Solar Photovoltaics

The challenges and potential for research into a sustainable future

(Fundação de Amparo á Pesquisa do Estado de São Paulo, 27th February 2009)

Dr. Ian Forbes

Northumbria Photovoltaics Applications Centre (NPAC)

School of Computing, Engineering and Information Sciences,
University of Northumbria

Photograph: NASA_-_Earth_And_Its_Moon,_Space_Shuttle_Discovery,_1998

Outline

The talk will cover the following topics:

- The Solar resource & Photovoltaics
- Challenges
- Potential as Energy solution
- NPAC
  - System performance
  - Environmental Impact
  - Courses/Learning
  - Cell Test Facility
  - Thermophotovoltaics
  - Thin Films
  - NPAC Links
- Opportunities
- Summary
- Acknowledgements

Solar Resource

Solar PV is the least geographically restricted of all renewable technologies

Prof N. Lewis, Caltech:

"Solar energy – *More energy from the sun hits the earth in an hour than all of the energy consumed on earth in a year*.

But technology would have to find a way to capture the sun's energy, store it, and do so cost-effectively".

*[World energy consumption ~13TW, US ~3.2TW compared to the Sun's total to the Earth of 120,000TW]**

* Estimated in 2000

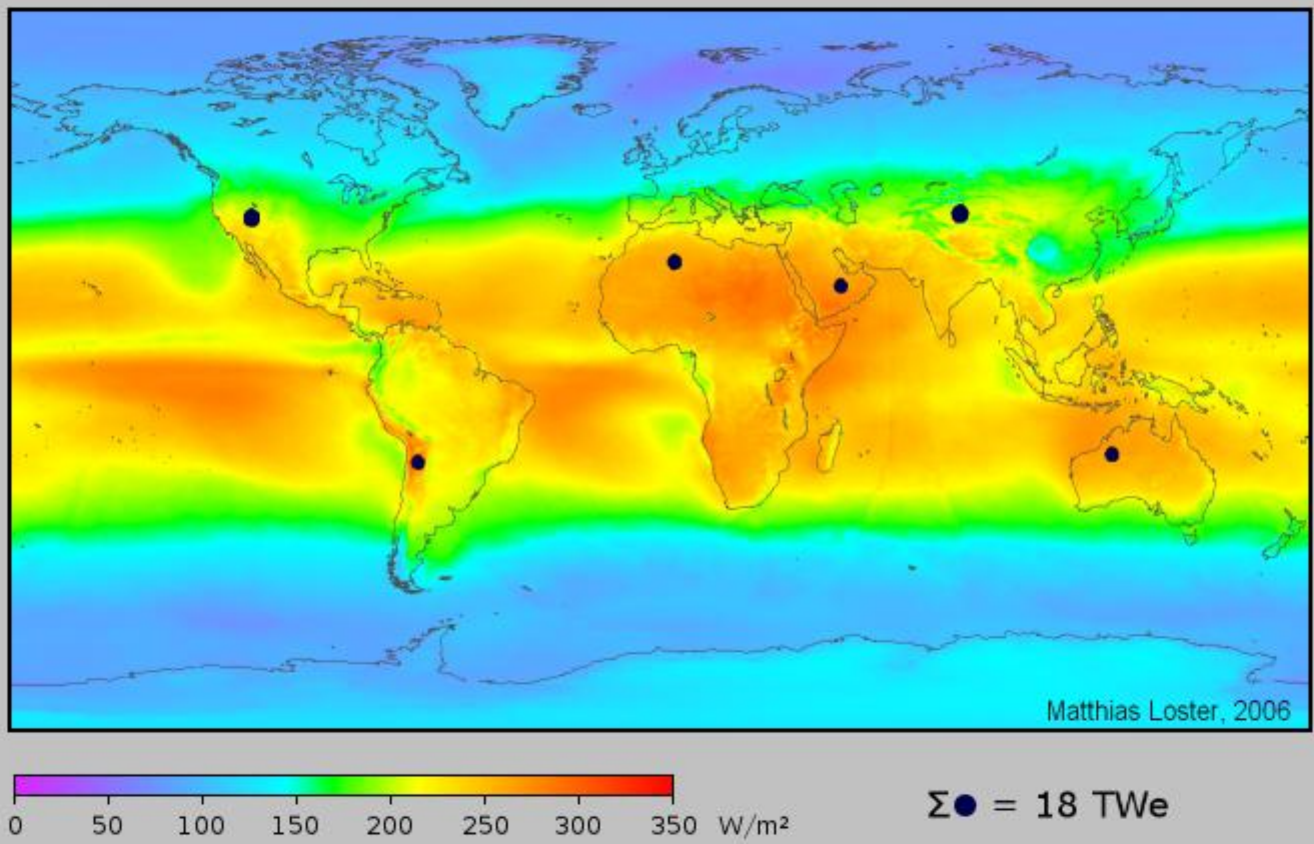
Nathan S. Lewis, Professor of Chemistry, California Institute of Technology, *Division of Chemistry and Chemical Engineering, Pasadena, CA 91125, http://nsl.caltech.edu/energy.html*

Solar Resource: Photovoltaics

- Photovoltaics (PV) - Semiconductor pn junction which absorbs light and generate/separate charge carriers
- PV is the direct conversion of sunlight into electricity and is technically elegant, with promise to supply a substantial part of the world's energy in the coming decades
- The PV market continues to grow rapidly, shipping 3.07 GWp in 2007 – an increase of 55% on the previous year (source: Navigant Consulting)
- Currently the total market is small and supported by market incentive schemes whilst costs remain above conventional energy supplies
- The Vision Report of the European PV Technology Platform set a target of 4% of the world's electricity supply by 2030, but is now looking at how to accelerate development in the light of the European 2020 targets

Solar Resource - PV

Mattais Loster Web site;http://www.ez2c.de/ml/solar_land_area/

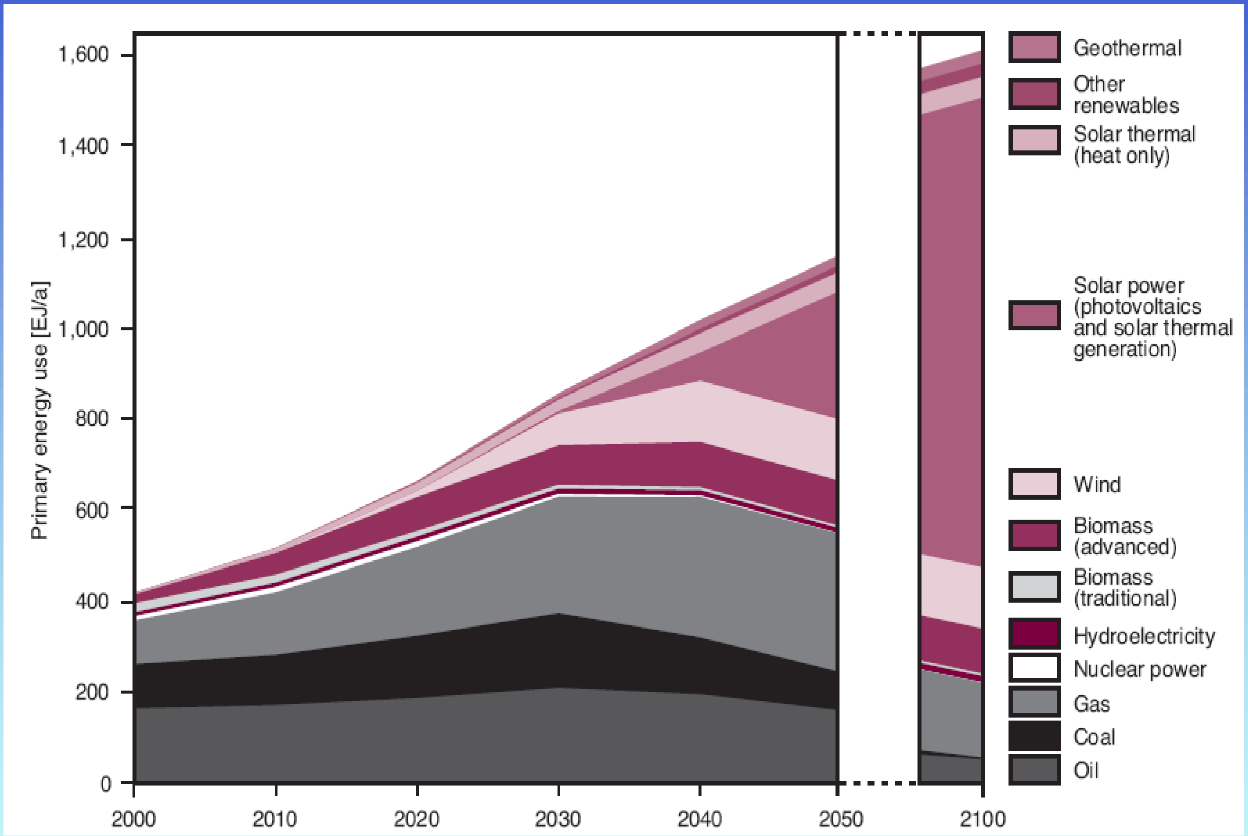


Work by Matthais Loster and colleagues in Germany (2006)

