Materials Research for Zero Emission Buildings

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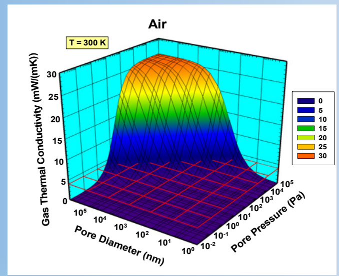
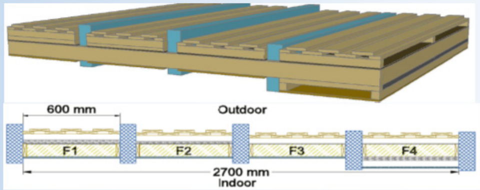
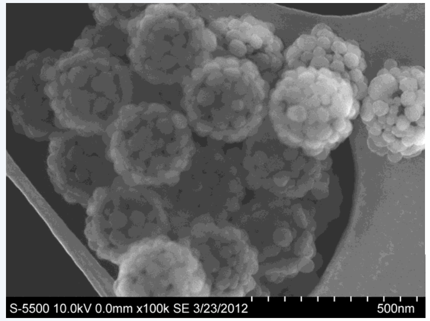
Examples of Materials Research Related to the Building Envelope

With selected commercial examples

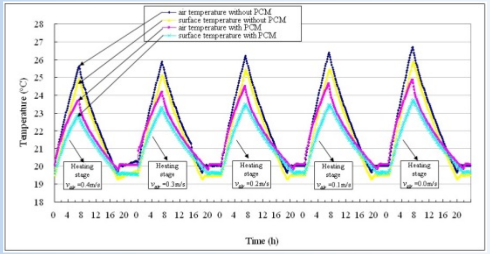
- Thermal Insulation
  - Traditional
  - State-of-the-art
  - Future



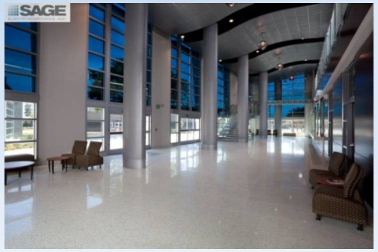


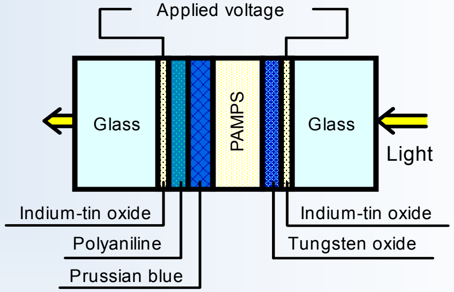


- Phase Change Materials



- Coating and Window Materials and Technologies
  - Low Emissivity Coatings
  - Electrochromic Materials
  - Aerogel Glazing
  - New Glass Materials

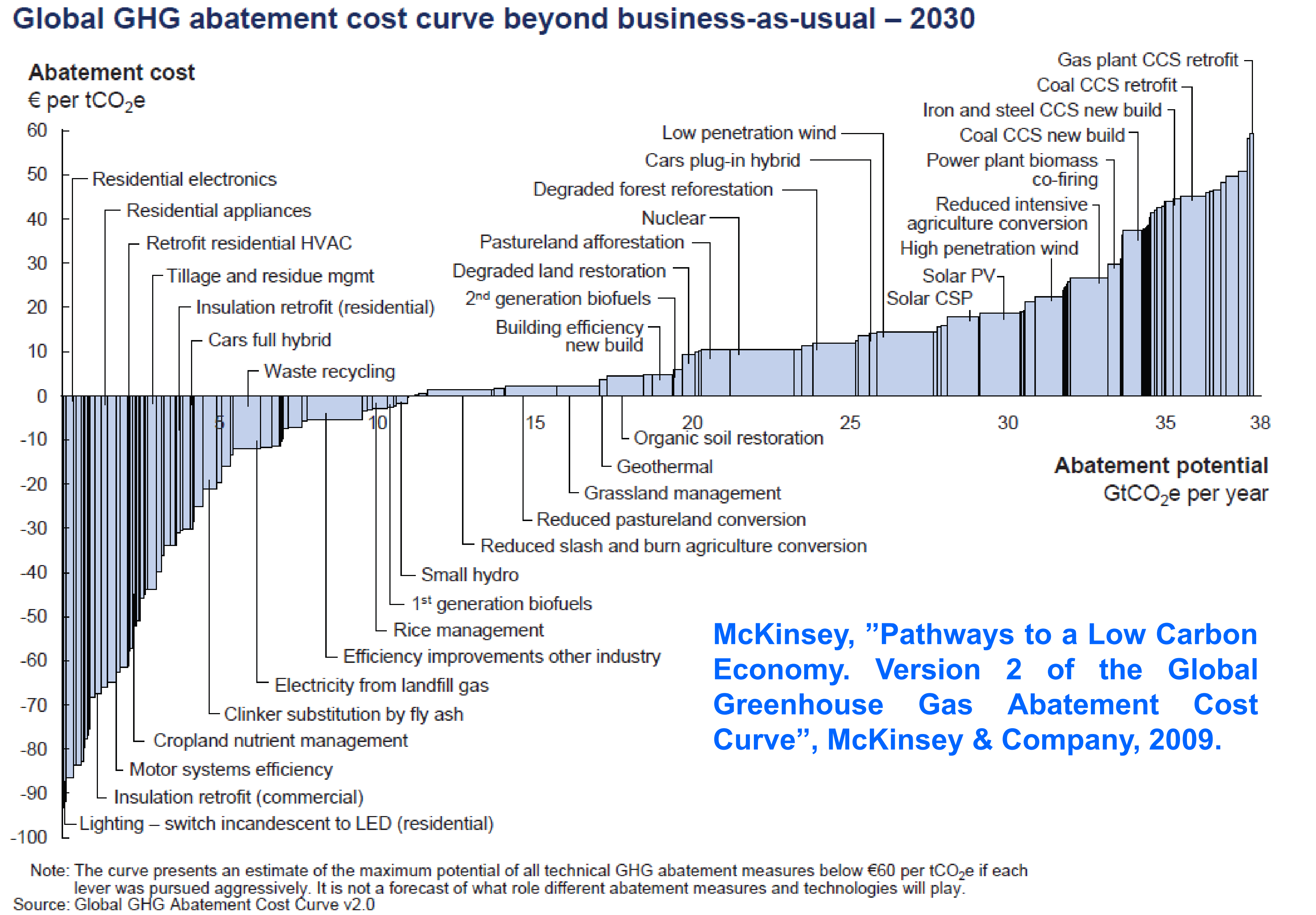




- Building Integrated Photovoltaics (BIPV)
  - Solar Cell Material Properties and Requirements
  - Building Envelope Properties and Requirements

Why is Thermal Insulation Important ?

- What Measures Amounts the Most ?



McKinsey, "Pathways to a Low Carbon Economy. Version 2 of the Global Greenhouse Gas Abatement Cost Curve", McKinsey & Company, 2009.

Thermal Background – Thermal Transport

- Thermal Conductivity Contributions

$$\lambda_{tot} = \lambda_{solid} + \lambda_{gas} + \lambda_{rad} + \lambda_{conv} + \lambda_{coupling} + \lambda_{leak}$$

λ_{tot} = total overall thermal conductivity
λ_{solid} = solid state thermal conductivity
λ_{gas} = gas thermal conductivity
λ_{rad} = radiation thermal conductivity
λ_{conv} = convection thermal conductivity
$\lambda_{coupling}$ = thermal conductivity term accounting for second order effects between the various thermal conductivities
λ_{leak} = leakage thermal conductivity

in mW/(mK)

Traditional Thermal Insulation of Today

- What is Out There?

- **Mineral Wool**
  - Glass wool (fibre glass)
  - Rock wool
  - 30-40 mW/(mK)

- **Expanded Polystyrene (EPS)**
  - 30-40 mW/(mK)

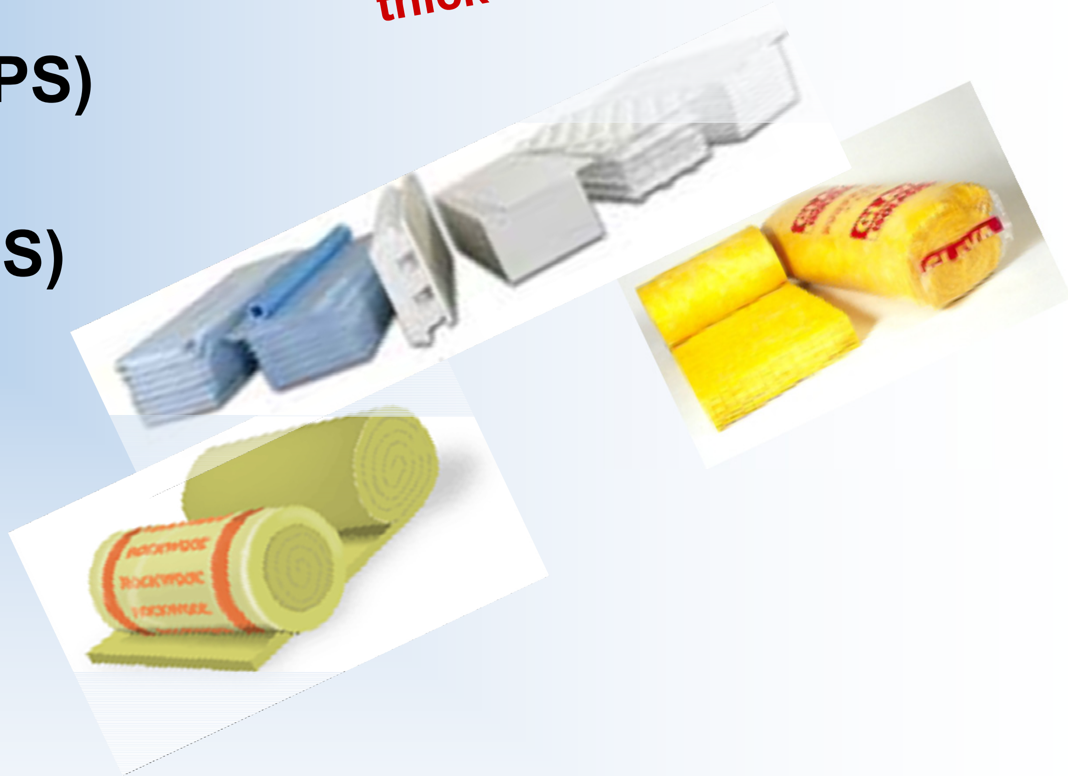
- **Extruded Polystyrene (XPS)**
  - 30-40 mW/(mK)

- **Cellulose**
  - 40-50 mW/(mK)

- **Cork**
  - 40-50 mW/(mK)

- **Polyurethane (PUR)**
  - Toxic gases (e.g. HCN) released during fire
  - 20-30 mW/(mK)

Will often require very thick building envelopes



State-of-the-Art Thermal Insulation of Today

- What is Out There?

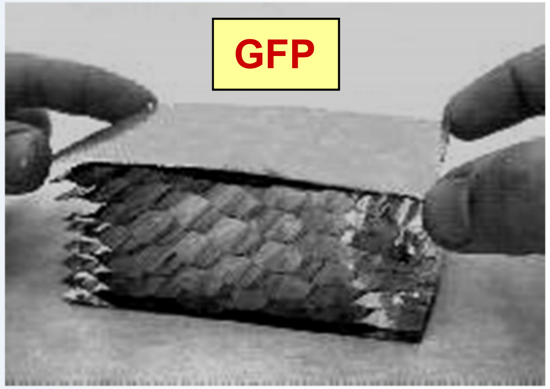
- **Vacuum Insulation Panels (VIP)**
  "An evacuated foil-encapsulated open porous material as a high performance thermal insulating material"
  - Core (silica, open porous, vacuum)
  - Foil (envelope) - 4 - 8 - 20 mW/(mK)

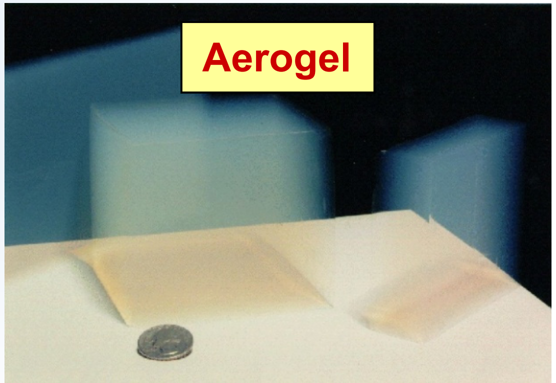
- **Gas-Filled Panels (GFP) - 40 mW/(mK)**

- **Aerogels - 12 - 20 mW/(mK)**

- **Phase Change Materials (PCM)**
  - Solid State ↔ Liquid
  - Heat Storage and Release

