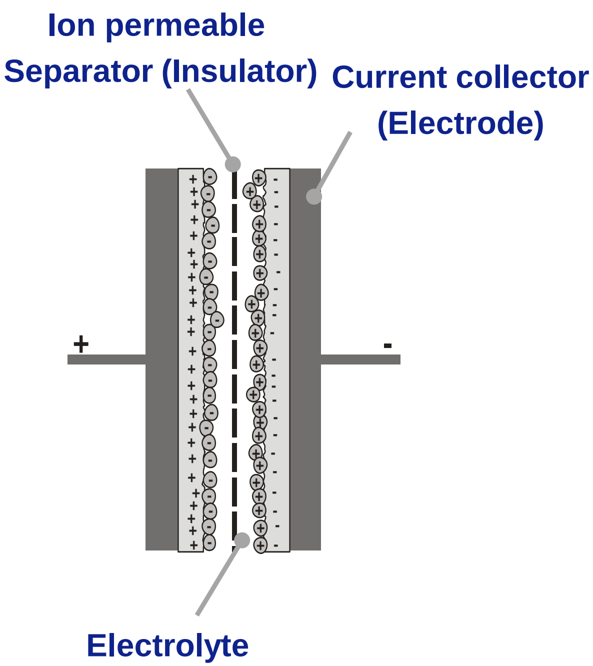
Integrating Energy Storage with Fabrication

Many energy-depended applications require reduced weight/volume to yield improved performance

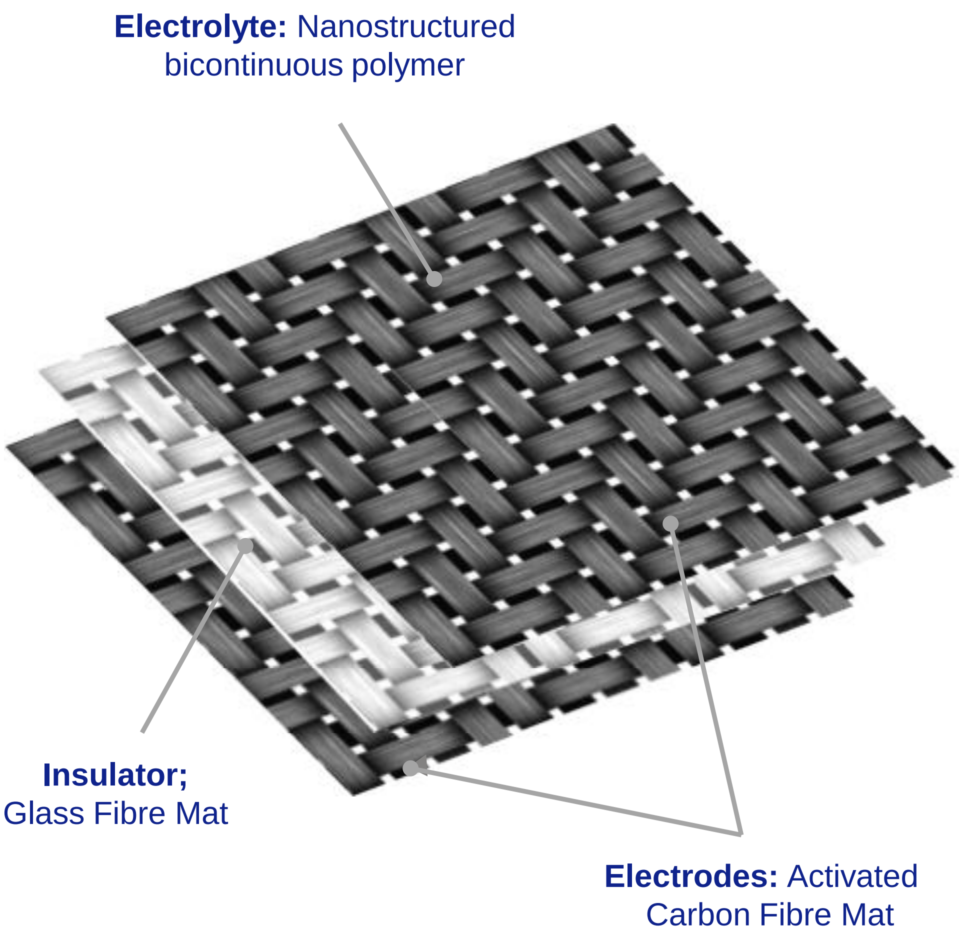
Energy storage device sector well established and forecast to grow rapidly in the future.
Improvements in terms of power & energy density are not keeping pace with demand.