Dots represent areas of 140,000 – 180,000 km^2

24hr data averaged over 3 years

Solar Resource - PV



Source: World in Transition. Towards Sustainable Energy Systems, German Advisory Council on Global Change (WBGU) 2003, Earthscan.

- **Solar PV is potentially the largest and most widely applicable renewable energy technology**
- **By 2100 over 50TW could be produced by a combination of Solar PV andThermal**
- **Applications vary small remote systems to large scale power plants**

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PV Potential - Industry View

A.Milner

(source: *The Solar Europe Initiative within the SET-Plan Valencia 3rd Sept 2008 5th European PV Industry Forum EPIA Director & CEO, Q-Cells AG*)

- **By 2020 PV can reach grid parity for more than 90% of the European electricity demand**
- **Even with grid limitations, PV can competitively supply more than 12% of Europe's electricity demand by 2020 with technology that is already available today (350GWp)**
- **Reaching this 12% goal implies that PV is responsible for more than 25% of capacity built until 2020 and becomes a mayor source of electricity supply in the EU**
- **Policy and industry need to work together to make this market accessible**

PV Potential - Europe

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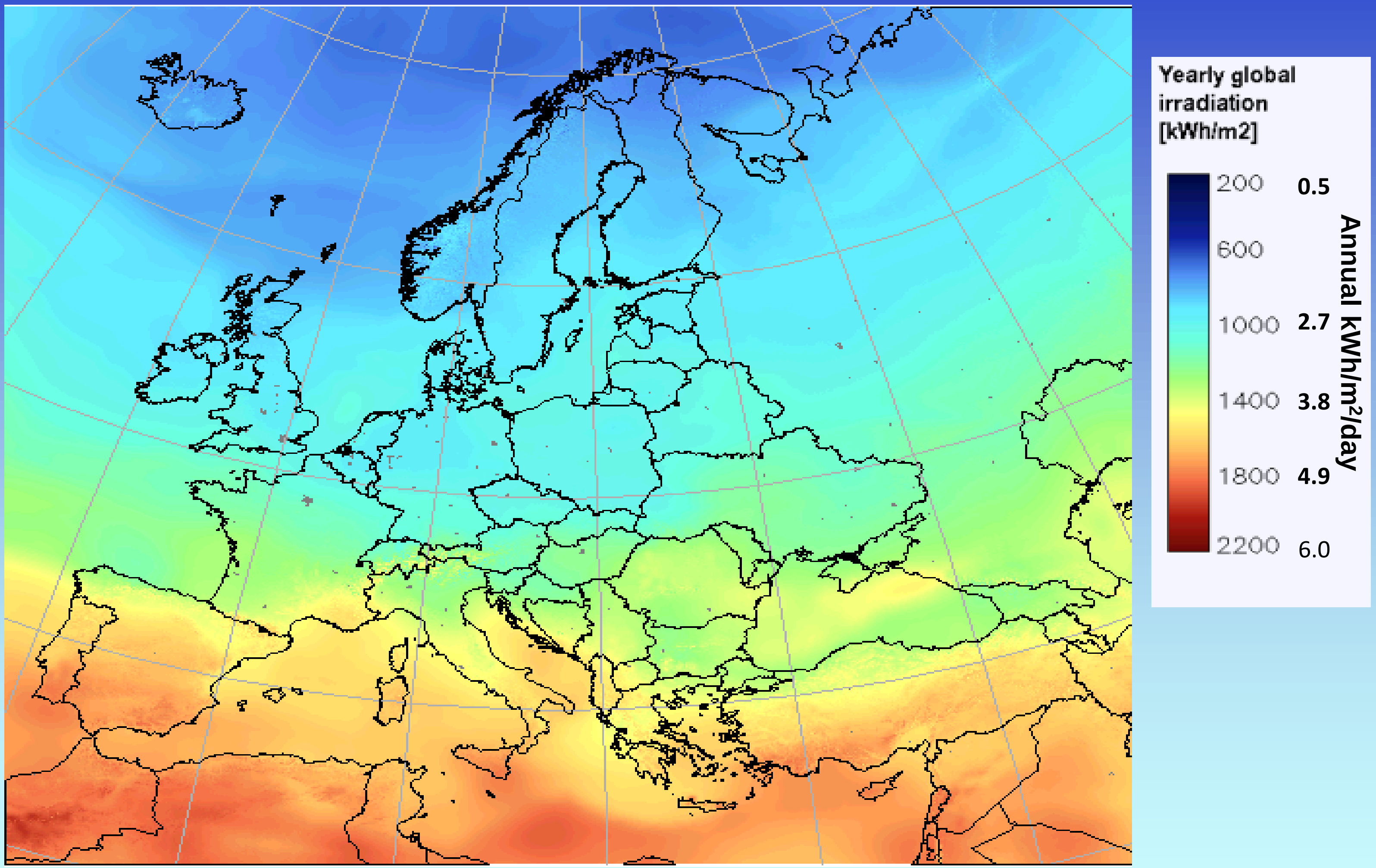
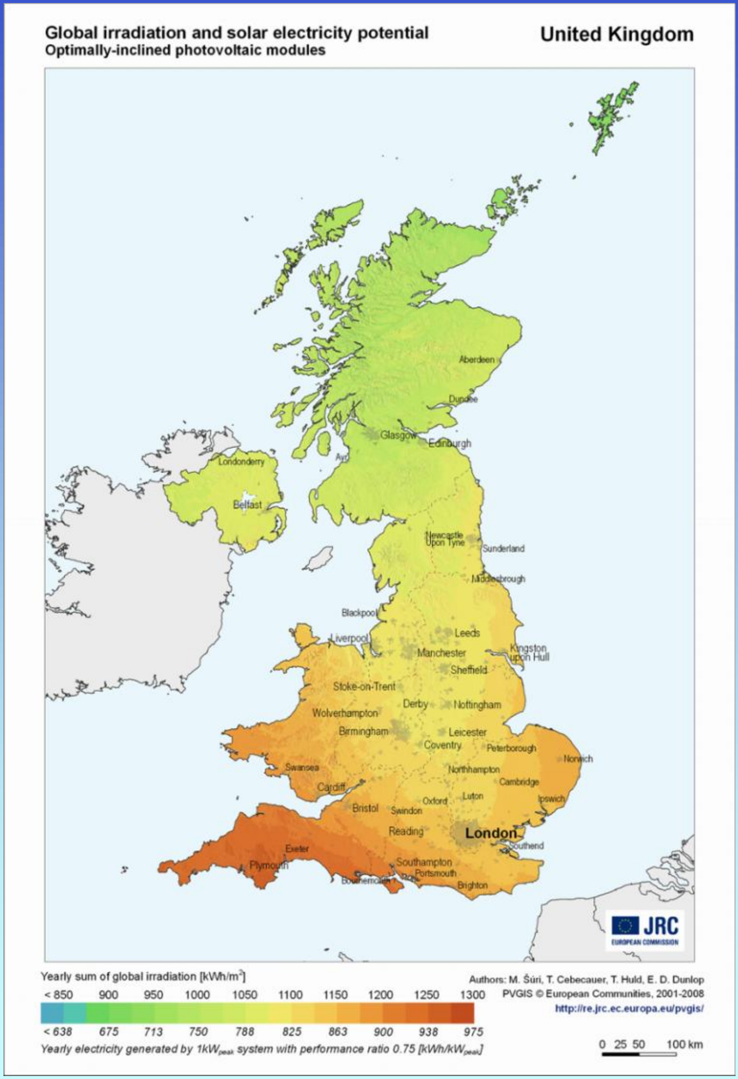