- **Beyond State-of-the-Art High Performance Thermal Insulation Materials ?**

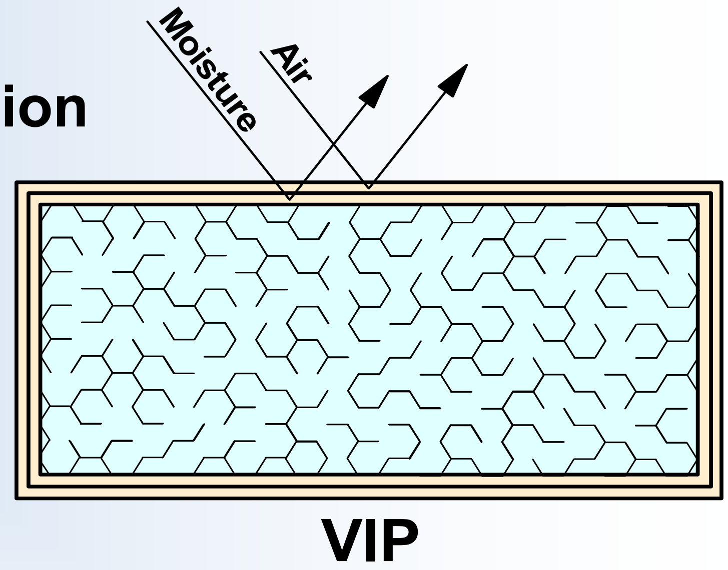




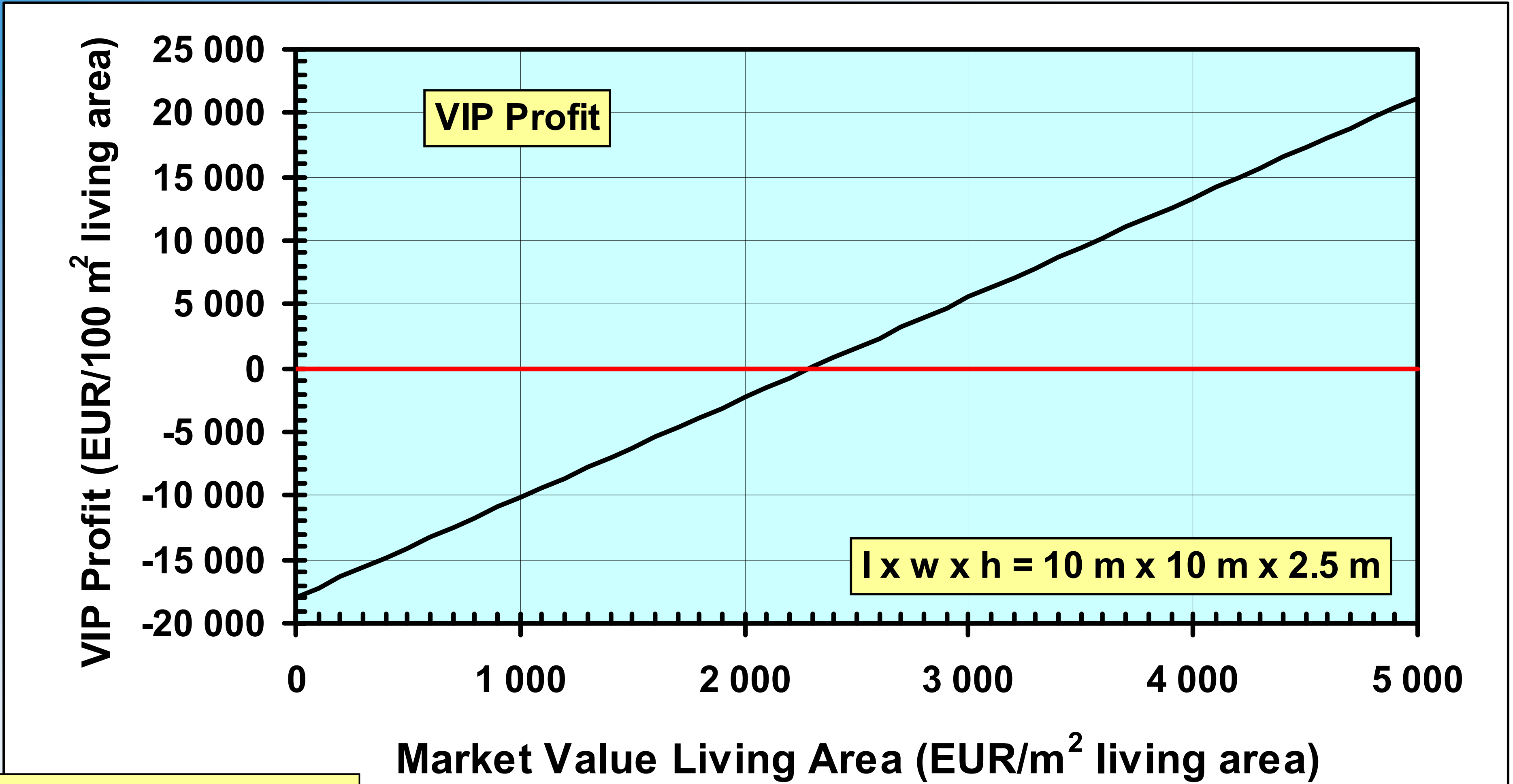
Major Disadvantages of VIPs

- Thermal bridges at panel edges
- Expensive at the moment, but calculations show that VIPs may be cost-effective even today
- Ageing effects - Air and moisture penetration
  - 4 mW/(mK) fresh
  - 8 mW/(mK) 25 years
  - 20 mW/(mK) perforated
- Vulnerable towards penetration, e.g nails
  - 20 mW/(mK)
- Can not be cut or adapted at building site
- Possible improvements?

- Vacuum Core
- Air and Moisture Tight Envelope



Potential Cost Savings by Applying VIPs



- **Assumed example values**
  - Building of 10 m x 10 m
  - Interior floor to ceiling height of 2.5 m
  - 20 cm wall thickness reduction
  - VIP costs 6 cm: 200 EUR/m²
  - Mineral wool costs 35 cm: 20 EUR/m²

B. P. Jelle, "Traditional, State-of-the-Art and Future Thermal Building Insulation Materials and Solutions - Properties, Requirements and Possibilities", *Energy and Buildings*, 43, 2549-2563, 2011.

Concrete – High Thermal Conductivity $\Rightarrow$ Large Heat Loss

- Thermal Conductivity

- Concrete
  - 150 – 2500 mW/(mK)

- Traditional Thermal Insulation
  - 36 mW/(mK)

- Vacuum Insulation Panels (VIPs)
  - 4 mW/(mK)

Possible to decrease the thermal conductivity of concrete?

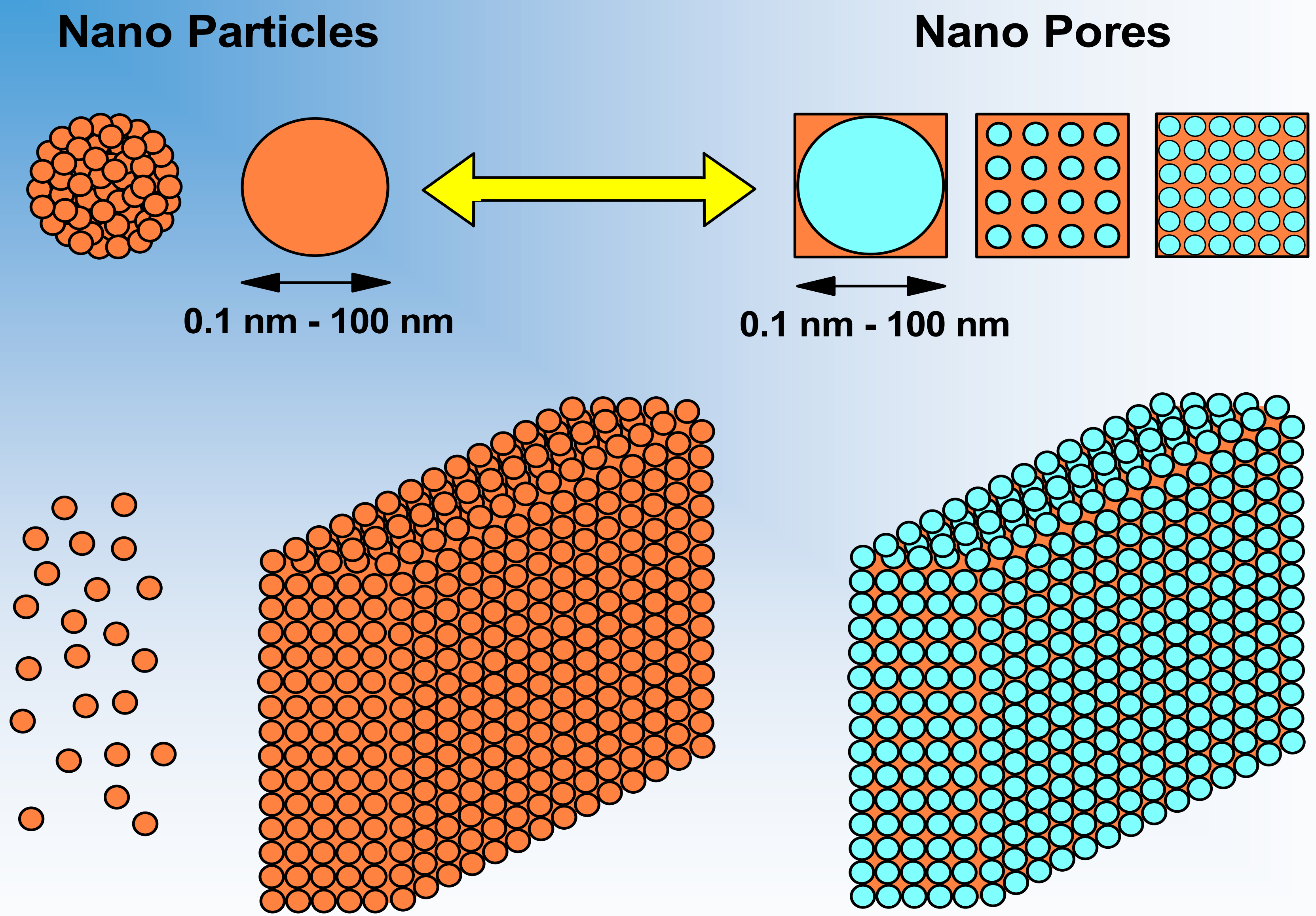
Large CO_2 Emissions from Cement Production

- The cement industry produces 5 % of the global man-made CO_2 emissions of which:
  - 50 % from the chemical process
    - e.g.: $3CaCO_3 + SiO_2 \rightarrow Ca_3SiO_5 + 3CO_2$
      $2CaCO_3 + SiO_2 \rightarrow Ca_2SiO_4 + 2CO_2$
  - 40 % from burning fossil fuels
    - e.g. coal and oil
  - 10 % split between electricity and transport uses

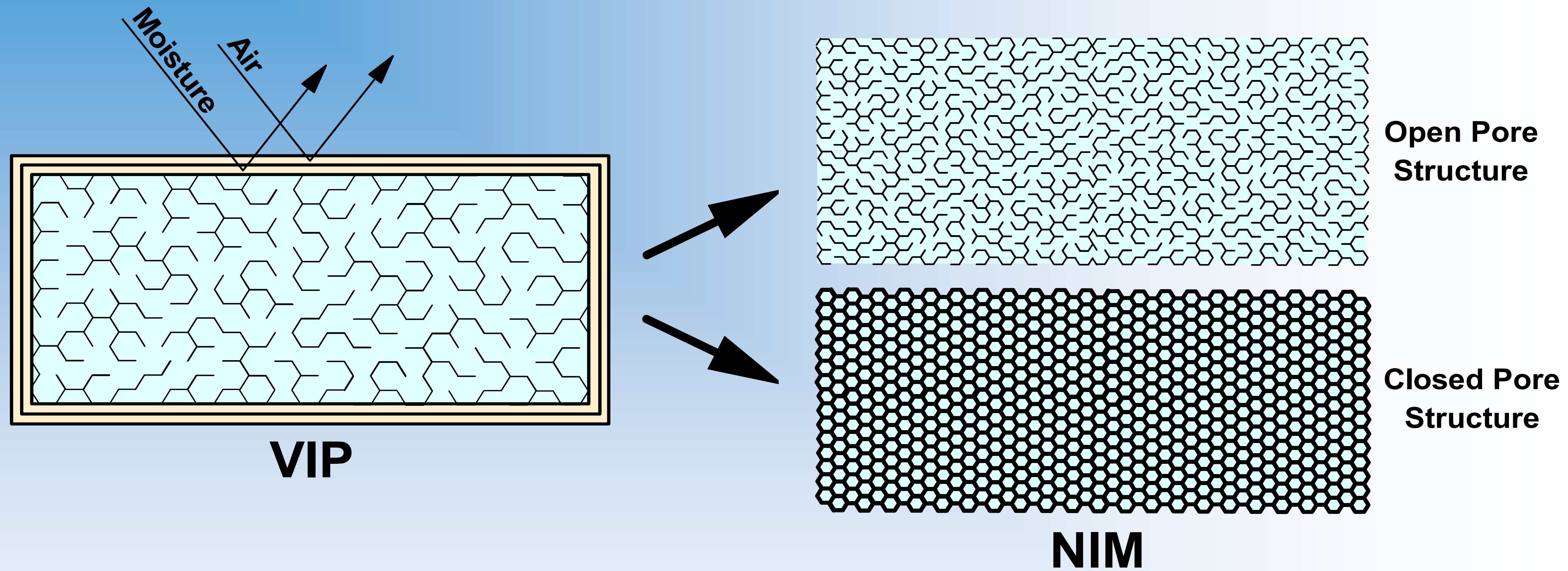
World Business Council for Sustainable Development, ”The cement sustainability initiative – Our agenda for action”, July 2002.

