Institute for Sustainable Energy and the Environment (I-SEE)
University of Bath

The continuing role of hydrocarbon fuels in any transition to a sustainable energy future

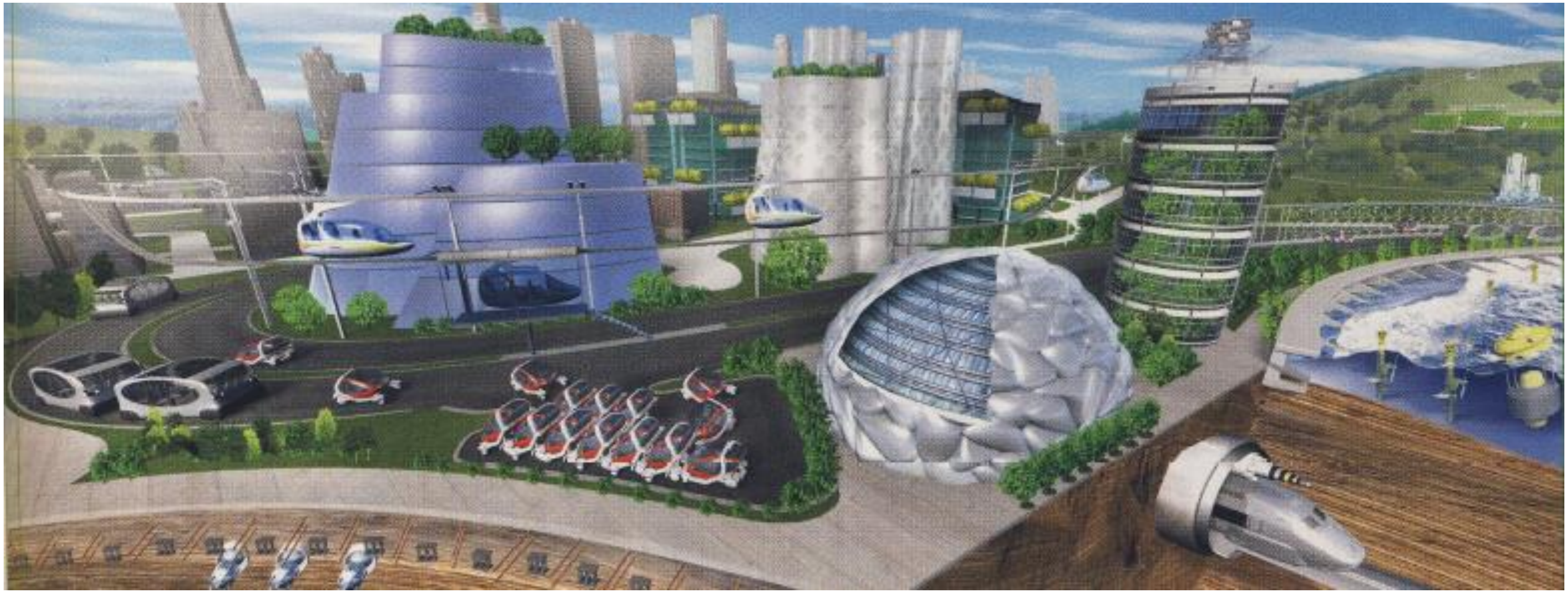
Peter P. Edwards
20th March 2018

‘ExxonMobil bows to shareholder pressure on climate reporting’

‘Shareholders should help deliver decarbonisation’

Financial Times, December 4, 2017

GREEN MEGALOPOLIS



Popular Science, July 2008 (*Courtesy of Kerrie Edwards)*

EXCELLENCE
IN SCIENCE

THE ROYAL SOCIETY

Harnessing the Solar Chariot

Each year the sun supplies 219 quadrillion kilowatt-hours of energy at absolutely no cost. That's 3,000 times more than is consumed by the world's entire population

The central body in our planetary system produces energy in excess. Like a gargantuan fusion reactor, it converts 650 million metric tons of hydrogen into helium every second. The temperature on the surface of the sun is a colossal 5,500 °C (Celsius); each square meter shines brighter than a million light bulbs. Here on earth, we benefit hugely: the sun provides light and warmth, controls our weather and climate, and makes the plants grow.

In a mere 30 minutes the sun supplies us with more energy than the world's population consumes in an entire year—and it does so entirely free of charge. In Germany the average solar radiation is around 1,000 kilowatt-hours per square meter per year; in the desert regions of the world's equatorial zone, it rises to between 2,500 and 3,000, which is the energy equivalent of as much as 300 liters of oil per square meter per year.

At today's efficiencies it would take an estimated 2,000 square kilometers of photovoltaic modules to cover Germany's power needs. The country already has 2,800 square kilometers of available roof surface, one-quarter of which could be used immediately.

Theoretically it would be possible to meet the world's energy needs in full by constructing a gigantic solar farm covering an area of 400 by 400 kilometers of the Sahara.