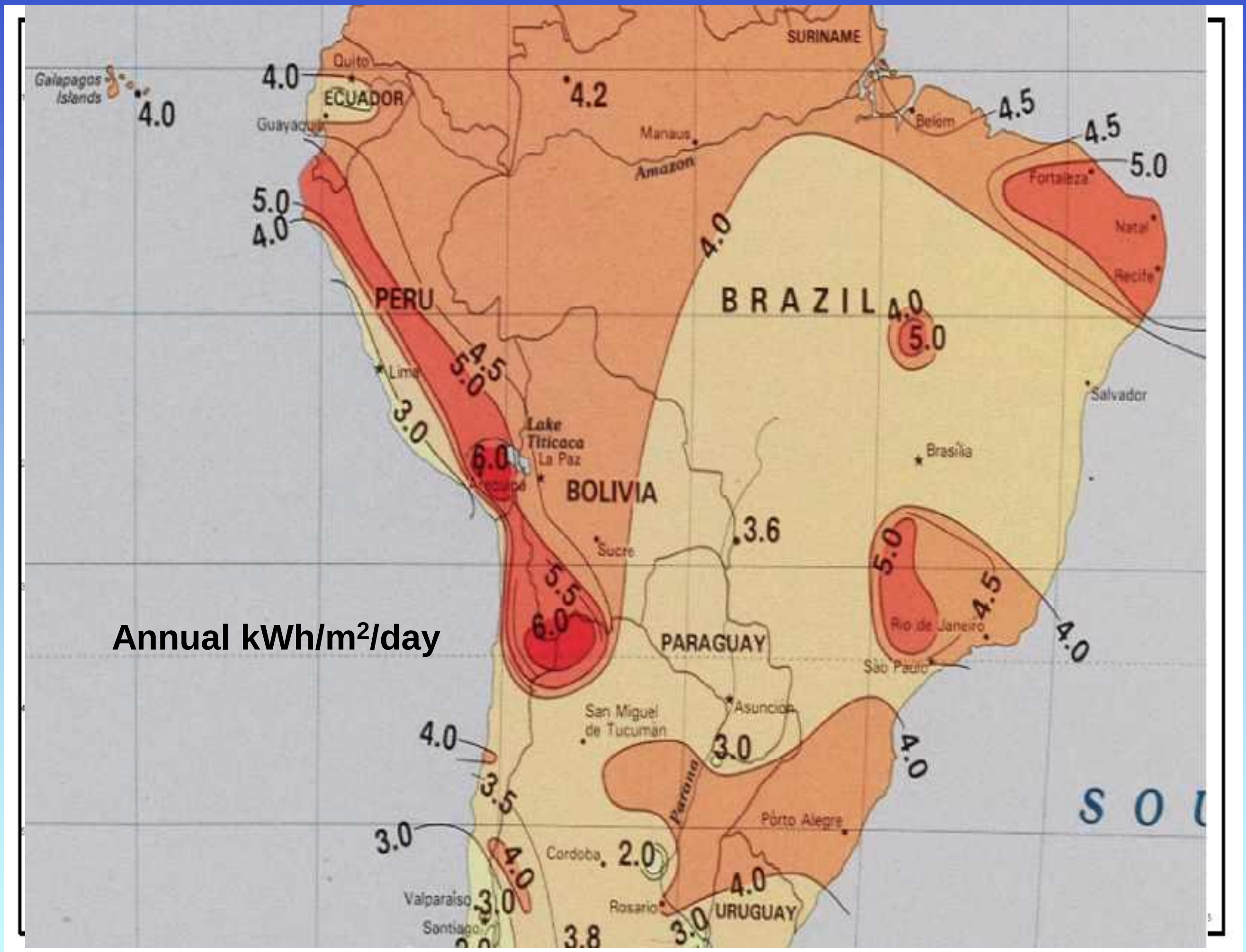
http://re.jrc.ec.europa.eu/pvgis/apps/radmonth.php?lang=en&map=europe

Solar PV – Potential: UK



- The UK has typical insolation levels that are 80% of those Germany - in the World's largest PV market.
- A UK domestic system will yield ~800 kWh/kWp - a 1.5 – 2 kWp system will typically provide around 50% (just under half is used directly and the rest is exported)
- EPIA's Prediction for grid parity of Solar PV Electricity includes most UK population centres
- The UK is overwhelmingly a city dwelling population. Building integrated PV - zero carbon houses 2016, commercial buildings 2018
- The EU SET-Plan (15% renewable electricity in the UK by 2020)

Solar PV – Potential: Brazil



- Population Centres in Brazil have insolation levels over twice those in Germany
- There is potential for PV to meet a considerable fraction of electricity demand
- Preparation is needed to take advantage of the opportunities for employment and wealth creation

http://www.solar4power.com/map4-globalsolar-power.html
http://swera.unep.net/index.php?id=solar

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Challenges

Status and issues

- Typical Silicon module efficiencies between 15% -20% 1 sun
- Concentrator III-V triple junction record efficiency >40% (C>500x)

Issues

- Reduce cost
  - Develop technologies that minimise materials and energy cost
  - Increase efficiency
- Increase long-term sustainability
  - Develop technologies that can meet TW demand
- Market Growth
  - Provide mechanism to build confidence in investment and training, grid connection
- Maximise exploitation of a fixed resource
  - Survey national resource and performance of technology combinations, grid models, operation / lifestyle and energy saving

Challenges

Cost reduction & sustainability

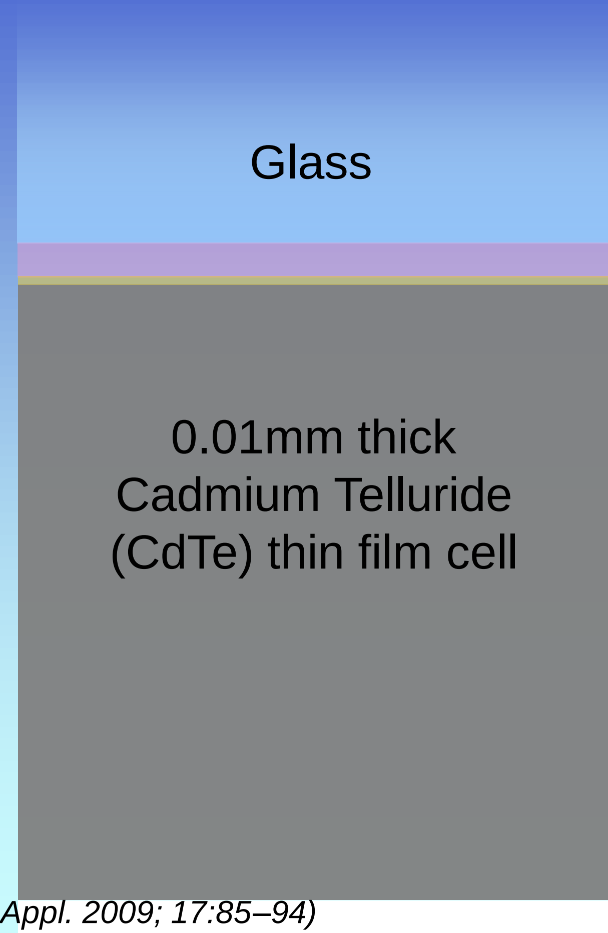
- Materials - currently over 85% is crystalline Si
- Recently, inorganic thin film technologies have increased rapidly (multi-GWp production by 2012 predicted) - will reduce costs - take PV generated electricity to grid parity
- These are based on thin film silicon (aSi, ucSi), CdTe and $CuInGaSe_2$ family of materials – latter have achieved a conversion efficiency of over 20%* - the highest of all thin film technologies
- Challenge: Improve performance – understand physics and chemistry of existing materials and processing
- Challenge: address long term sustainability questions at the 100s GWp production level (use of Cd, Te, In, Ga) – develop new concepts (η >50%)