And let us not forget the corrosion issues with reinforced concrete…

Nano Technology and Thermal Insulation



Nano Insulation Material (NIM)



NIM - A basically homogeneous material with a closed or open small nano pore structure with an overall thermal conductivity of less than 4 mW/(mK) in the pristine condition

The Knudsen Effect – Nano Pores

Gas Thermal Conductivity λ_{gas}

$$\lambda_{gas} = \frac{\lambda_{gas,0}}{1+2\beta Kn} = \frac{\lambda_{gas,0}}{1+\dfrac{\sqrt{2}\beta k_B T}{\pi d^2 p\delta}}$$

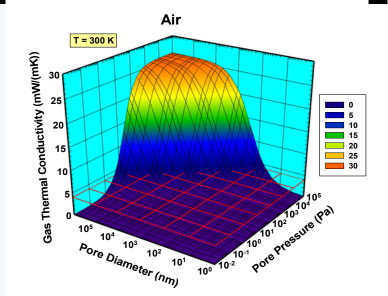
$\sigma_{mean} > \delta$
$\Rightarrow$ low λ_{gas}

where

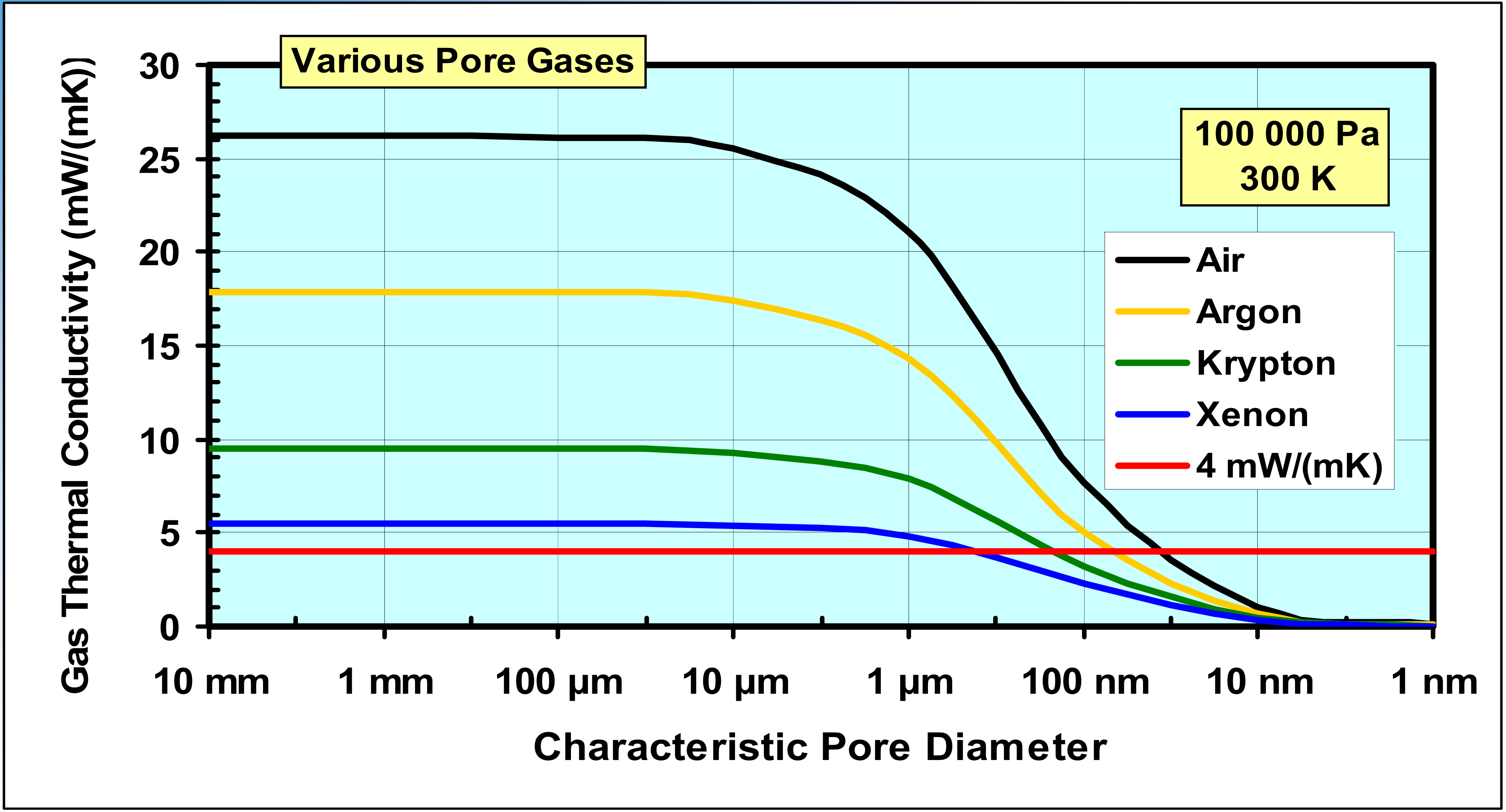
$$Kn = \frac{\sigma_{mean}}{\delta} = \frac{k_B T}{\sqrt{2}\pi d^2 p\delta}$$

λ_{gas} = gas thermal conductivity in the pores (W/(mK))
$\lambda_{gas,0}$ = gas thermal conductivity in the pores at STP (standard temperature and pressure) (W/(mK))
β = coefficient characterizing the molecule - wall collision energy transfer efficiency (between 1.5 - 2.0)
Kn = $\sigma_{mean}/\delta = k_B T/(2^{1/2}\pi d^2 p\delta)$ = the Knudsen number
k_B = Boltzmann's constant $\approx 1.38\cdot10^{-23}$ J/K
T = temperature (K)
d = gas molecule collision diameter (m)
p = gas pressure in pores (Pa)
δ = characteristic pore diameter (m)
σ_{mean} = mean free path of gas molecules (m)

Gas Thermal Conductivity



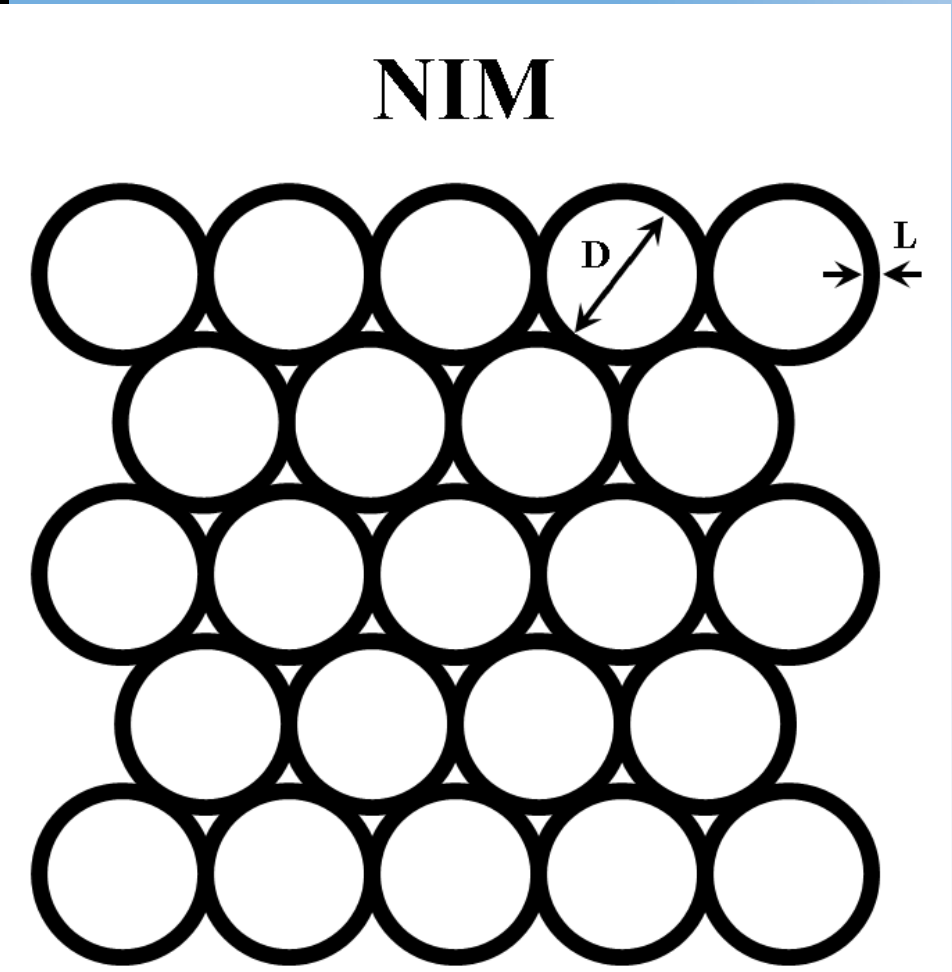
Conductivity vs. Pore Diameter

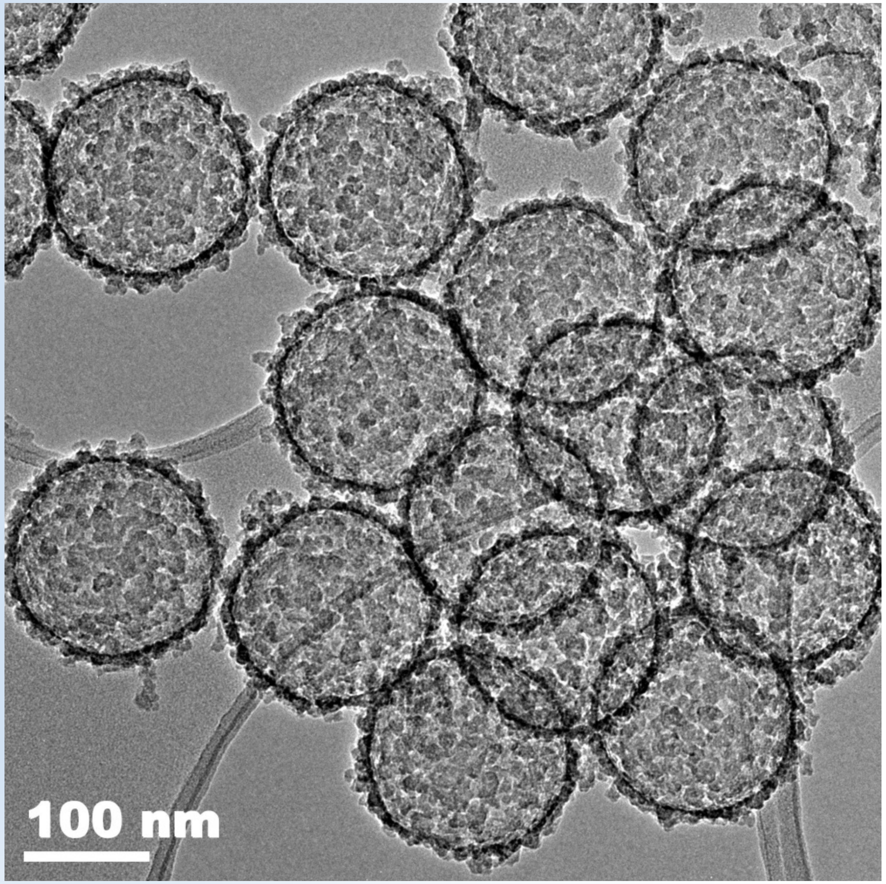


Hollow Silica Nanospheres (HSNS)

Hollow silica nanospheres by making and applying equal-sized templates

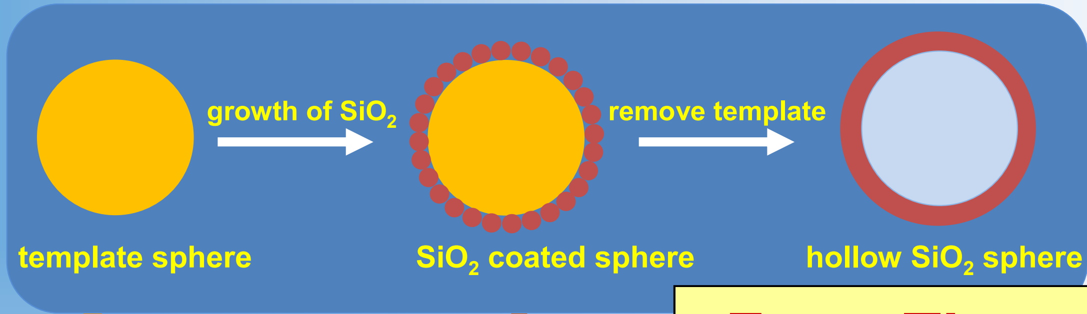
From Theory to Experiment

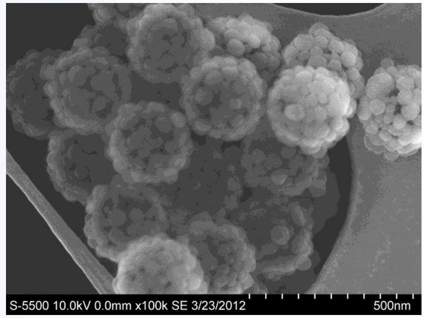




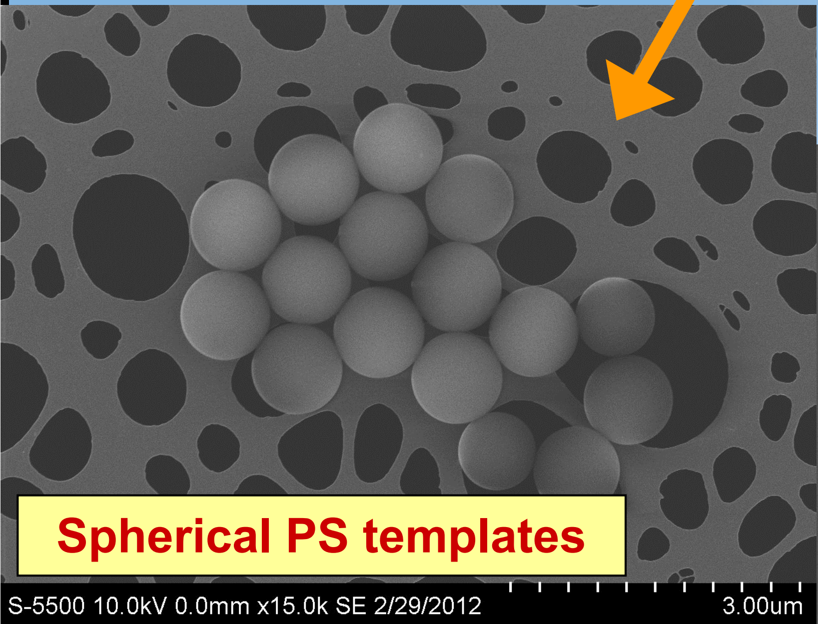
- **Controlling:**
- **Sphere inner diameter**
- **Sphere wall thickness**