Oil well probe

ICL Studies – Device Concept



Conventional Supercapacitor



Structural Power Supercapacitor

"Cars of the Future to Power Themselves"

Nanocomposites formed into chassis, doors, which store electricity:
Dr Emile Greenhalgh, Professor Alexander Bismarck, Professor Milo Shaffer, Imperial College London

Challenges for Energy Storage at Grid Scale

- No one storage technique meets all requirements – need a portfolio
- Lifetime of devices vs performance is key
  - Lifetime of Li-ion batteries increased by operating over only a fraction of full duty cycle... what fraction optimal?
  - Control strategy crucial
- 3-6 hrs storage time optimal for both bulk and distributed storage; limits search for solutions
- Low cost solutions that decouple power and energy required as energy increases
- Requires new breakthrough solutions

EPSRC funded grand challenge in energy storage for low Carbon Grids

£5.5M 5 year programme funded by EPSRC, starting Oct 1st 2012.

Imperial College London

Durham University

The University Of Sheffield.

UNIVERSITY OF LEEDS

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

UNIVERSITY OF CAMBRIDGE

University of St Andrews

UNIVERSITY OF OXFORD

UCL

- Modelling and analysis of network, control and storage technologies as a ‘system’
- Research into four innovative storage technologies
- We wish to engage with others interested in this area from an end user, developer, and policy perspective.

nationalgrid

ALSTOM

axeon technologies

Highview Power Storage

NORTHERN POWERGRID

M-SOLV Limited

electricity north west

Isentropic

UK Power Networks

DEPARTMENT OF ENERGY & CLIMATE CHANGE

EDF ENERGY

WILLIAMS ADVANCED ENGINEERING

ABB

THE ELECTRICITY STORAGE NETWORK

CARBON TRUST

nexeon

DONG energy

WorleyParsons resources & energy

energy technologies institute

e·on

Sodium - Ion Batteries

- Low cost (cheaper than lithium)
- High natural abundance and wide availability of Na
- High energy density compared with Pb-acid
- Designed specifically for **NETWORKS**
- More scope for step-change than lithium-ion - **a white space**.
- Team combines expertise in materials innovation at St Andrews with materials characterisation at Cambridge, and build on a significant track record in Li-ion batteries.

Challenge: to find new anode and cathode materials that will make Na –ion batteries for networks viable. Achievable with the resources available. Will