Current Thin Film Technologies

The two highest performance Thin Film PV materials

- **Copper indium (gallium) diselenide (NREL WR efficiency - 20.2%)**
- **Cadmium Telluride (NREL WR efficiency - 16.5%)**

- **Thin Film processing offer large area fast, low cost processing compared to crystalline Si**
- **Short energy payback time less than two years quoted and as low as 1 month**
- **Multi GWp production predicted by 2012 – will help achieve competitive Solar PV electricity**



**M. A. Green et al,, Solar Cell Efficiency Tables (Version 33), Prog. Photovolt: Res. Appl. 2009; 17:85–94)*

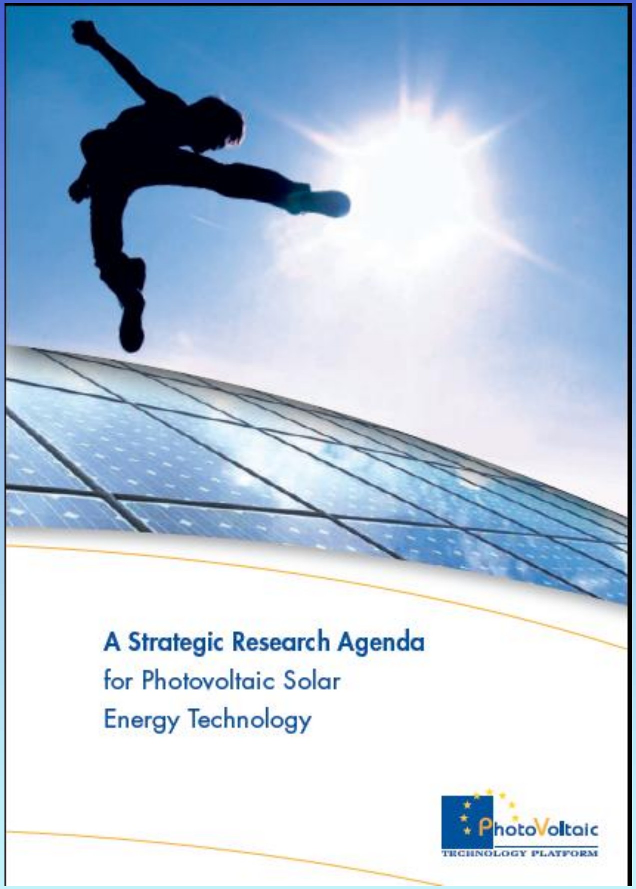
Current Thin Film Technologies

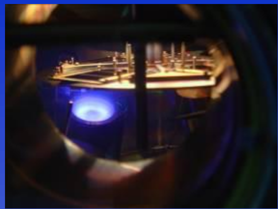
Status and issues

- Thin film GuInGaSe$_2$ is a member of the Chalcopyrite family of materials
- Longer term sustainability may become a problem (Only ~6000 Tonnes of indium in reserves – USGS)
- Gallium is also a rare material but is a key component in maximising the cell performance (bandgap grading)

Strategic effort to reduce cost

- **The European SRA outlines R&D priorities for competitive PV**
- **Thin film technologies near–medium term route to competitive PV electricity**
- **In the UK, The Supergen Consortium PV21 had already begun addressing these issues**





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- Areas Exploitation
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Northumbria University

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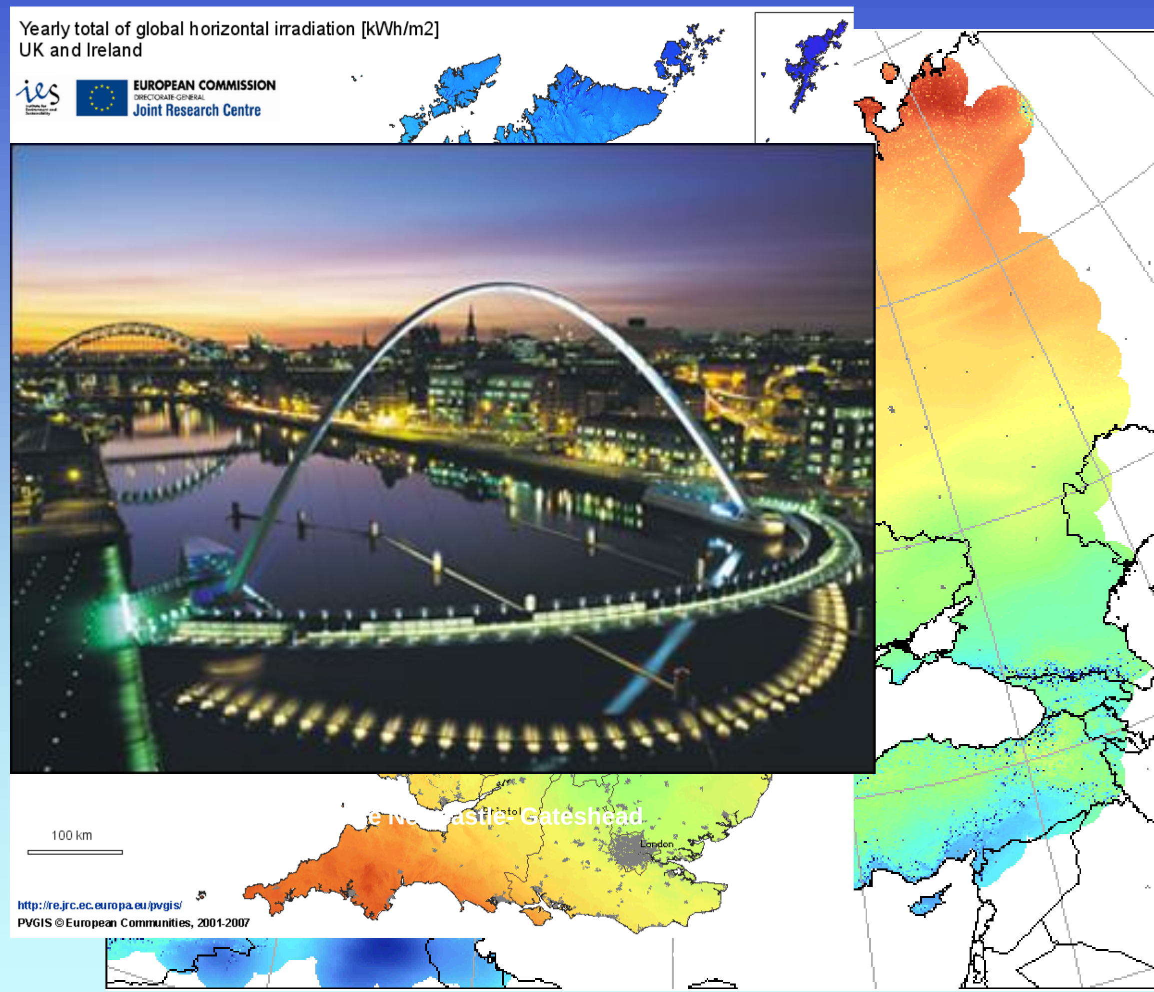
Northumbria Photovoltaics Applications Centre (NPAC)

- Located in the North East of England
- Largest of 4 universities in the region
- ~31,500 students just under 5,000 of these are postgraduate; 3,000 international students
- Major building refurbishment programme (new £100 million campus opened 2008)