Hollow Silica Nanospheres

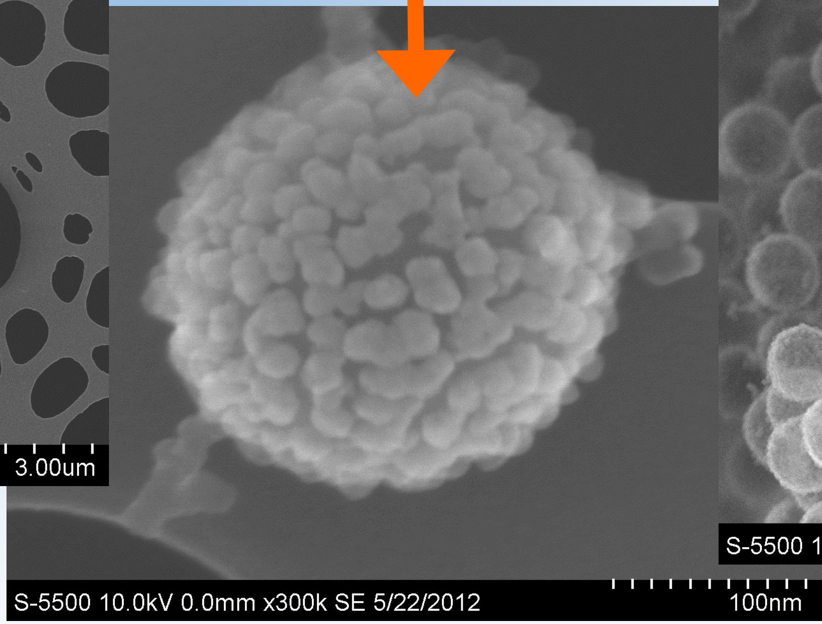




From Theory to Experiment



Spherical PS templates



Small silica particles coated around a spherical PS template

HSNS after removal of PS

SEM Photos

PS = Polystyrene
HSNS = Hollow Silica Nanospheres

To Envision Beyond Concrete ?

- *In the community of concrete it might be compared to using profane language in the church and close to blasphemy to suggest that maybe the answer is not concrete after all… 👍☺*

Emphasis on Properties and Functional Requirements

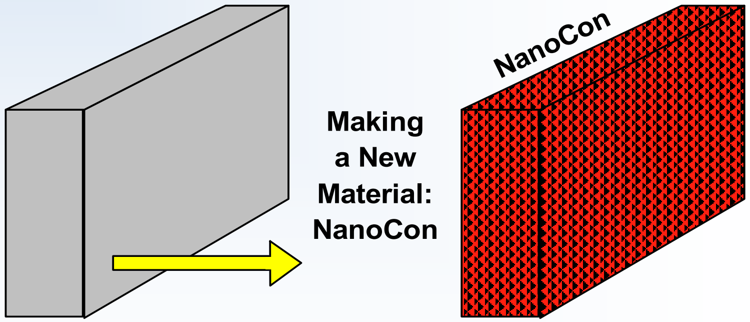
- **Concrete:**
- **High thermal conductivity.**
- **Total thickness of the building envelope will often become unnecessary large (passive house, zero energy building or zero emission building).**
- **Large CO_2 emissions connected to the production of cement.**
- **Prone to cracking induced by corrosion of the reinforcement steel.**
- **Easy accessible and workable, low cost and local production.**
- **High fire resistance.**

- **Is it possible to envision a building and infrastructure industry without an extensive usage of concrete?**

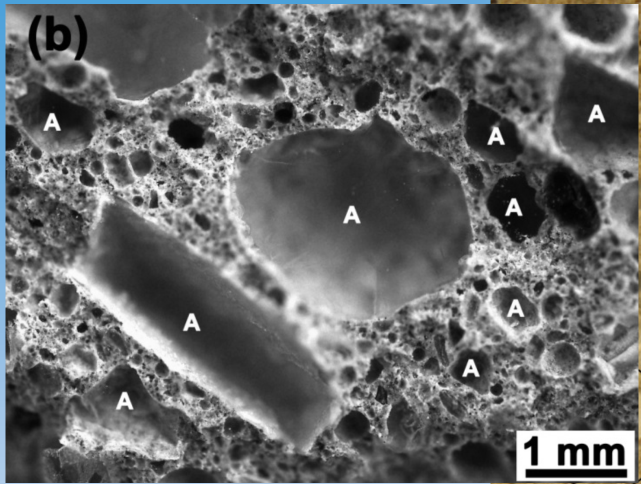
NanoCon – Introducing a New Material

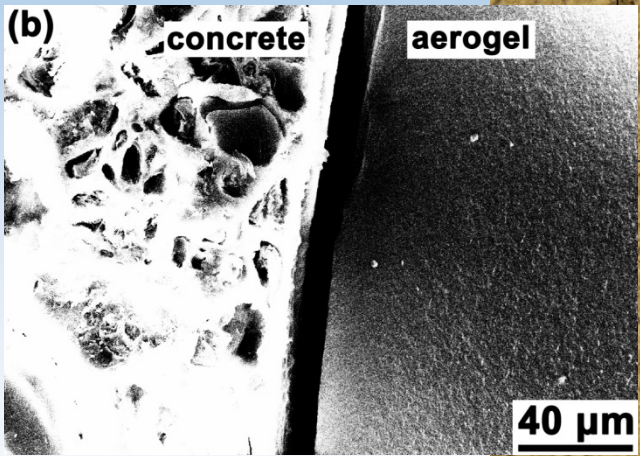
- NanoCon
- Basically a homogeneous material
- Closed or open small nano pore structure
- Overall thermal conductivity < 4 mW/(mK) (or another low value to be determined)
- Exhibits the crucial construction properties that are as good as or better than concrete.
  - Utilize carbon nanotubes (CNT)? Tensile strengths of 63 GPa (measured) and 300 GPa (theoretical). (Steel rebars 500 MPa and concrete 3 MPa.)

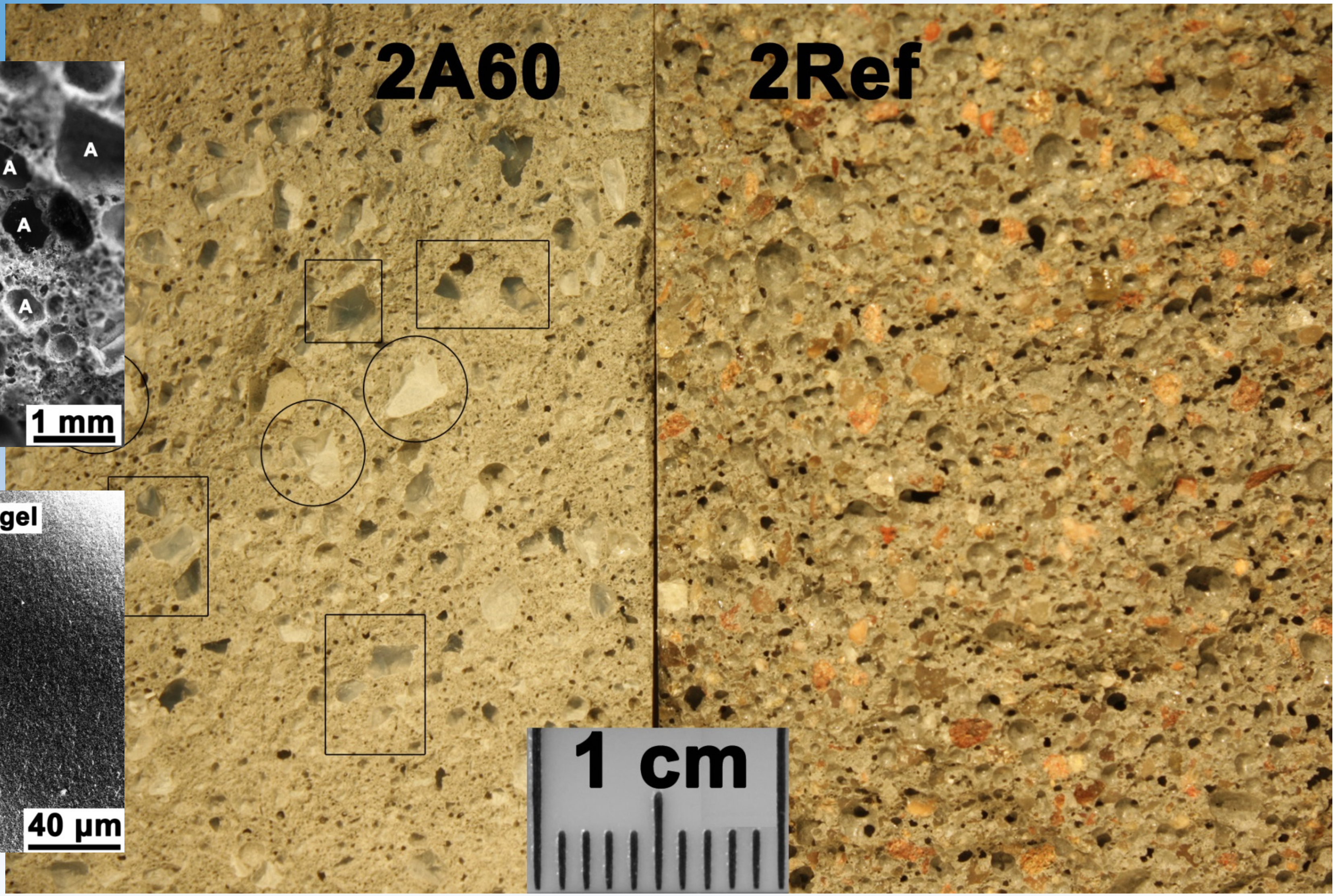
- Essentially, NanoCon is a NIM with construction properties matching or surpassing those of concrete.



The First Step - Aerogel Incorporated Concrete





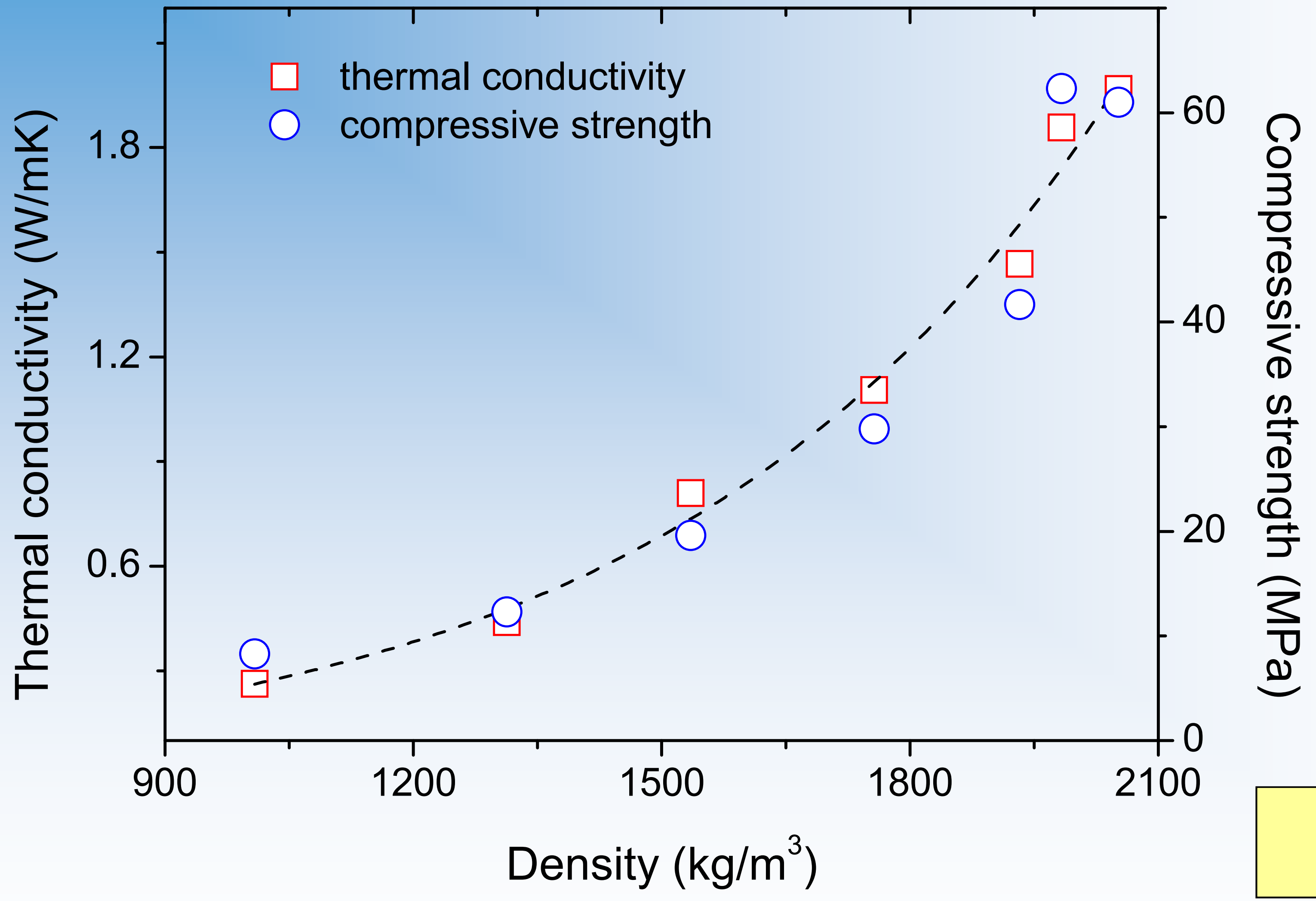


Aerogel in concrete

Reference concrete

Aerogel Incorporated Concrete

Thermal conductivity and compressive strength vs. mass density for varying aerogel content