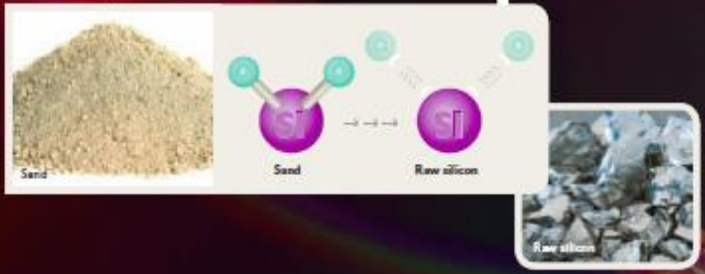
The challenge is to harness this huge potential in a manner that is both technically and economically feasible. We all know that urgent action is required to avert the catastrophic consequences of climate change on earth. That said, the sun is not pressed for time: according to astrophysicists, it will continue shining for another five billion years or so.

From sand to solar cells—the chemistry of photovoltaics

From sand to raw silicon

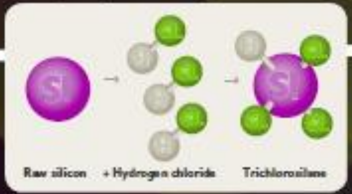
To capture the sun's rays, silicon of a purity of at least 99.999 percent is required. This ensures that the defects and impurities in the crystal lattice are so few that the efficiency of the conversion of solar energy into electricity remains economically attractive.

The first stage is to melt naturally occurring silicon oxide compounds—as a rule, quartz sand—in an electric arc furnace at a temperature of approximately 2,000 °C and then reduce it with coke or coal to raw silicon, which has a purity of between 97 and 99 percent.



From raw silicon to trichlorosilane

Using a new process, Evonik then converts the raw silicon into trichlorosilane. This takes place at the Rheinfelden Plant, Germany, where chlorosilanes (brand name SIRIDION) are traditionally manufactured. The raw silicon is reacted with hydrogen chloride (HCl) to produce trichlorosilane plus the byproduct silicon tetrachloride, which is used in silicic acid (AEROSIL) production at the plant. Evonik has over 60 years of experience in handling chlorosilanes, which are toxic, flammable, and corrosive. Today the company is the world's largest supplier of this class of product.



Purifying trichlorosilane by distillation

Trichlorosilane is a liquid that can easily be purified by rectification. This, in the language of chemists, is a thermal separation process involving a large number of distillation steps carried out in series. Rectification plants can be operated continuously, and therefore separate much more effectively at a low energy input.

EXCELLENCE IN SCIENCE

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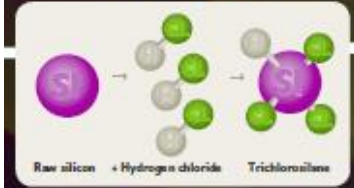

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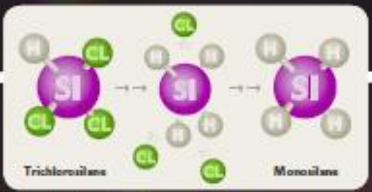


From trichlorosilane to monosilane

The third stage of the process is to convert the purified trichlorosilane into so-called monosilane. This involves a number of parallel reactions. As a rule of thumb, 17 kilograms of trichlorosilane are required to produce one kilogram of monosilane plus 16 kilograms of silicon tetrachloride, which is used in the production of silicic acid at the Rheinfelden Plant.

Purifying monosilane by distillation

Purity is crucial when it comes to generating solar power. The gaseous monosilane is therefore purified once again by means of distillation. Up to this point, the entire process is carried out by Evonik.

Decomposing monosilane to produce solar silicon

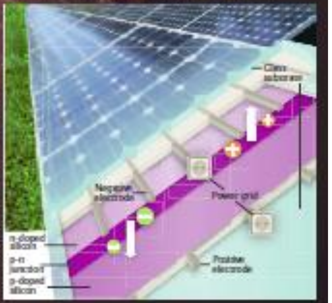
The purified monosilane is then delivered to Joint Solar Silicon (JSSi), a joint venture between Evonik and SolarWorld. The gas is fed into the top of a reactor, where it is split into its elementary constituents, silicon and hydrogen. The latter, a valuable source of energy, is also put to good use at the Rheinfelden Plant. The reactor operates continuously in what is an exceptionally energy-efficient process. The end product is powdered solar silicon of the requisite purity.