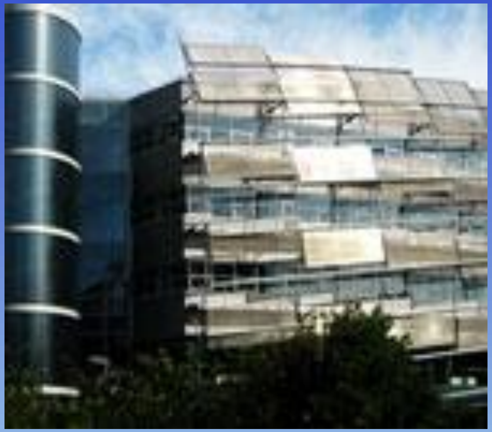


Introduction to NPAC

Northumbria Photovoltaics Applications Centre (NPAC)

Director: Prof. Nicola Pearsall

Dr. Ian Forbes
Dr. Robert Miles
Dr Guillaume Zoppi



NPAC Activities

- Systems and Grid Connection
- Economic and Environmental Analysis
- Thin Film Solar PV Devices
- PV Cell Test Facility
- Thermophotovoltaics

Research in Renewable Energy

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Northumbria Photovoltaics Applications Centre (NPAC)

Energy Systems and Advanced Materials Research Group

Leader:
Prof. Nicola Pearsall

Northumbria Photovoltaics Applications Centre

Photovoltaic devices
Photovoltaic systems

Power and Wind Energy (PAWER)

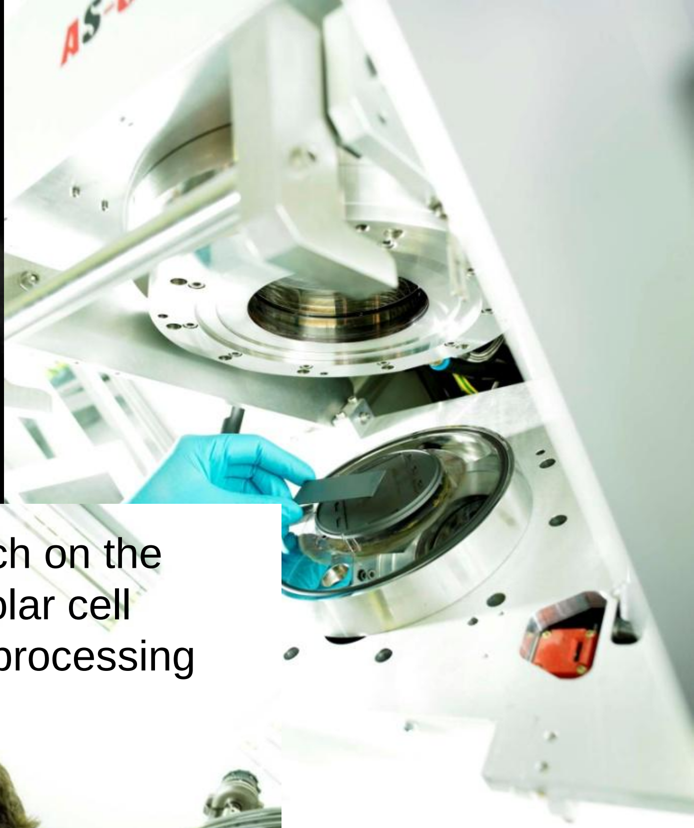
Wind energy systems
Distributed generation

Advanced Materials

Materials analysis
Materials for corrosion protection

Northumbria Photovoltaics Applications Centre (NPAC) – Northumbria University

Thin Film cell research on the $CuInSe_2$ family of Solar cell materials – Vacuum processing



Highest reported performance for experimental $Cu_2ZnSnSe_4$ cells in the World

Systems & Environmental Impact

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- The measurement and analysis of solar cell performance
- Monitoring and analysis of PV system performance (particularly for building integrated systems)
- Environmental impact and life cycle analysis for energy systems, particularly PV cells and modules
- Current European FP6 Projects: PERFORMANCE & ATHLET

Cell Test Facility & Thermophotovoltaics

Cell Test Facility

- Simulators
  - Class A and Close Match
- Spectral Response
- UV Ageing

Thermophotovoltaics

(PV conversion of radiation from man-made sources)

- Survey of Applications
- Development of systems spectral control
- Testing capability

Courses/Learning

European Masters in Renewable Energy

- 16 month course, 3 semester course
- Semester 1 – core, overview of renewable technologies at 1 of 4 European Universities
- **Semester 2 – specialisation (wind, photovoltaics, biomass, hybrid systems, energy efficiency in buildings) at one of 5 European Universities (different to the core)**
- Semester 3 – project in industry or research institute (usually in area of specialisation)
- Students must spend time in two European countries
- Degree is awarded by core university
- Students have a good general renewables knowledge with a more in-depth knowledge of one technology or topic area

SUPERGEN
Photovoltaic Materials for the 21st Century

Mission:

"To make a major contribution to achieving competitive PV solar energy"

Maximise use of materials:

- Use less – thinner devices
- Develop emerging materials – replace costly and scarce materials
- Increase efficiency – more output from the same or less material

Cadmium Telluride (CdTe) reduce thickness and maintain or increase performance

Copper Indium diselenide ($CuInSe_2$) based materials reduce thickness, develop materials with reduced Ga and In and develop and replace with abundant materials

Develop strategies to increase performance

PV-21 Consortium

Academic Partners

Durham University
(Finance Hub; fundamentals)

Optic Technium (Glyndwr Univ)
(Management Hub; producability)

Univ Bath *(new materials)*

Univ Southampton
(platforms and photonics)

Northumbria Univ *(new materials)*

Cranfield Univ *(rapid test)*

London South Bank Univ *(thin film Si)*

Imperial & Edinburgh *(techno-economic)*

Industrial Partners

Pilkington Technology
Semimetrics
Kurt J Lesker
Plasma Quest
Millbrook Instruments
SAFC Hitech
CSMA Ltd

Industrial Advisors

Dr Dieter Bonnet
Dr Spencer Jannsen

Replacing gallium with aluminium

PV21 will use aluminium to:

- To maximise single junction cell absorption of the suns light increase bandgap to optimum (1.4-1.5eV, $CuInSe_2$ -1.04eV)

- Grade the aluminium content to help collect electrons

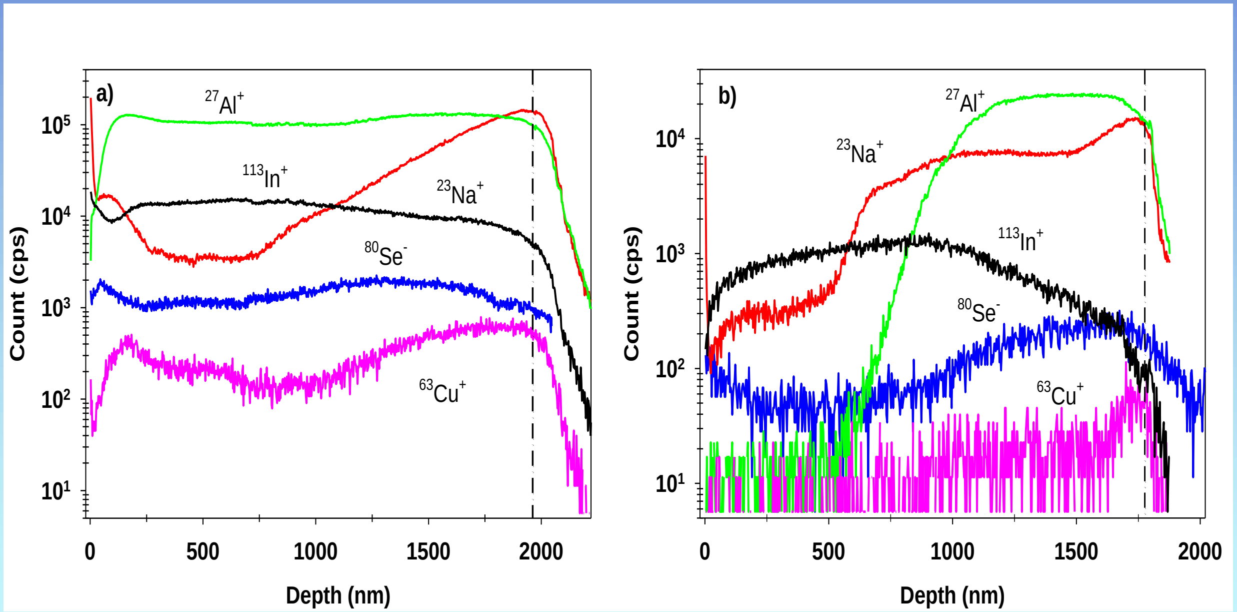
This will be needed for very thin films (0.001mm or less)