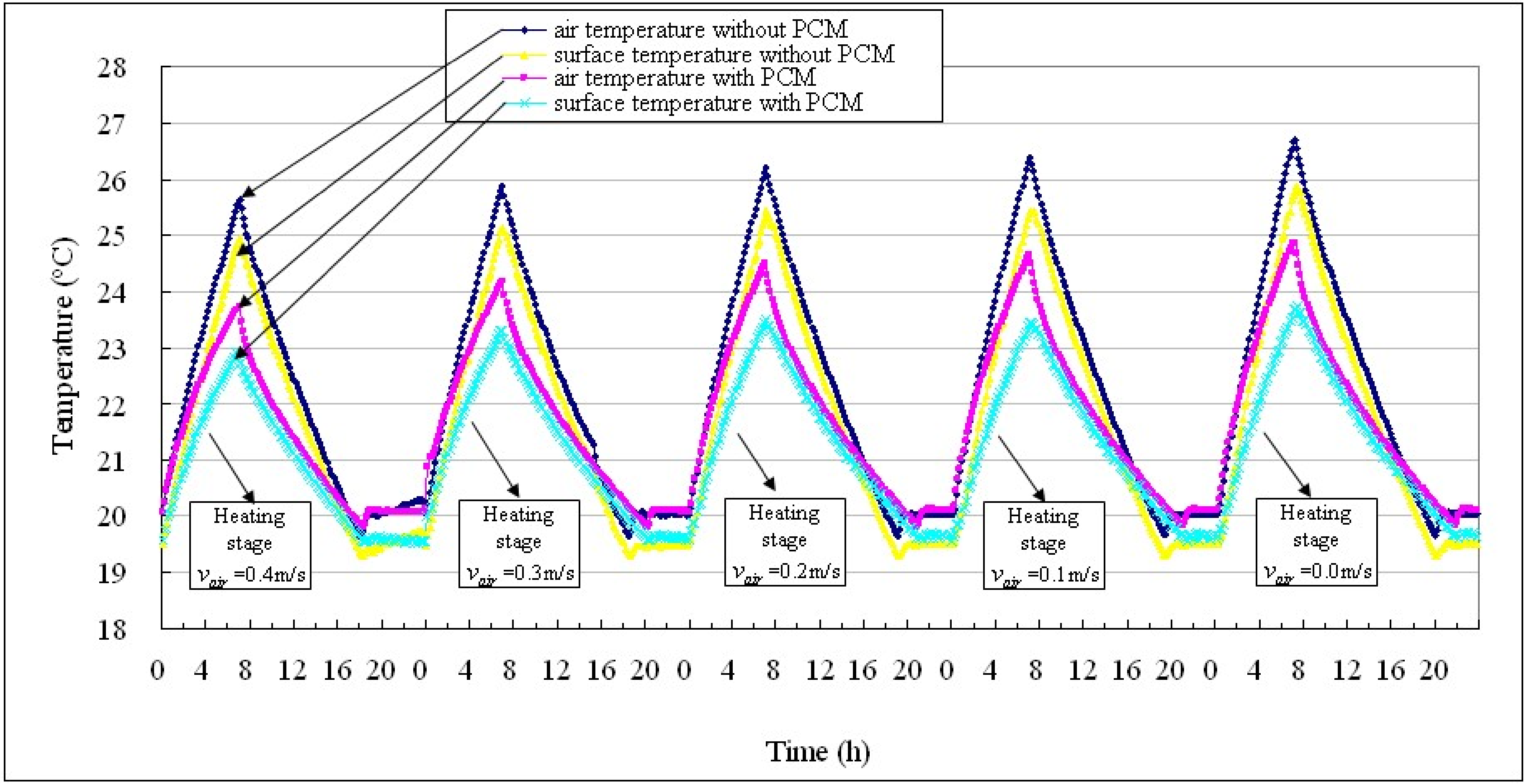
Dashed line = y = Aexp(Bx)

Concrete with NIM – The Path Further Ahead

- Investigate better mixtures of aerogel and concrete.
  - Smaller aerogel granulates.
  - Larger aerogel content (> 60 vol%) in concrete.
- Tailor-make NIM.
  - Pursue the lowest possible NIM thermal conductivity.
  - Incorporation of NIM into concrete.
- Mechanical strengthening remidies.
  - Various carbon nano tubes (CNT) possibilities.
  - Other possibilities.
- Life cycle analysis (LCA).
  - Different concrete og nano material combinations.
  - Comparison with other materials and solutions.

Phase Change Materials (PCM)

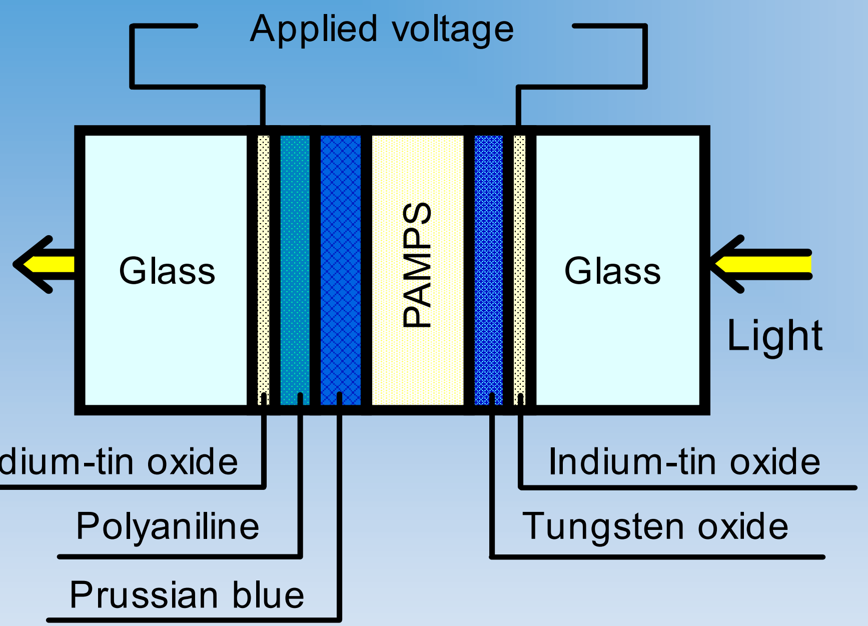
- Solid State ↔ Liquid
- Heat Storage and Release

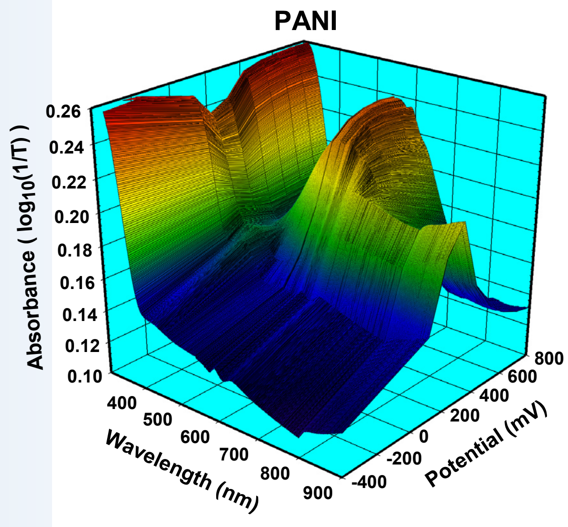


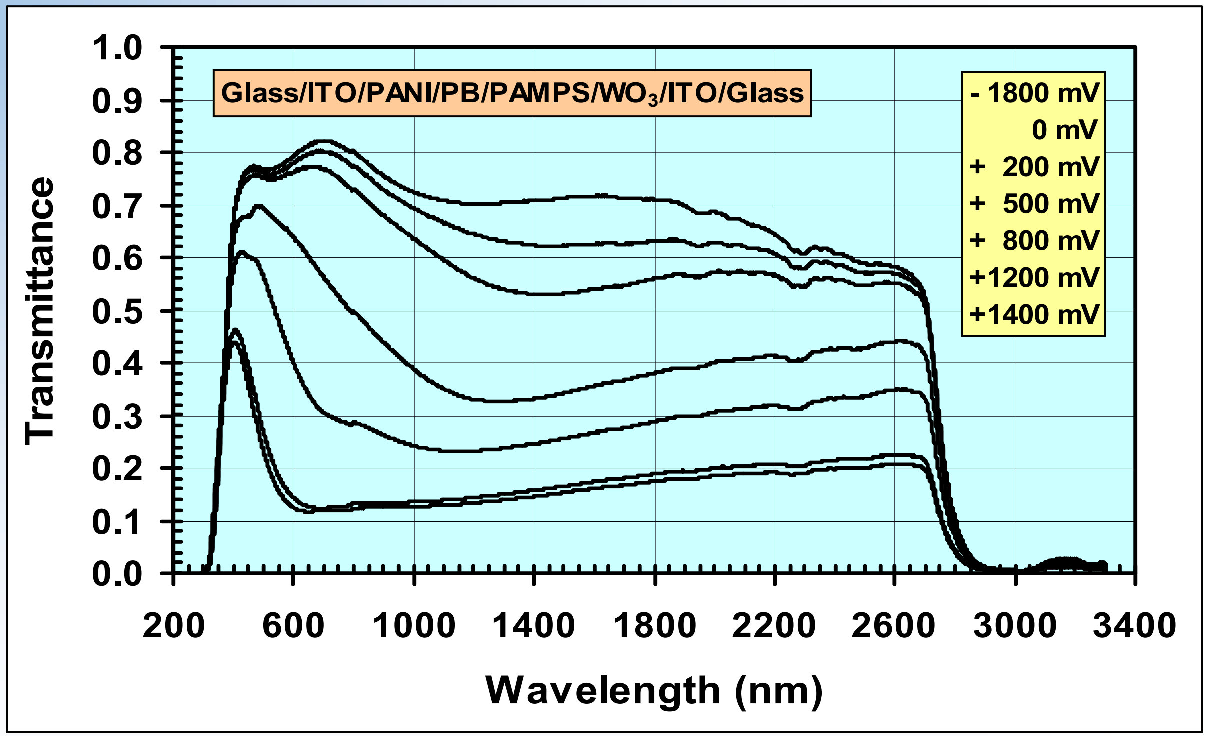
Decreasing the Peak Temperatures

Electrochromic Windows

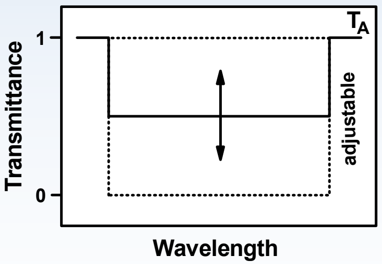
Regulating Solar Radiation Throughput by an External Voltage