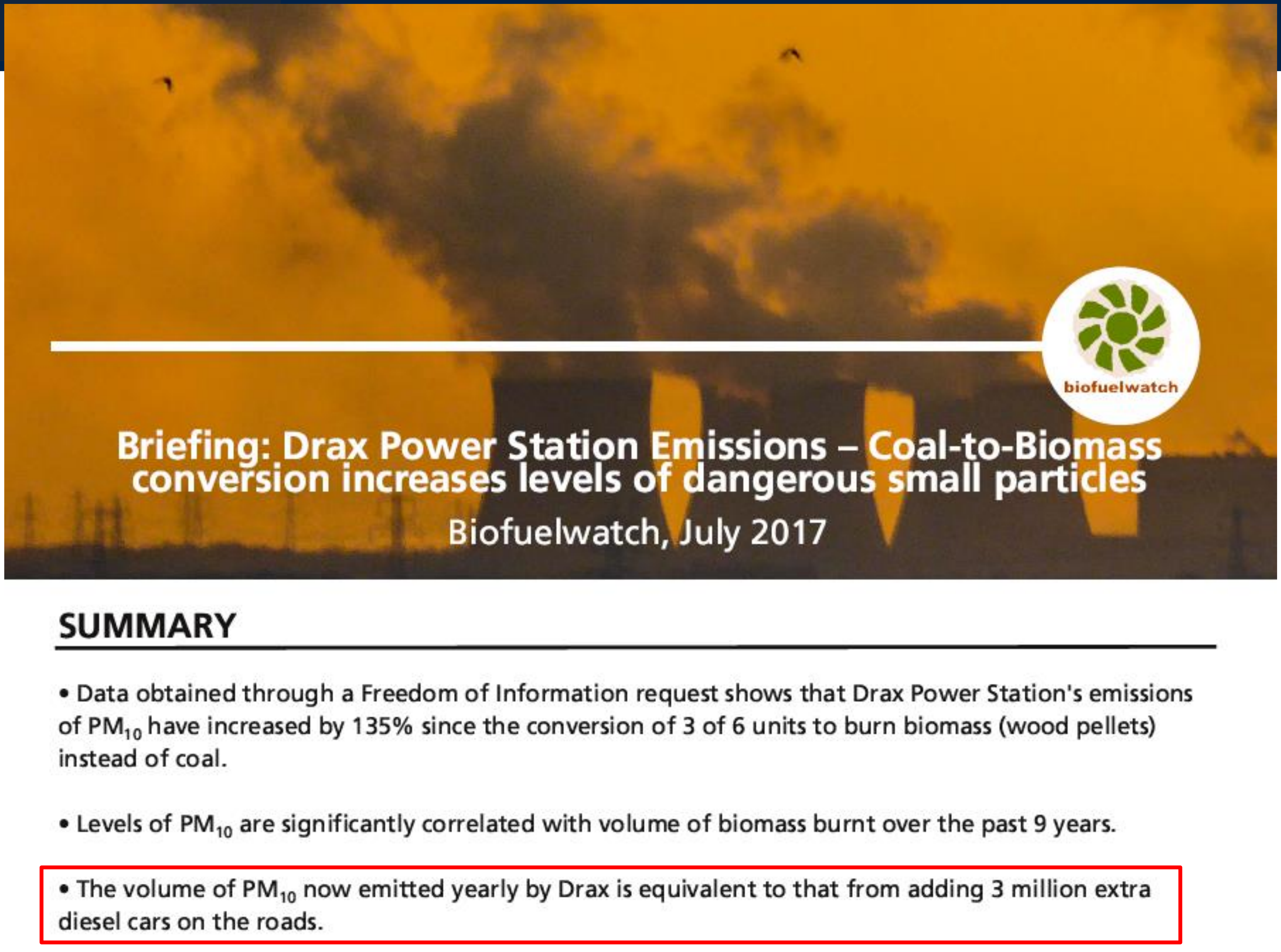
From brown powder to blue cell

The high-purity solar silicon—in the form of a brown powder—is fed into a special melting furnace. The molten silicon can then be processed using a variety of methods. One important process is the extrusion of monocrystalline rods, which can then be sliced into thin wafers. These must then be selectively contaminated with foreign atoms in a process known as doping. Finally, individual solar cells are combined to form large-surface modules.

The photovoltaic cell

The classic silicon-based solar cell consists of two layers of the semiconductor silicon, which has been differently doped, thus producing a p-type majority charge carrier (p-conducting layer) and an n-type majority charge carrier (n-conducting layer). At the junction between the two—the p-n junction—an electrical field is generated. When the cell is struck by light, the field delivers an electric current, which in turn is tapped by metal contacts.





Briefing: Drax Power Station Emissions – Coal-to-Biomass conversion increases levels of dangerous small particles