Wider Eg absorber layers - $CuInAlSe_2$

- **Successful incorporation of Al into the CIS chalcopyrite**

  [$CuInGaSe_2$ cells hold record efficiency – replace Ga ($900/kg) with Al ($2/kg)]

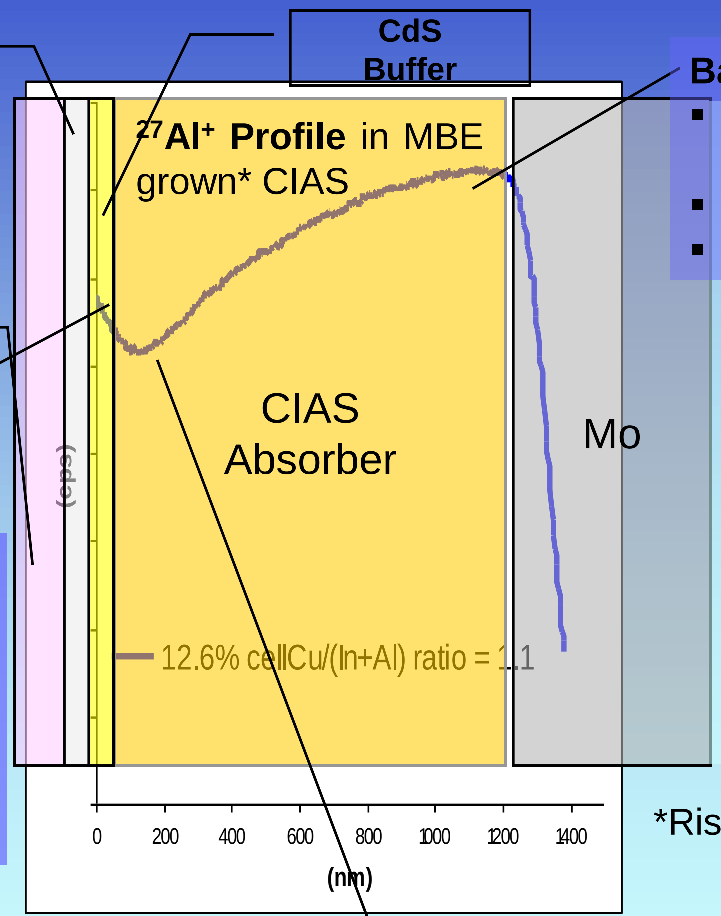
- **Al behaviour critical to high quality absorber layers (analogous to Ga in $CuInGaSe_2$).**
- **Devices with V_{oc}>380mV, η~5%**



MiniSIMS depth profiles of selenised $CuIn_{1-x}Al_xSe_2$ films (x=0.18). a) For a film showing the CIAS quaternary phase and b) for a film behaving like CIS.

G. Zoppi, et al. Thin-Film Compound Semiconductor Photovoltaics, edited by T. Gessert, S. Marsillac, T. Wada, K. Durose, C. Heske (Mater. Res. Soc. Symp. Proc.), San Francisco (2007) Y12-02

Graded composition and bandgap



Back Surface Field BSF

- **suppression of back contact recombination**
- **increase in j_{SC}**
- **decrease in j_0 → increase in V_{OC}**

Increased surface band gap:

- **Suppression of Space Charge Region recombination**
- **Decrease in j_0**
- **Increase in V_{OC}**

Ref. *T Hayashi et al., Effect of composition gradient in Cu(In,Al)Se2 solar cells. Solar Energy Materials and Solar Cells* **in press**

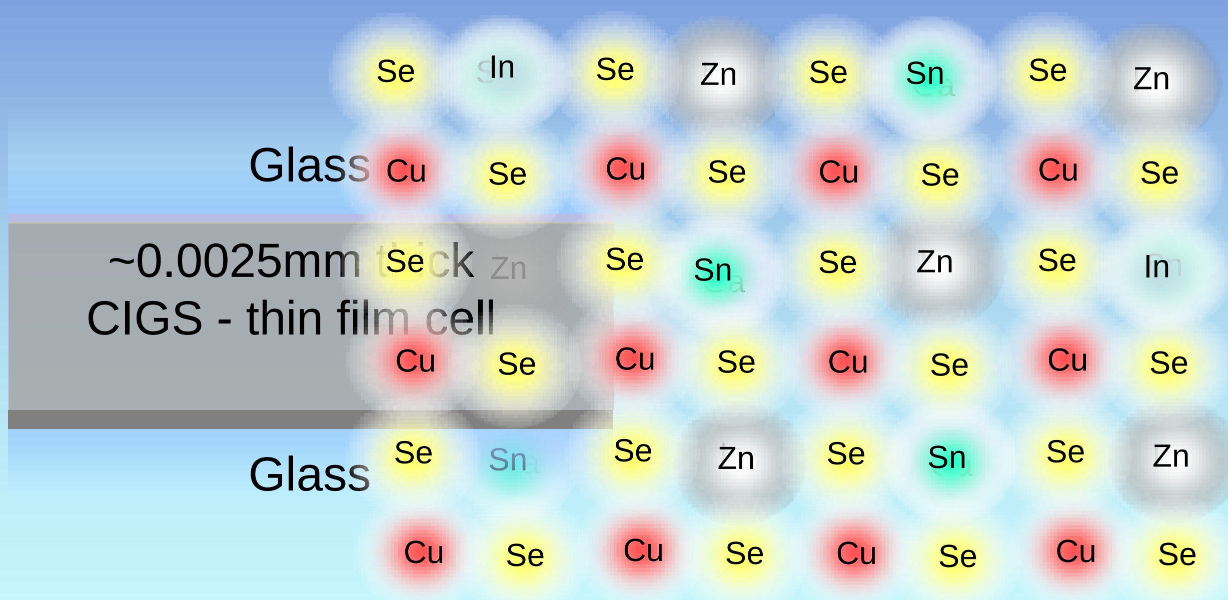
*Ristsumeikan University, Kyoto, Japan

minimum well within Space Charge Region

- **avoid barrier and decrease in FF**

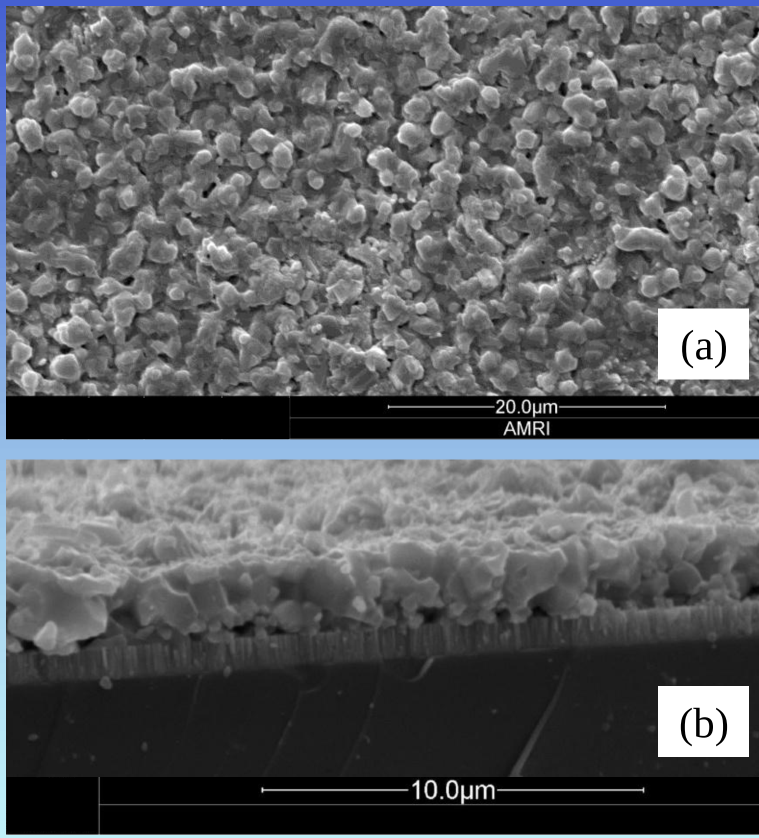
In & Ga free absorber :