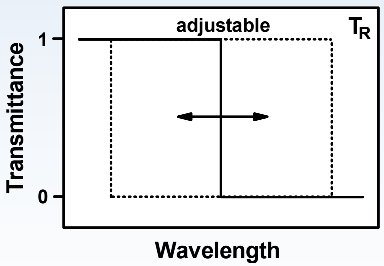






- **Transmittance Regulation by:**
- **Absorbance or Reflectance**

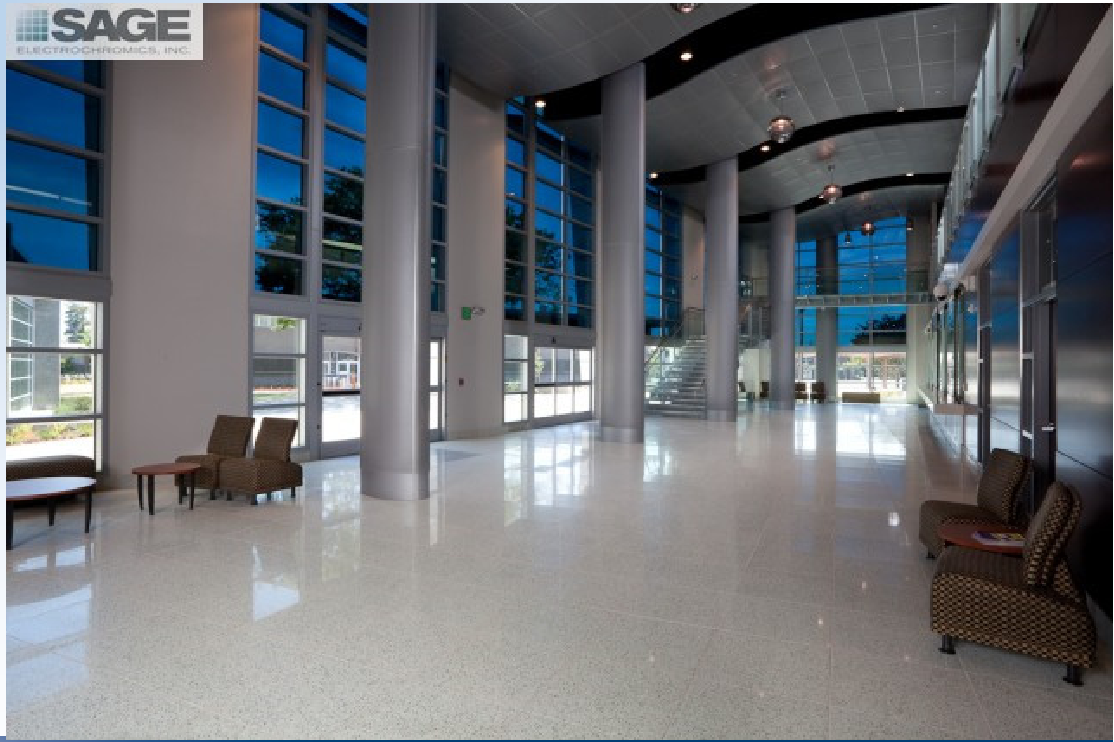




Commercial Electrochromic Windows

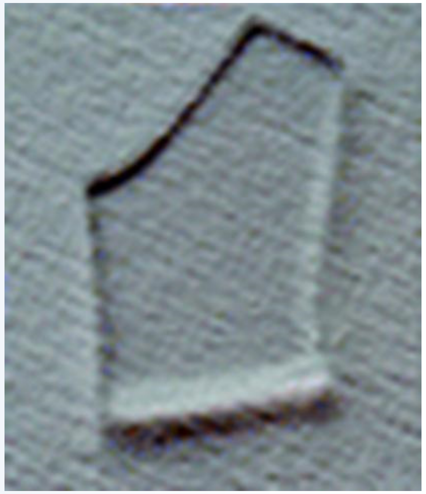
Coloured

Transparent



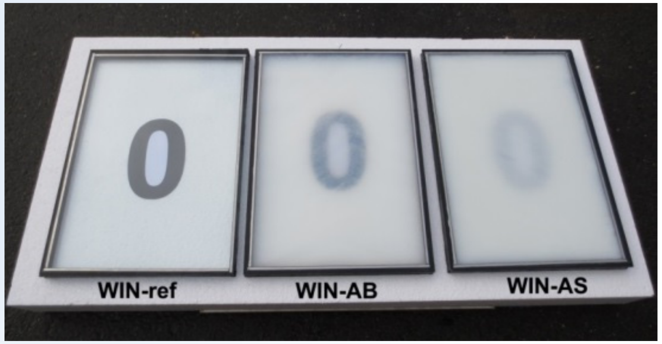
Development of a New Glass Material

- A new glass material has been made: →
- Reduced mass density (weight) by a factor 1.6
- Reduced thermal conductivity by a factor 5.4
- Increased solar transmittance



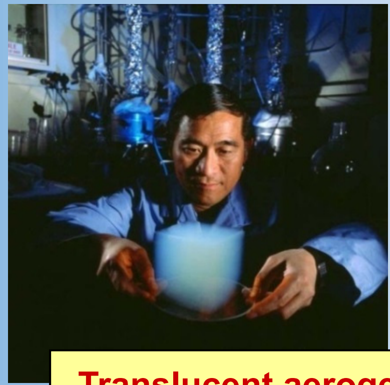
Insulating Glazing with Silica Aerogel Granules

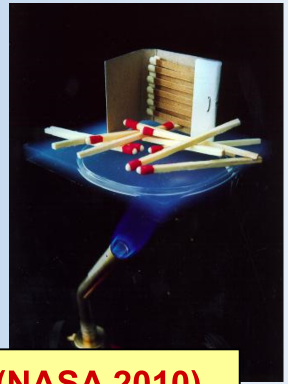
- Miscellaneous investigations:
- Particle size impact
- Convection studies
- Characterization and method development
- Energy and daylight calculations and evaluations



Aerogels

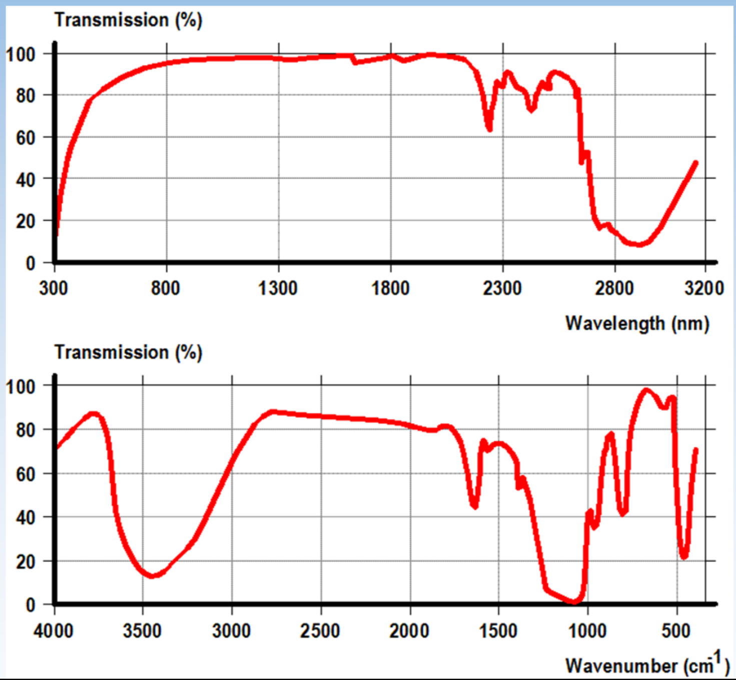
Aerogel for opaque building applications (Aspen Aerogels 2009).





Translucent aerogel (NASA 2010).

Transparent aerogel (although blurred) (Jensen et al. 2004).



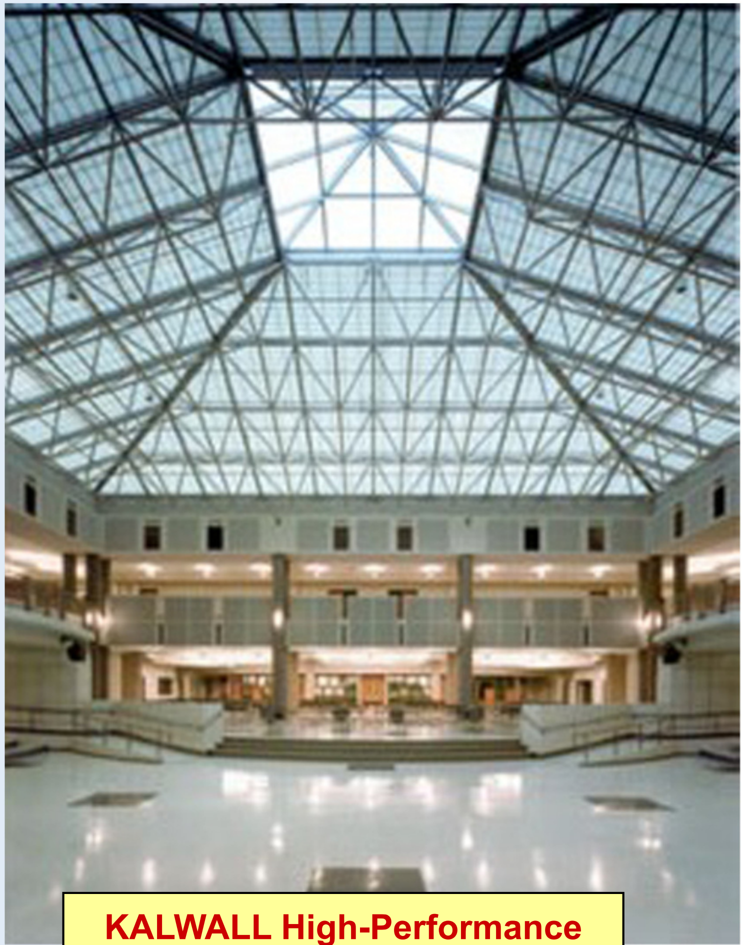
UV-VIS-NIR and IR transmittance of translucent/transparent aerogel (redrawn from Ramakrishnan et al. 2007).

- **Aerogels:**
- Opaque
- Translucent
- Transparent

Transparent aerogel (although blurred) (Airglass 2014).

Aerogels

Translucent aerogel in use in Sculpture Building and Gallery of Yale University, New Haven, Connecticut, USA.

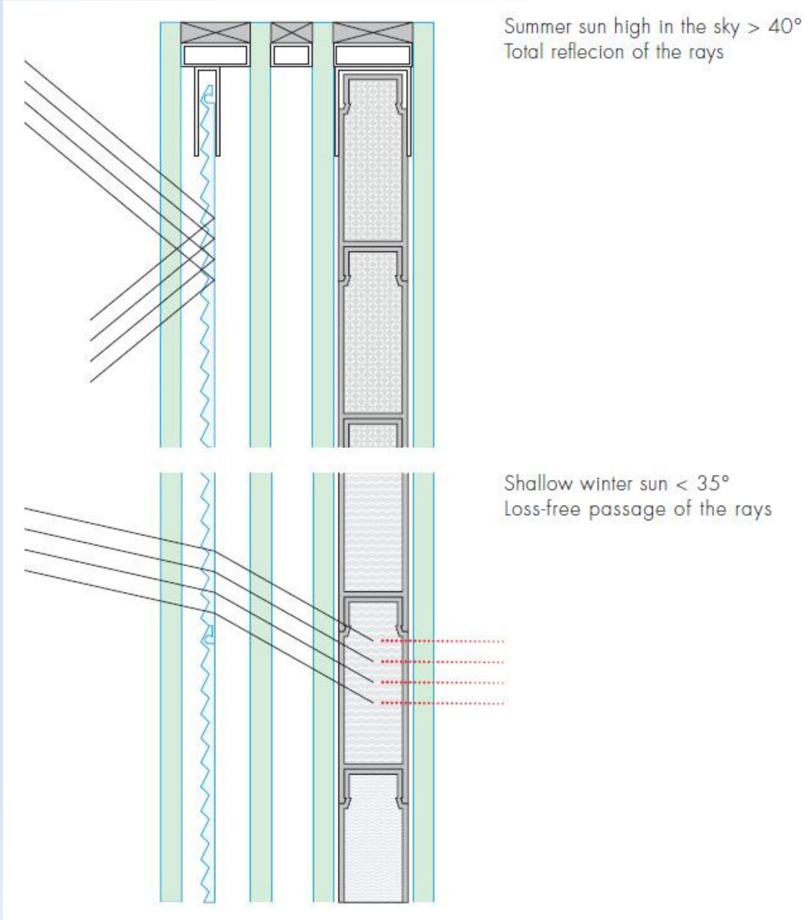


KALWALL High-Performance Translucent Building Systems.