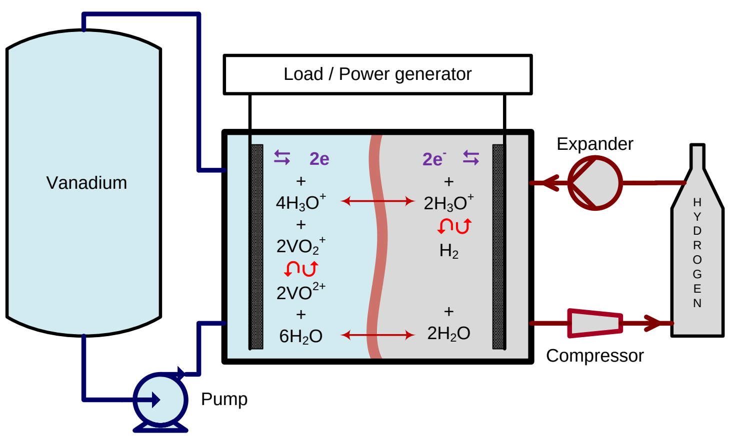
Anodes – Si, Bi, titanates

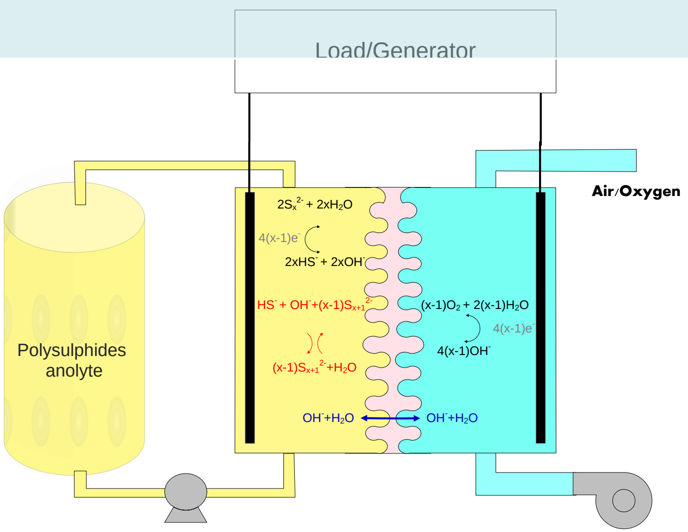
Cathodes - Na_2MnSiO_4, $NaNi_{1-x}Mn_xPO_4$

Redox Flow Batteries

- Energy and power can be de-coupled making RFBs well suited to grid storage applications.
- Low cost offered through the development of novel liquid-gas and semi-solid concepts – significant scope for innovation over current RFB technology.
- Team combines expertise in new materials and catalysts at UCL with electrochemical engineering capability at Imperial College, and builds on two recent liquid-gas patents at Imperial.

Challenge: to develop novel low cost redox flow batteries based around new liquid-gas and semi-solid concepts.

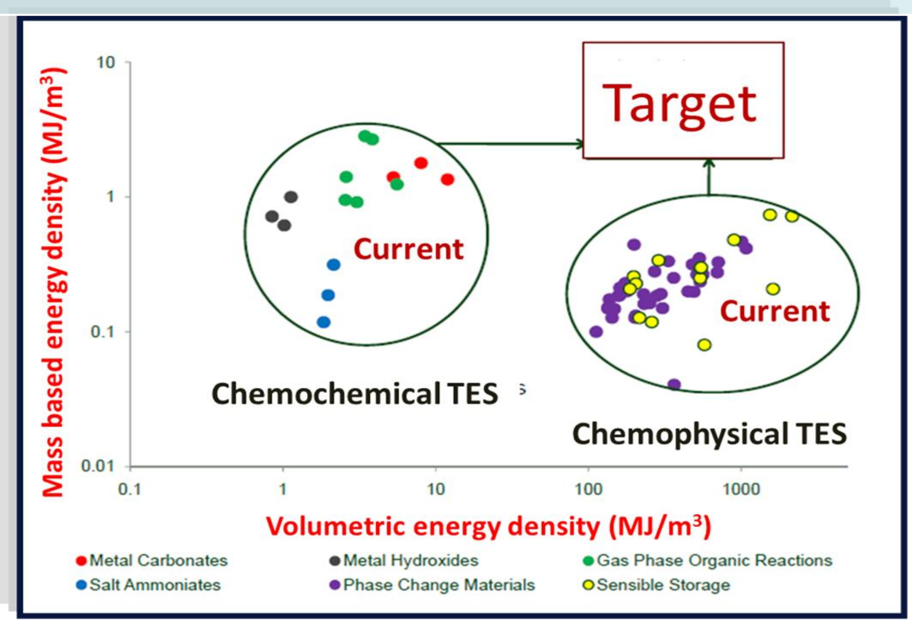




Thermal Energy Storage

- Thermal Energy Storage (TES) suited for grid-scale storage and long life (20 years +).
- Potential for low cost.
- High energy density (in terms of both mass and volume).
- Designed for integration with NETWORKS
- Led by Leeds University, who have a significant track record in this field.