Gallium (Ga) ~ $600/kg and Indium (In) ~ $500/kg

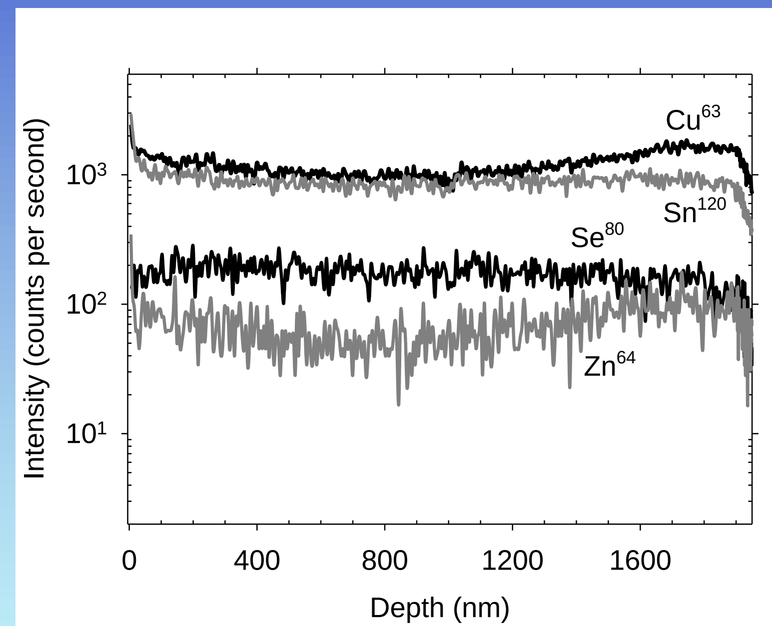


Replace with tin (Sn) ~ $15/kg and zinc (Zn) ~ $10/kg

$Cu_2(ZnSn)Se_4$ Absorber Layers

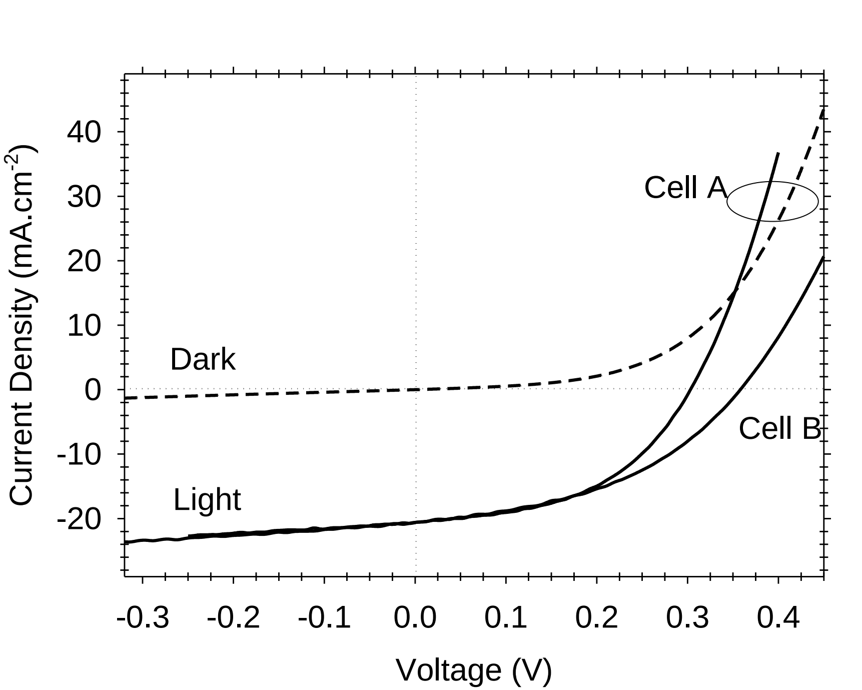


Scanning electron micrograph of a CZTSe film on Mo-coated glass. (a) Surface image and (b) cross-sectional image.



MiniSIMS depth profiles of a CZTSe film deposited on glass. The precursor was selenised at 500 C for 30 min.

$Cu_2(ZnSn)Se_4$ Thin Film Cells



Dark and light current density – voltage curves of the best performing CZTSe solar cells recorded under AM1.5 (100 mW.cm-2, 25 C) illumination and total device area of 0.229 cm2.

Active area device efficiency: 4% AM1.5 - highest reported

REF: G. Zoppi, I. Forbes, R. W Miles, P. J Dale, J.J. Scragg and L. M. Peter, *"$Cu_2ZnSnSe_4$ thin film solar cells produced by selenisation of magnetron sputtered precursors",* Progress in Photovoltaics: Research and Applications expected online in March 2009

NPAC Links

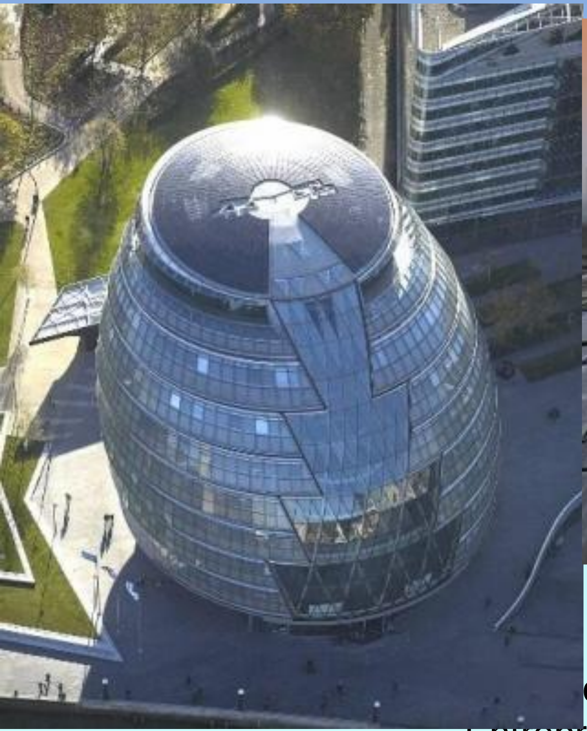
Strong regional links

- The New and Renewable Energy Centre (NaREC), Blyth, Northumberland, Wind, Wave and PV test
- Romag, Glass-Glass module manufacturer
- One North East – Regional Development Agency
- PV North East
- Newcastle University
- Durham University