Biofuelwatch, July 2017

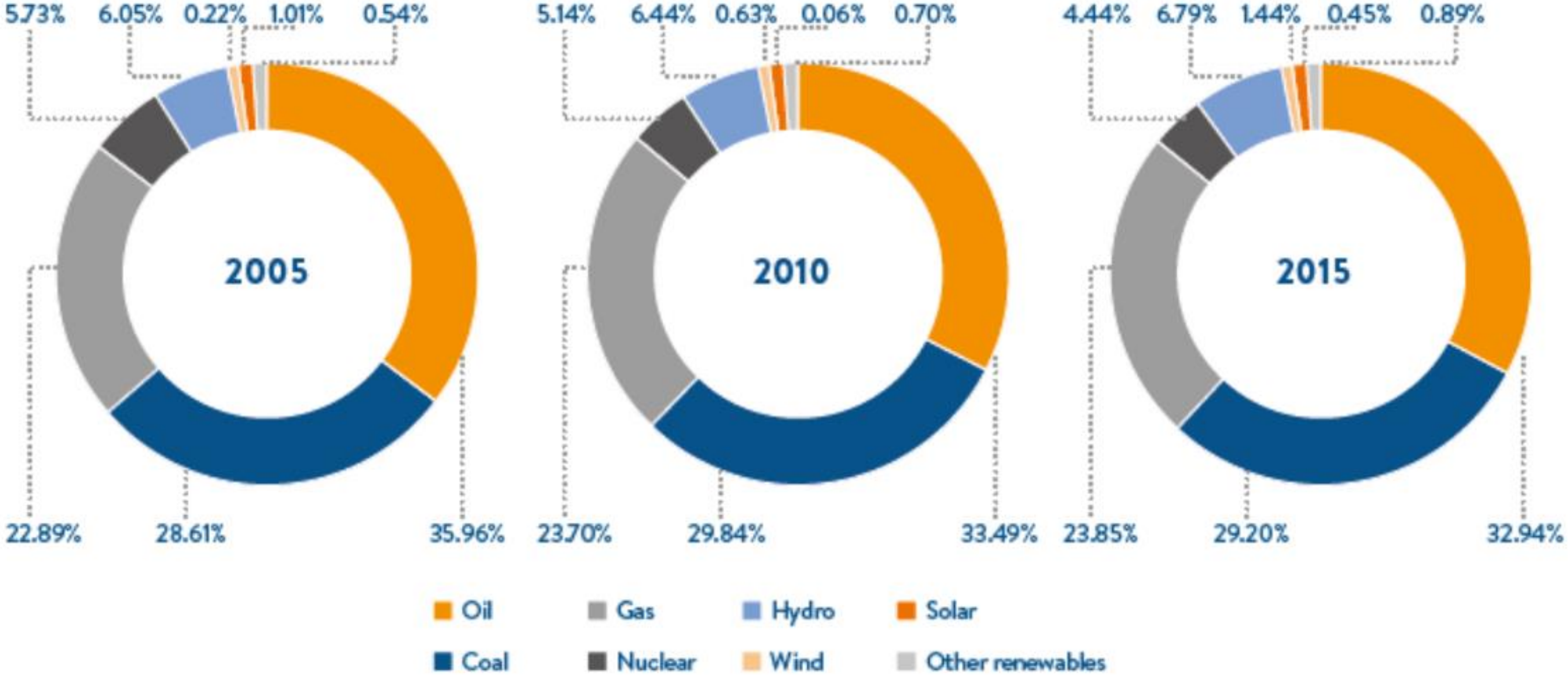
SUMMARY

- Data obtained through a Freedom of Information request shows that Drax Power Station's emissions of PM_{10} have increased by 135% since the conversion of 3 of 6 units to burn biomass (wood pellets) instead of coal.

- Levels of PM_{10} are significantly correlated with volume of biomass burnt over the past 9 years.

- The volume of PM_{10} now emitted yearly by Drax is equivalent to that from adding 3 million extra diesel cars on the roads.

World Energy Use



A Plan to Keep Carbon in Check

Getting a grip on greenhouse gases is daunting but doable. The technologies already exist. But there is no time to lose

BY ROBERT H. SOCOLOW AND STEPHEN W. PACALA

OVERVIEW

- Humanity can emit only so much carbon dioxide into the atmosphere before the climate enters a state unknown in recent geologic history and goes haywire. Climate scientists typically see the risks growing rapidly as CO_2 levels approach a doubling of their pre-18th-century value.
- To make the problem manageable, the required reduction in emissions can be broken down into "wedges"—an incremental reduction of a size that matches available technology.

Retreating glaciers, stronger hurricanes, hotter summers, thinner polar bears: the ominous harbingers of global warming are driving companies and governments to work toward an unprecedented change in the historical pattern of fossil-fuel use. Faster and faster, year after year for two centuries, human beings have been transferring carbon to the atmosphere from below the surface of the earth. Today the world's coal, oil and natural gas industries dig up and pump out about seven billion tons of carbon a year, and society burns nearly all of it, releasing carbon dioxide (CO_2). Ever more people are convinced that prudence dictates a reversal of the present course of rising CO_2 emissions.

The boundary separating the truly dangerous consequences of emissions from the merely unwise is probably located near (but below) a doubling of the concentration of CO_2 that was in the atmosphere in the 18th century, before the Industrial Revolution began. Every increase in concentration carries new risks, but avoiding that danger zone would reduce the likelihood of triggering major, irreversible climate changes, such as the disappearance of the Greenland ice cap. Two years ago the two of us provided a simple framework to relate future CO_2 emissions to this goal.

We contrasted two 50-year futures. In one future, the emissions rate continues to grow at the pace of the past 30 years for the next 50 years, reaching 14 billion tons of carbon a year in 2056. (Higher or lower rates are, of course, plausible.) At that point, a tripling of preindustrial carbon concentrations would be very difficult to avoid, even with concerted efforts to decarbonize the world's energy systems over the following 100 years. In the other future, emissions are frozen at the present value of seven billion tons a year for the next 50 years and then reduced by about half over the following 50 years. In this way, a doubling of CO_2 levels can be avoided. The difference between these 50-year emission paths—one ramping up and one flattening out—we called the stabilization triangle [*see box on page 52*].