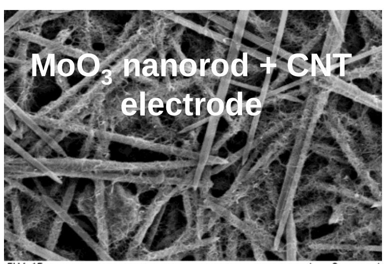
Challenges: to develop nano –structured TEM materials that are chemically stable, have a high thermal conductivity and are able to withstand over 20000 heating-cooling cycles; to develop scalable and fast response heat exchange systems with minimal effect of interfacial resistance.

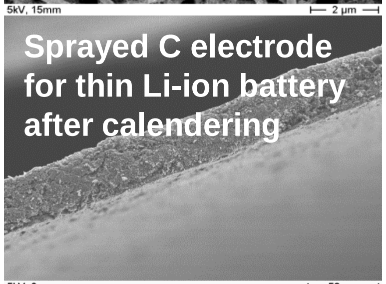


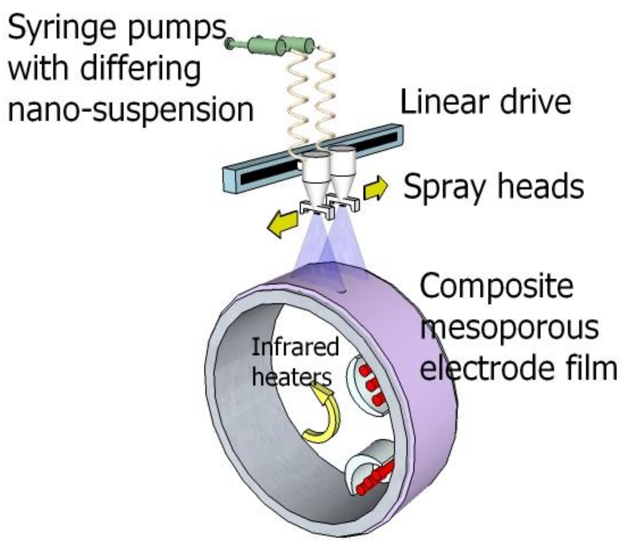
Science to manufacturing

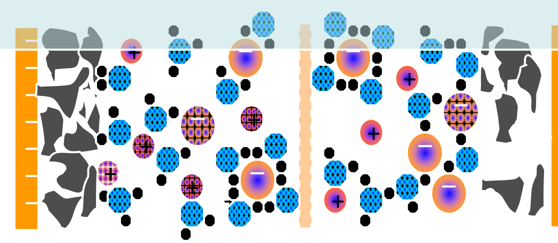
- Previous UK innovations in EC storage (Li-ion battery, Oxford 1979) not fully exploited in UK partly because manufacturing technology ignored.
- Start with supercapacitors to drive the exploitation of large area, thin film electrode manufacture, then exploit in novel systems e.g. Na-ion batteries; battery-supercapacitor hybrids.
- Use whole systems modelling to set the “right” performance-cost targets.
- Use experimental performance-cost data to re-calibrate models and iterate.
- Team combines expertise in supercapacitors at Sheffield with expertise in materials manufacturing at Oxford.

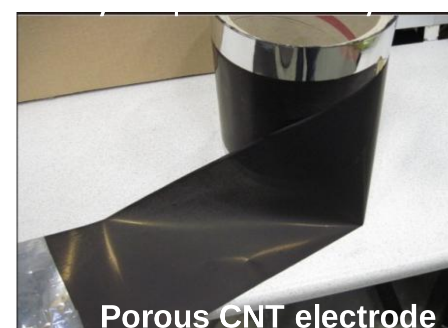
Challenge: grid storage mandates innovative manufacturing approaches - low cost, large area, environmental compatibility.











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