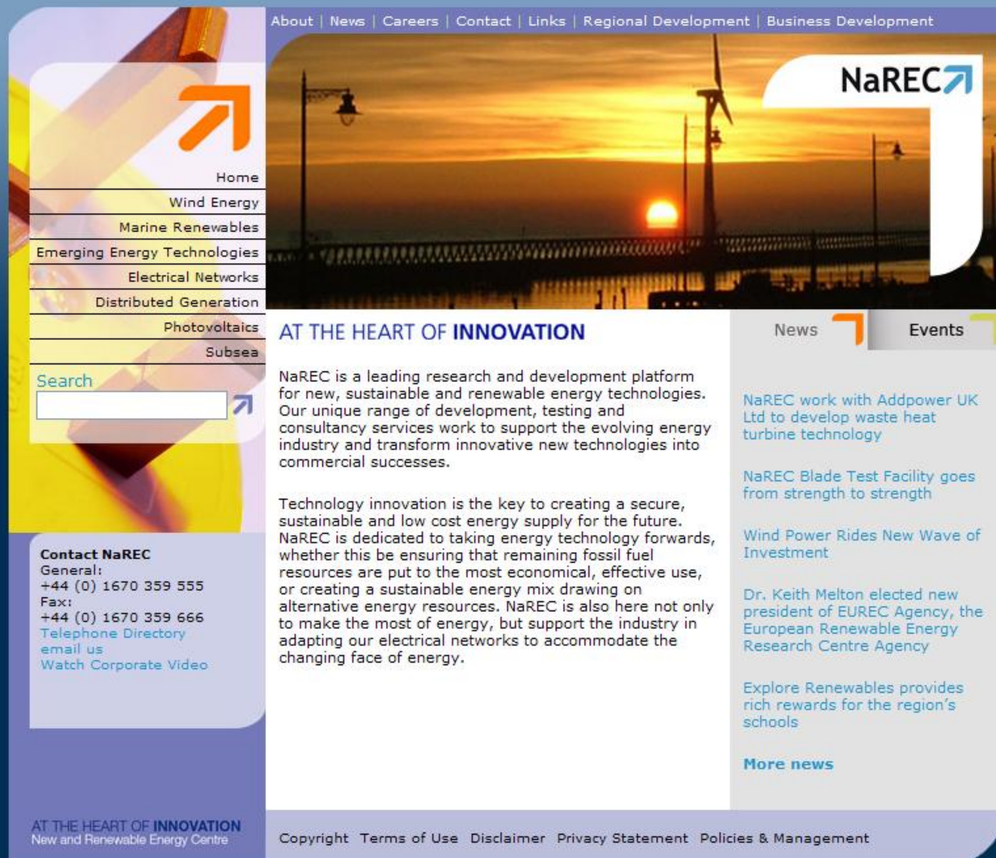
Romag Limited
Leadgate Industrial Estate
Leadgate
Consett
County Durham
DH8 7RS
http://www.powerglaz.co.uk/

City Hall, one of the capitals iconic building, and home of the Greater London Authority and Assembly now generates its own clean electricity from the sun using Romag's PowerGlaz modules

More than 600 bespoke PowerGlaz modules
Designed by Foster and Partners
Installed by Solar Technologies
28 Tonnes of CO_2 emmisions saved when compared with normal fossil fuel electricity
Photo's courtesy of Paul Rapson

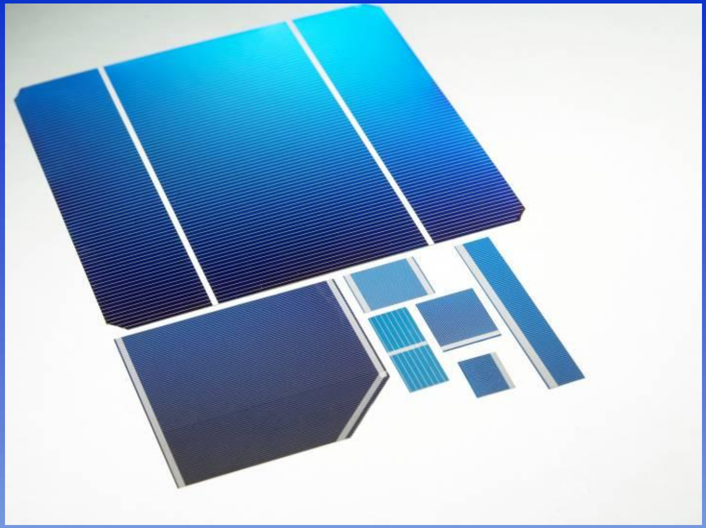


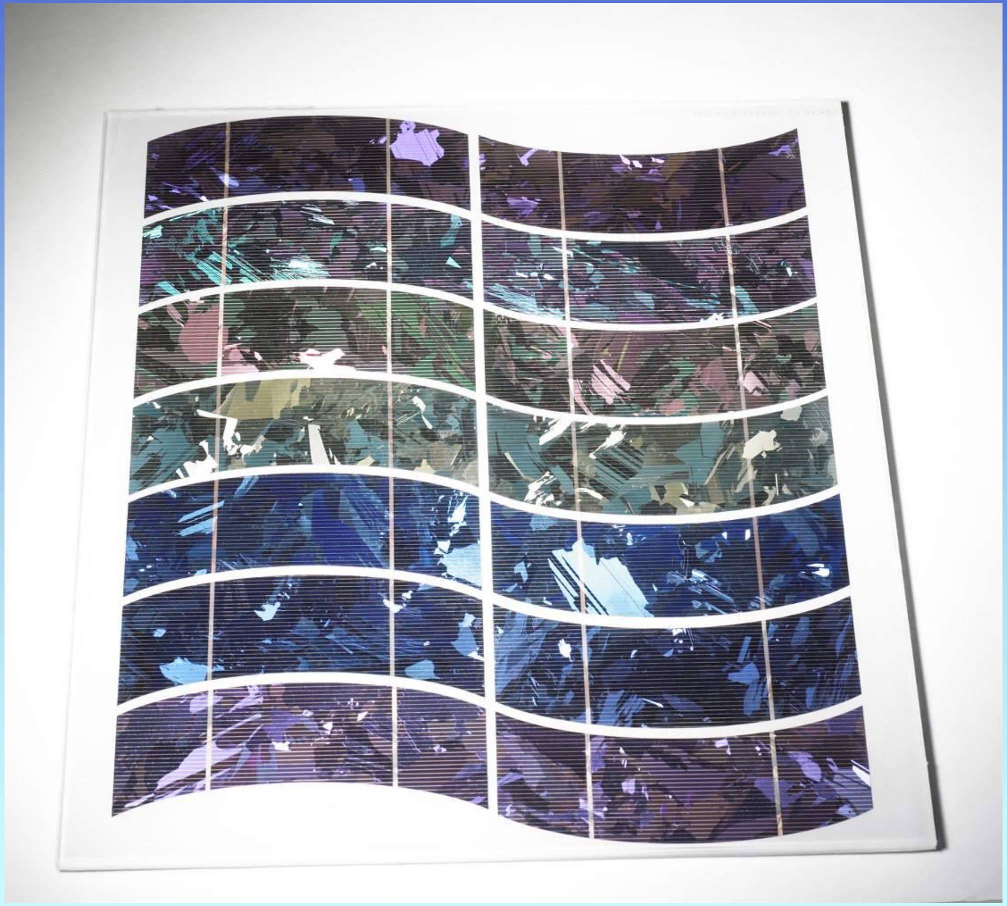
Romag panels - PowerGlaz® Sits Comfortably on the Capital's Seat of Power



Photovoltaics:
Alex Cole
Process Technologist
Alex.cole@narec.co.uk, Phone +44 (0)1670 357 731
http://www.narec.co.uk/main/st1704/photovoltaics.htm


NaREC
Photovoltaics





NPAC Links

National

- PV21 SUPERGEN Consortium (8 UK universities)

International

- Prof. Pearsall Vice President of EUREC Agency
- PV Platform Working Group 3
- EUREC Masters Course
- FP6 Projects ATHLET, PERFORMANCE

• European and IEEE Conference Committees

• Informal links with Universities in Japan (Ritsmuken) and Luxembourg

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Opportunities

General

Rapidly expanding global market potentially the largest of all renewable technologies

Participation in the future requires preparation now

Government national and regional play a vital role in establishing the conditions for the market to grow

Requires a strategic approach, training at all levels – installers, research scientists and policy makers, architects and building products, research into near, medium and long term technologies, public awareness and engagement, market building, infrastructure (grid) and planning, use of demonstrators and systems monitoring, sustainable technologies.

Confidence in a developing market, research and training provide the basis for entrepreneurial activity.

Opportunities

Collaboration and development in several areas

- Technology development (including materials, devices, characterisation)
- Systems monitoring
- Environmental impact
- Training, development and exchange

Summary

- PV rapidly growing renewable energy
- Underlying drivers will remain (energy security, climate change combined with the need for economic growth)
- Applicable worldwide
- Opportunities from systems performance and design to manufacturing training and development of new technologies.
- The current period before grid parity should be seen as an opportunity to prepare for participation in this new technology
- Delay will reduce the potential benefits

Acknowledgements

- Colleagues in NPAC and collaborating institutions
- IOP, RSC and FAPESP
- British Consulate in Sâo Paulo and the Royal Society
- The UK-Brazil Year of Science & Innovation
- EPSRC
- European Commission FP7

Thank You

Contact Details