- Aerogels:
- Opaque
- Translucent
- Transparent

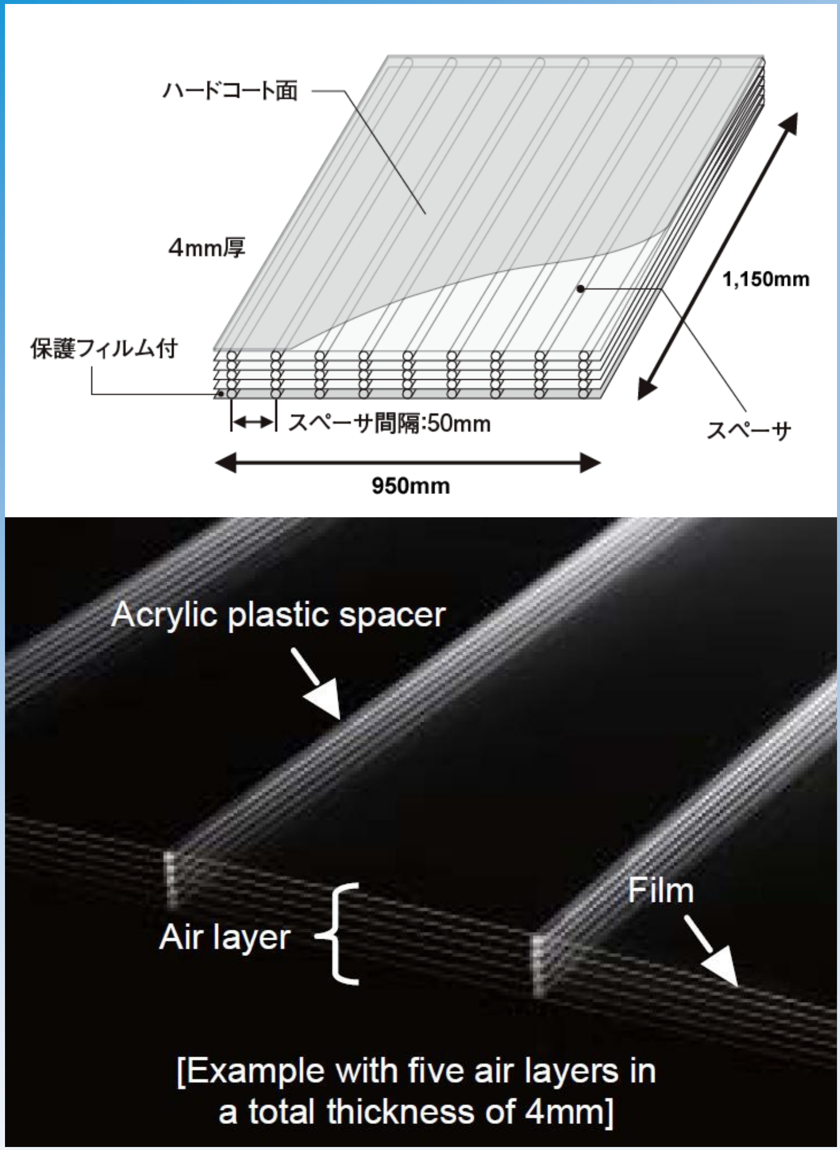
Phase Change Materials (PCM) in Windows

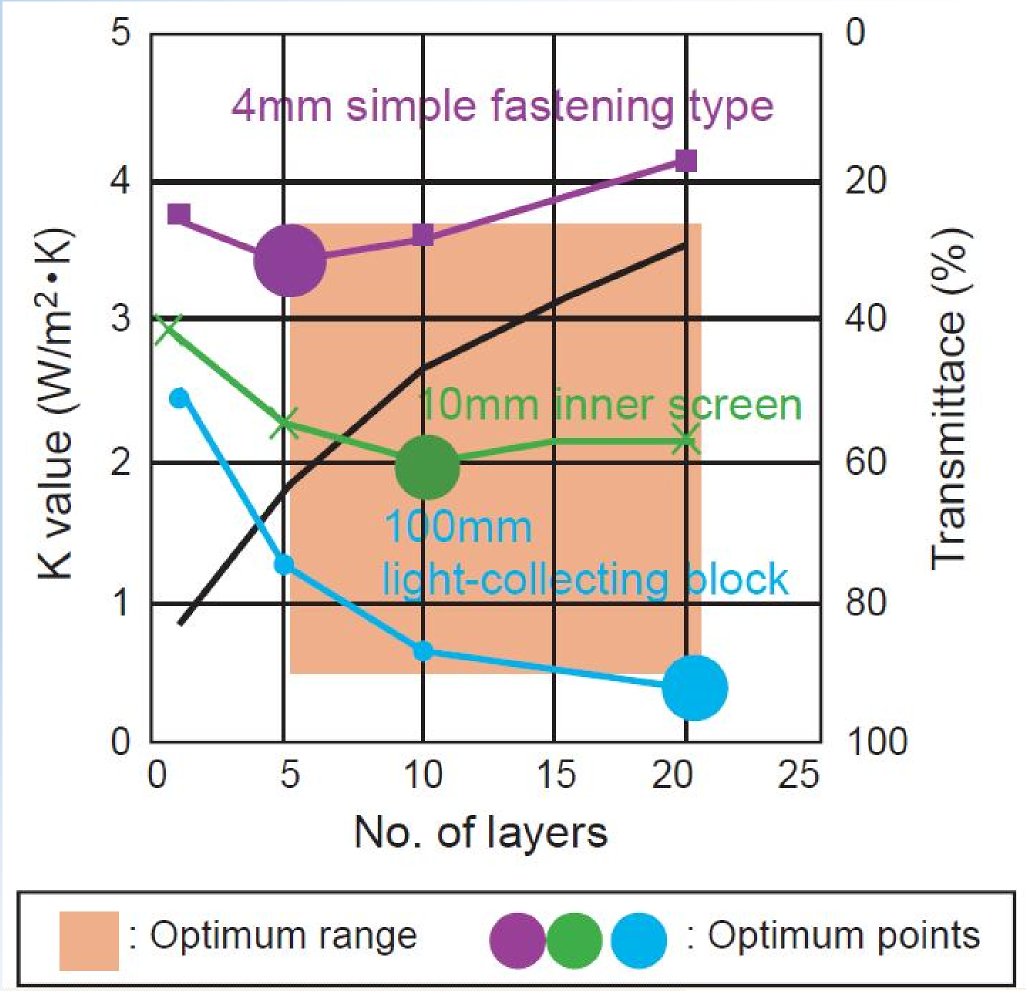
Building with the GlassX crystal translucent wall element incorporating PCMs.



Principal drawing of the GlassX crystal PCM window system.

Air Sandwich



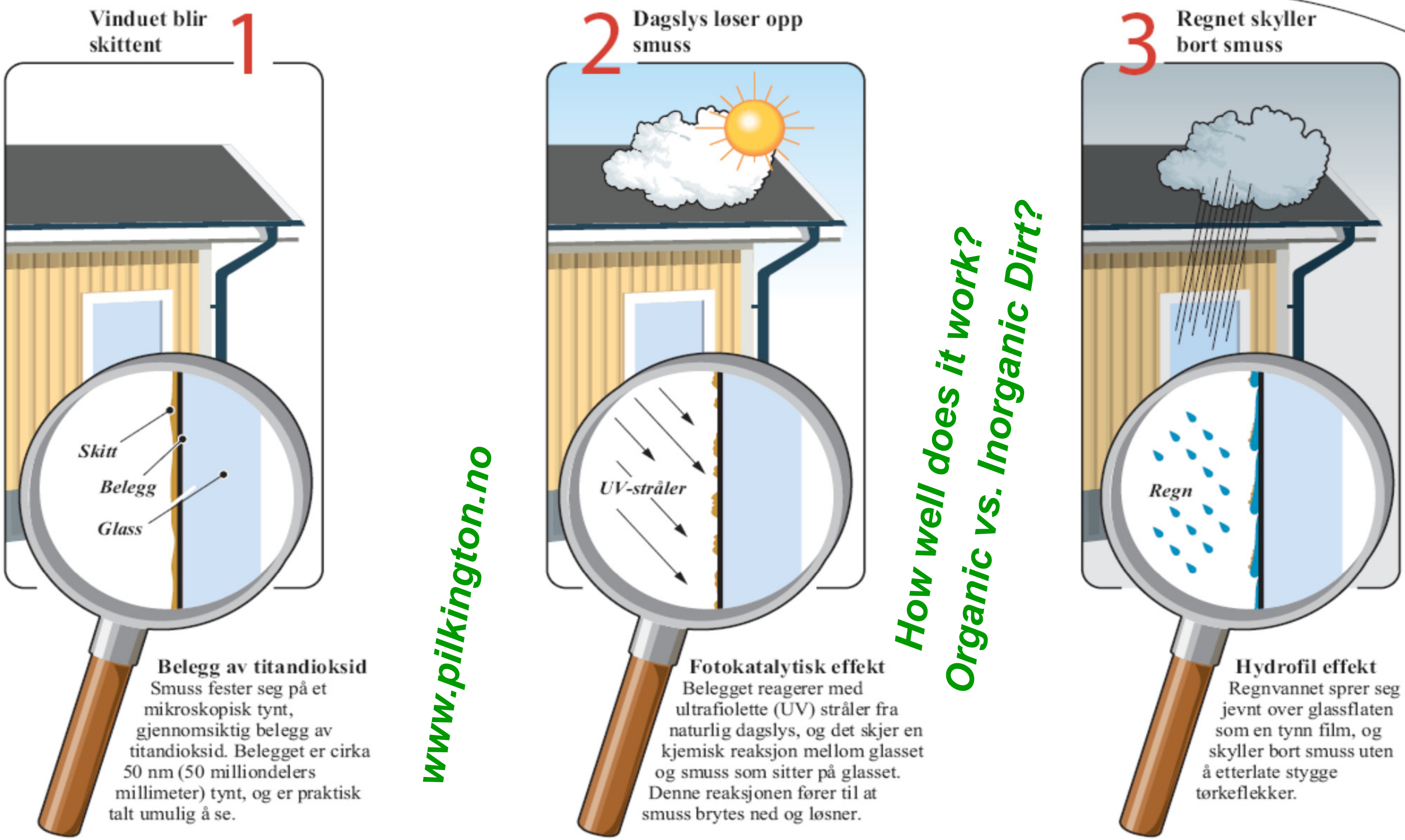


Sekisui air sandwich with principal drawings and U-value and T_{vis} performance with respect to number of air layers divided by thin plastic films. The U-value is depicted for three given fixed widths (i.e. 4, 10 and 100 mm) (Sekisui 2007, 2010).

Glass – Solar Radiation – Self-Cleaning Window Panes

Window Panes Cleaning Themselves? How?

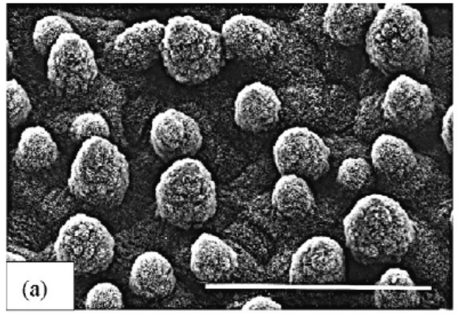
Solar Radiation (UV) + Water + Special Coating (e.g. TiO_2)



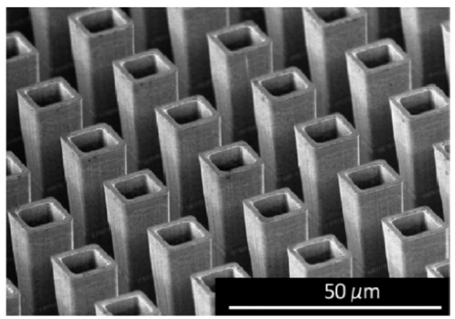
www.pilkington.no

How well does it work?
Organic vs. Inorganic Dirt?

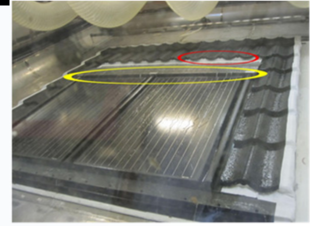
Other Pathways
- Superhydrophobic



From Nature To Artificial



Building Integrated PhotoVoltaics (BIPV)
- Today and Tomorrow

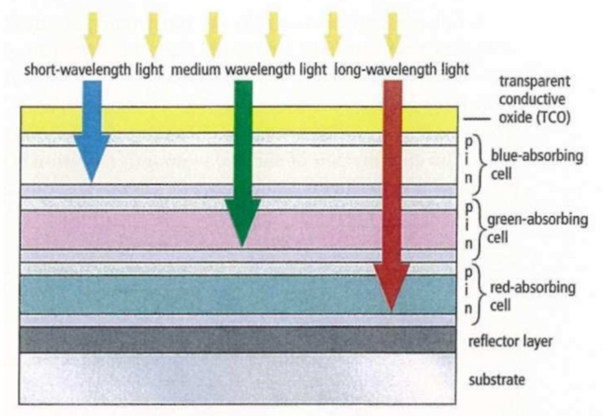


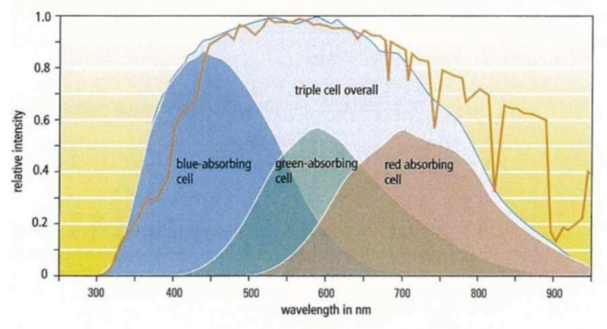
- Replacing the outer building envelope skin, i.e. both a climate screen and a power source generating electricity.

- Fulfil the requirements of both:
  - Building envelope.
  - PV solar cells.

- Durability in general and vs. climate exposure factors.
- Rain, air and wind tightness, various building physical aspects like heat and moisture transport, etc.
- Reducing electricity costs.
- Savings in materials and labour.
- State-of-the-art BIPV products.
- Possible future BIPV research paths.