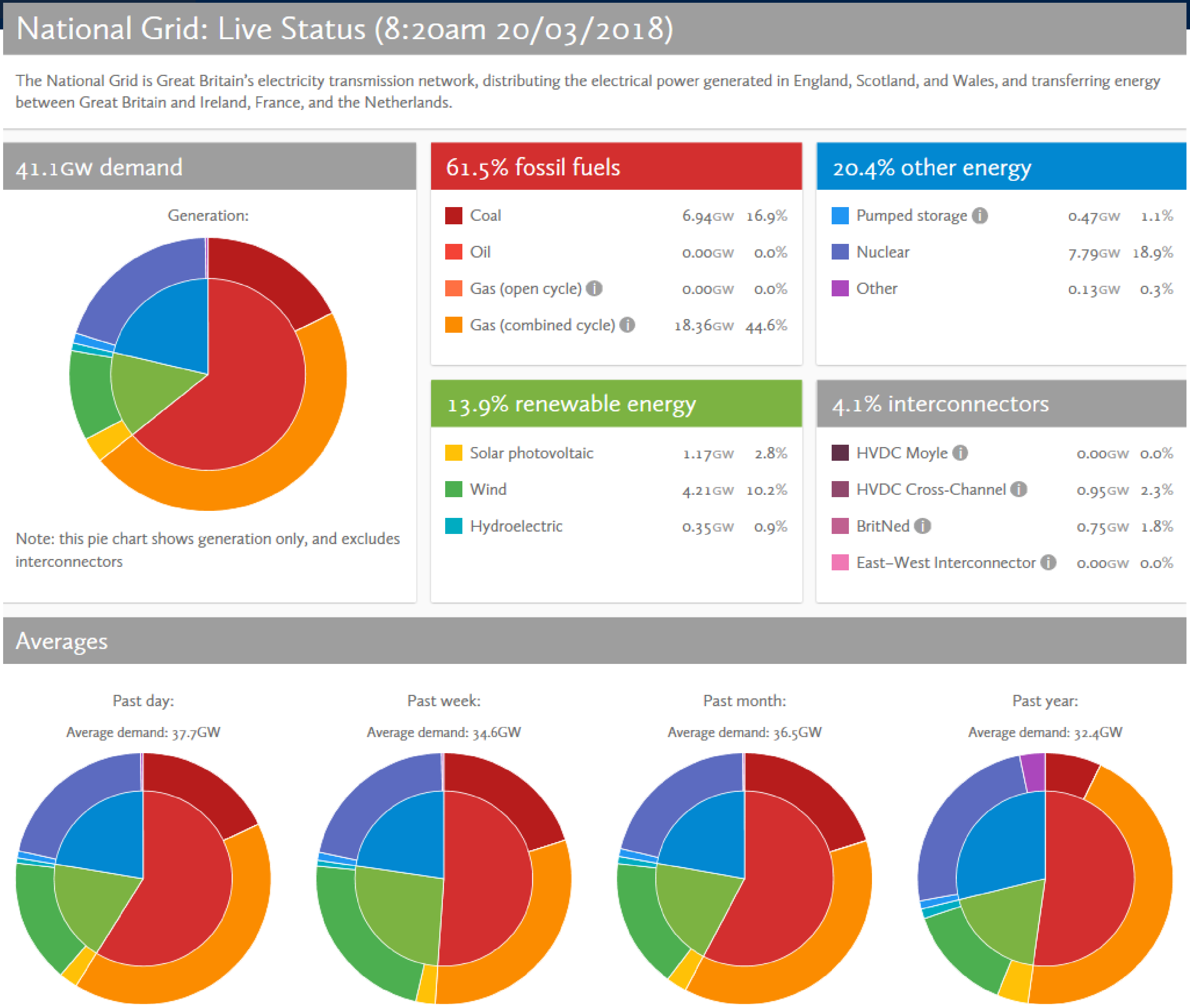
To hold global emissions constant while the world's economy continues to grow is a daunting task. Over the past 30 years, as the gross world

▸ Humanity faces a choice between two futures: doing nothing to curb emissions (which poses huge climate risks) and bringing them under control (which has costs but also benefits).

KENN BROWN

Fossil-Fuel Dragons!

Drowning in oil



National Grid: Live Status (8:20am 20/03/2018)

The National Grid is Great Britain's electricity transmission network, distributing the electrical power generated in England, Scotland, and Wales, and transferring energy between Great Britain and Ireland, France, and the Netherlands.

41.1GW demand

Generation:

Note: this pie chart shows generation only, and excludes interconnectors

61.5% fossil fuels

Coal	6.94GW	16.9%
Oil	0.00GW	0.0%
Gas (open cycle)	0.00GW	0.0%
Gas (combined cycle)	18.36GW	44.6%

20.4% other energy

Pumped storage	0.47GW	1.1%
Nuclear	7.79GW	18.9%
Other	0.13GW	0.3%

13.9% renewable energy

Solar photovoltaic	1.17GW	2.8%
Wind	4.21GW	10.2%
Hydroelectric	0.35GW	0.9%

4.1% interconnectors

HVDC Moyle	0.00GW	0.0%
HVDC Cross-Channel	0.95GW	2.3%
BritNed	0.75GW	1.8%
East-West Interconnector	0.00GW	0.0%

Averages

Past day:
Average demand: 37.7GW

Past week:
Average demand: 34.6GW

Past month:
Average demand: 36.5GW

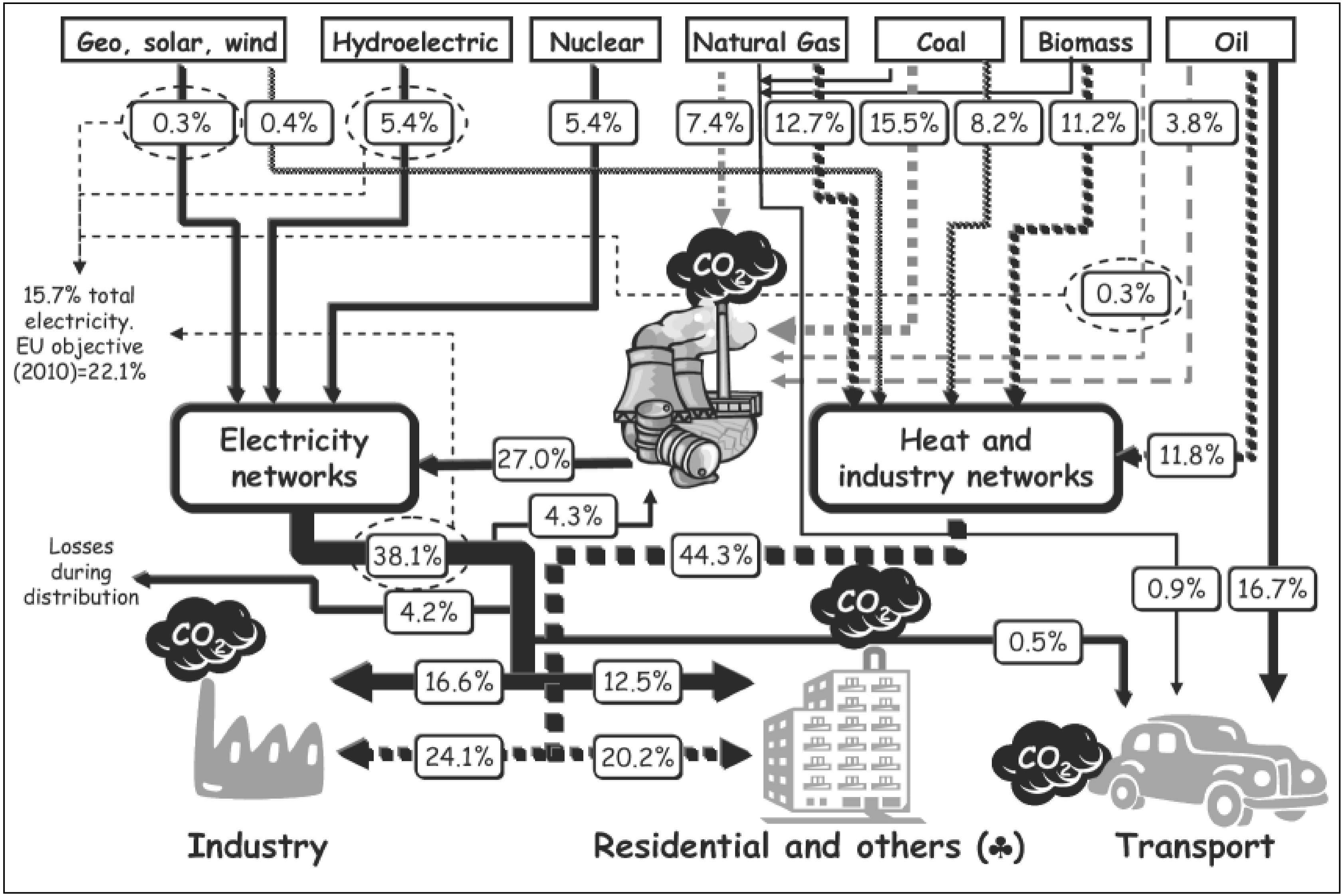
Past year:
Average demand: 32.4GW

Petroleum (Gasoline) and Diesel

Three fundamental reasons why fossil fuels will remain popular for ..?.. years/centuries(!)