New Materials and Solutions for BIPV



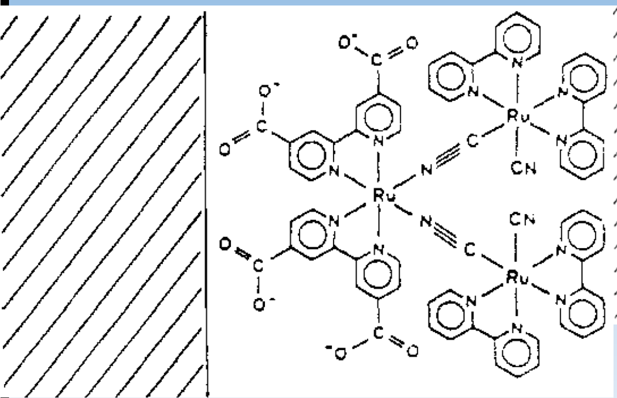


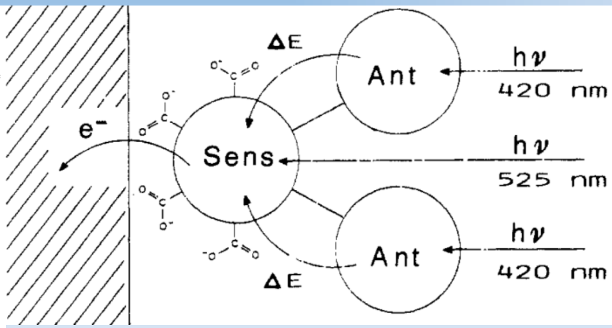
"think thoughts not yet thought of"

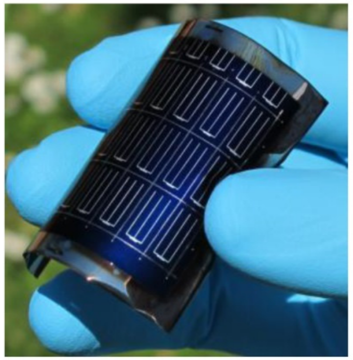
and

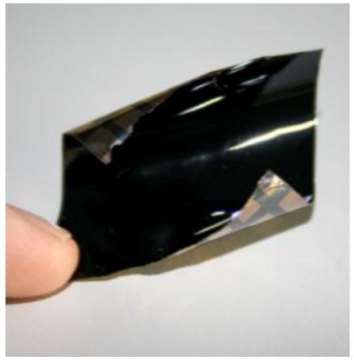
"the more we know the more we know we don't know"

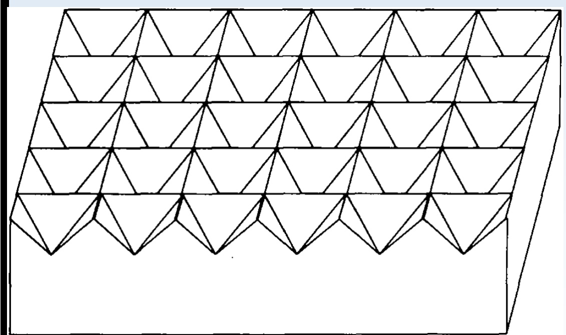
(Jelle et al. 2010).

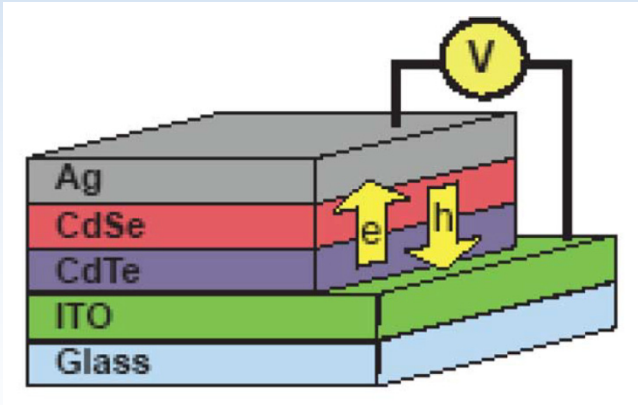


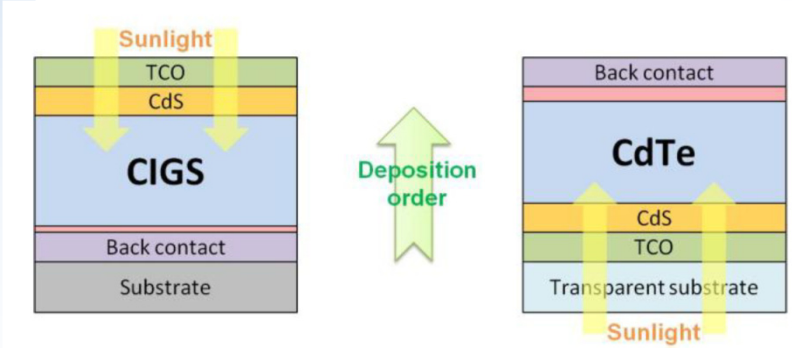




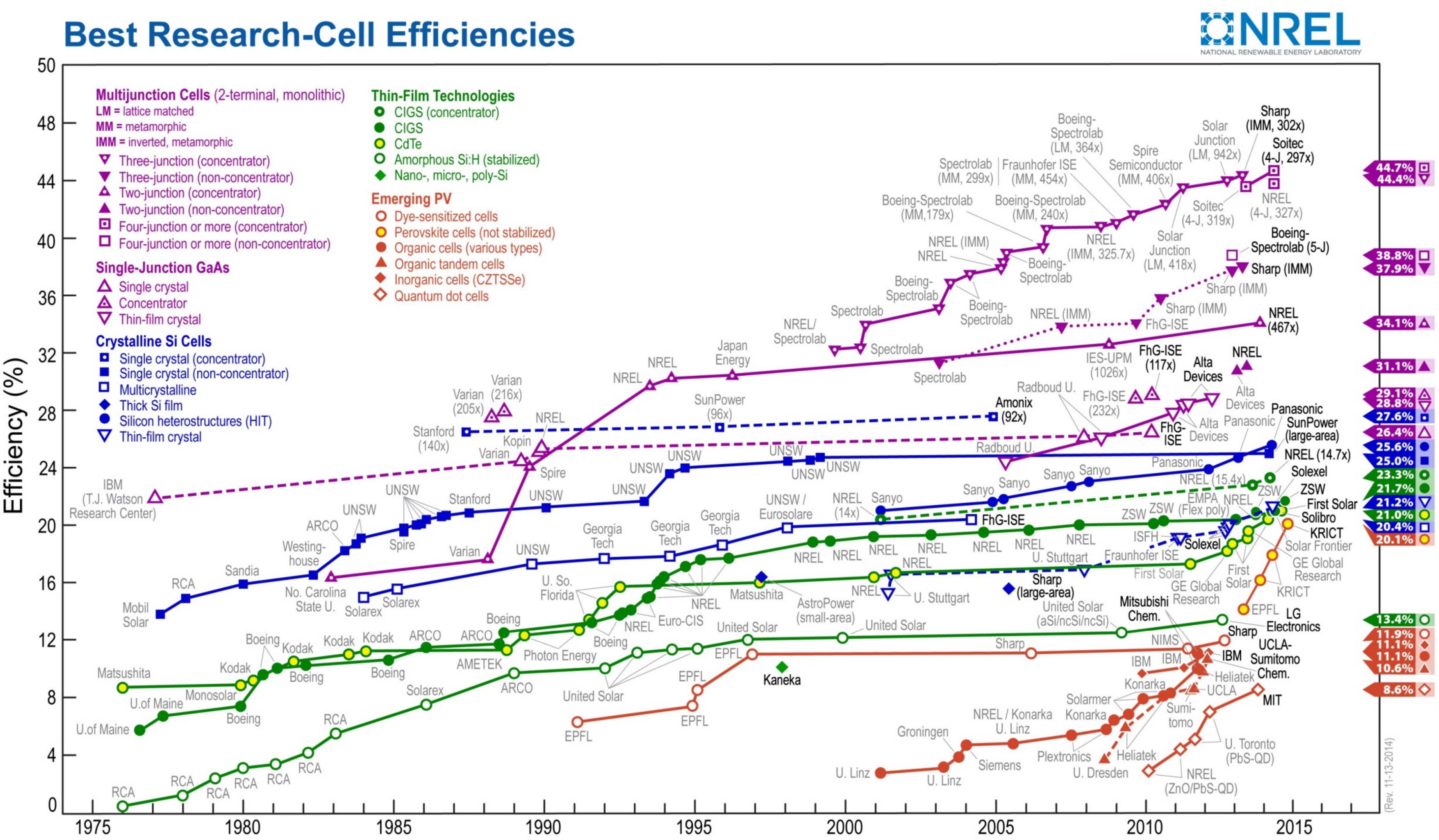








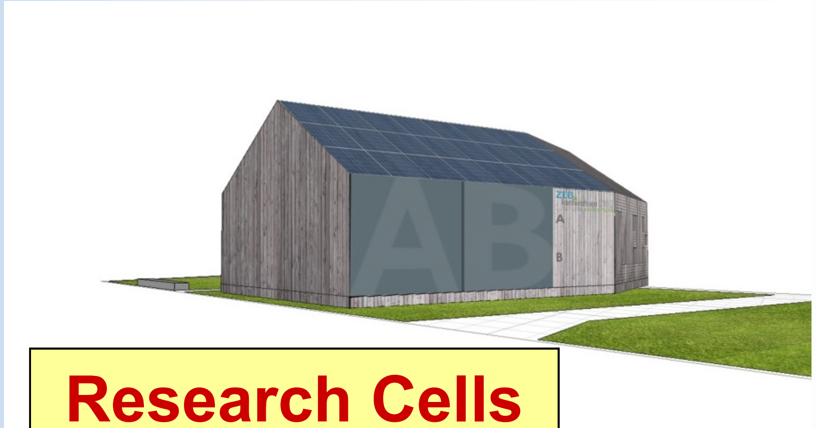
PV Development and Impact on BIPV



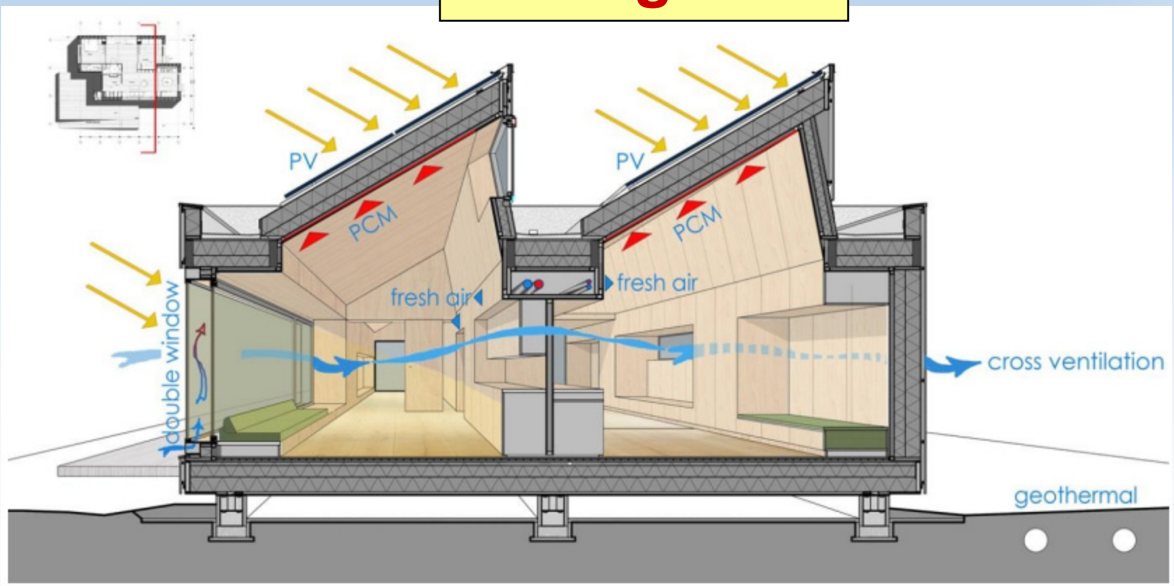
ZEB Living Lab and ZEB Research Cells

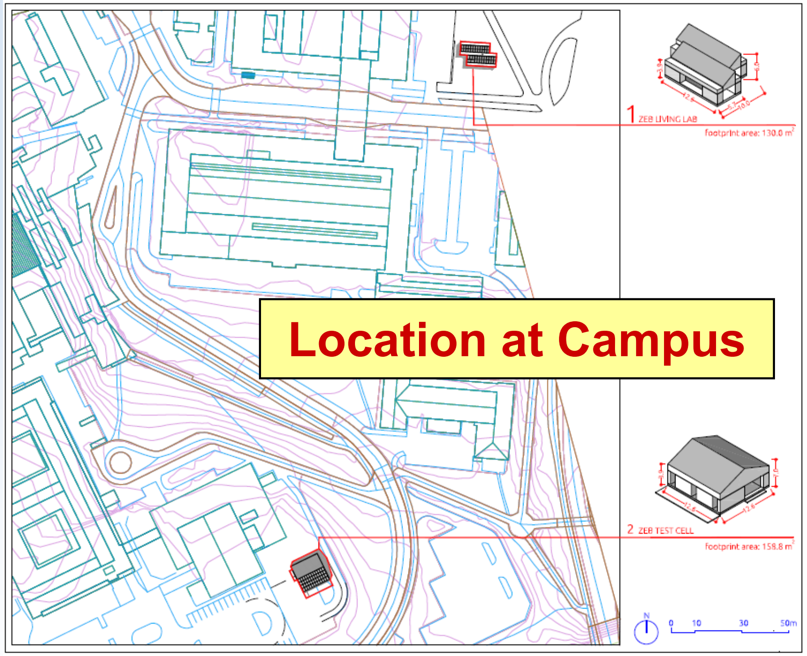
- Establishment of Research Buildings at NTNU Campus

Living Lab



Research Cells





Location at Campus

Conclusions

- **Materials Research for Zero Emissions Buildings**
  - Developing New Materials
  - Functions, Properties and Requirements
  - Material, Component and Building Level
  - Material Scarcity, Embodied Energy, Environmental Impact
  - Life Cycle Assessment
- **Many Topics to be Considered**
  - Thermal Insulation
  - Phase Change Materials
  - Coating and Window Materials and Technologies
  - Building Integrated Photovoltaics
  - And many others…!