The attraction of liquid carbon-based fuels

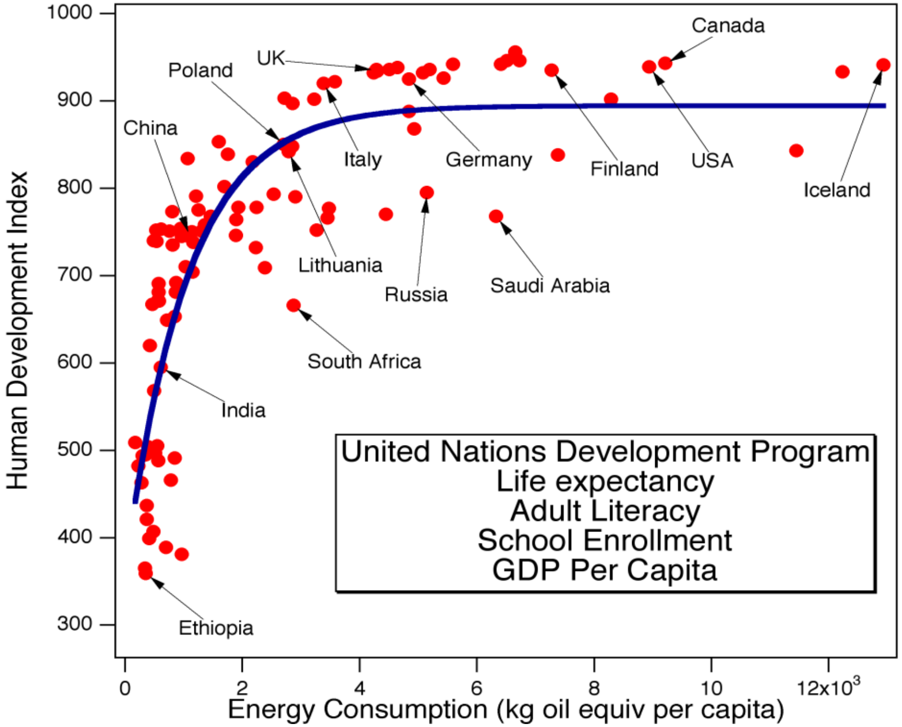
I. The Hydrocarbon Economy

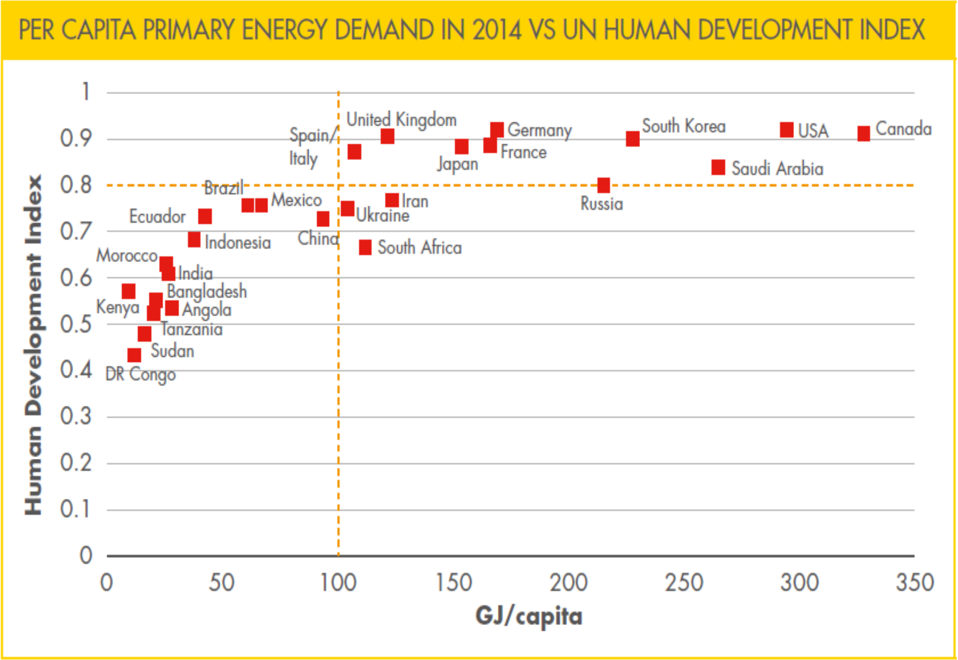


G. Marban, T. Valdes-Solis. *Int. J. Hydrogen Energy,* **32** (2007) 1625

The attraction of liquid carbon-based fuels

II. The link to human development





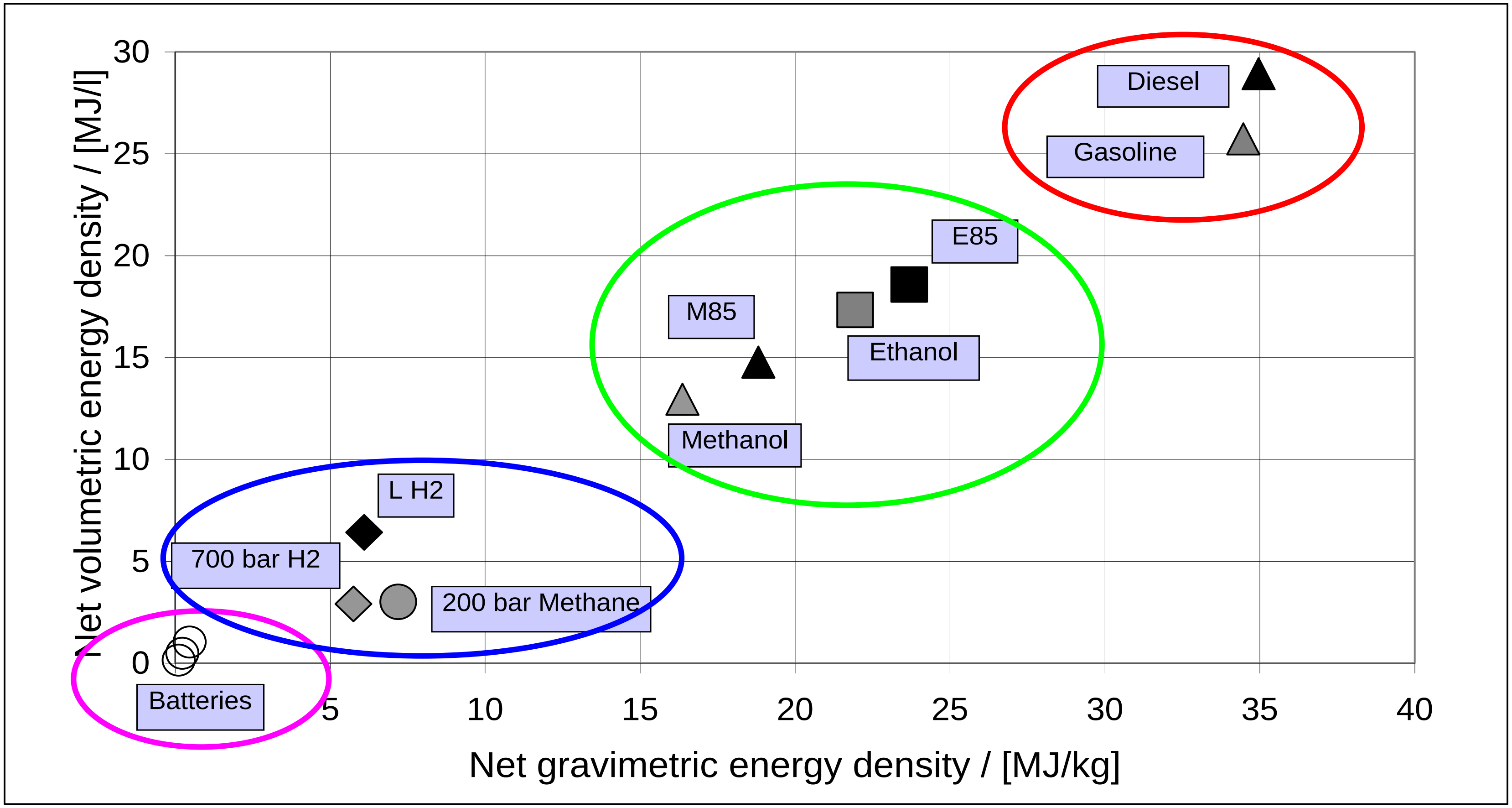
Source: Shell analysis – UN Human Development Index

Kurt W. Kolasinski, *Current Opinion in Solid State and Materials Science* (2006) 10, 129-1312

Shell: A better life with a healthy planet: Pathways to net-zero emissions

The attraction of liquid carbon-based fuels:

III. Ideal for transportation: On-board energy density

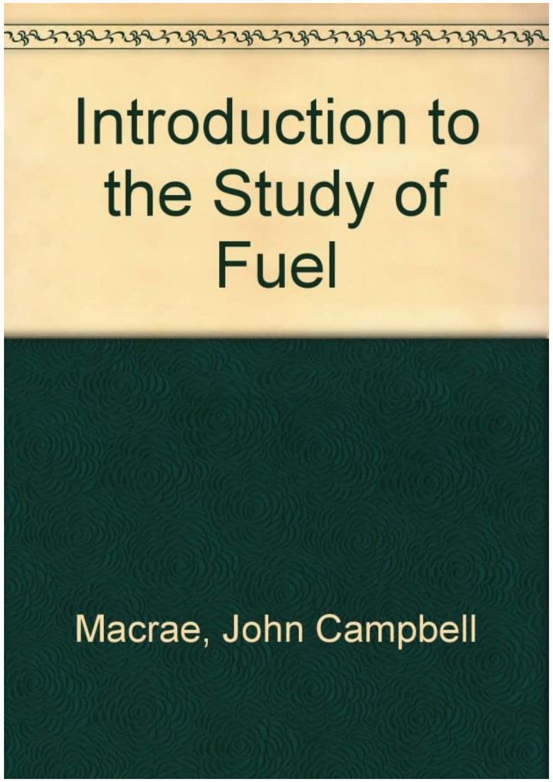


- Liquid fuels can be stored on vehicles at high energy densities in simple low-cost storage systems and are distributed via low-cost, low-loss infrastructures.
- ANL estimate \$650x10^9 for a refuelling infrastructure for a 100x10^6 vehicle fleet.

R. J. Pearson *et al.*, *Proceedings of the IEEE*, 100, 440 (2012)

Definition of a Fuel

An Introduction to the Study of Fuel
J. C. MaCrae, Elsevier, 1966



Introduction to the Study of Fuel

Macrae, John Campbell

- Any substances which unite with the evolution of heat;
- Important fuels are carbon compounds... *“not too much to say that our whole industrial society is based upon the reactions”:*

$$C + O_2 = CO_2$$

$$H_2 + O = H_2O$$

Clean Energy from Fossil Fuels

> *"Until other energy sources supplant coal, oil and natural gas, the technological challenge is clear: extract maximum energy from the old standbys while minimizing harm to the environment."*
>
> W. Fulkerson et al.,
> Scientific American, 1990, p.128

The King Abdulaziz City for Science and Technology-Oxford Petrochemical Research Centre (KOPRC)

KOPRC I

Clean Combustion of Diesel

Solid Acid Catalysts for Alkylation

Heavy Oil to Olefins

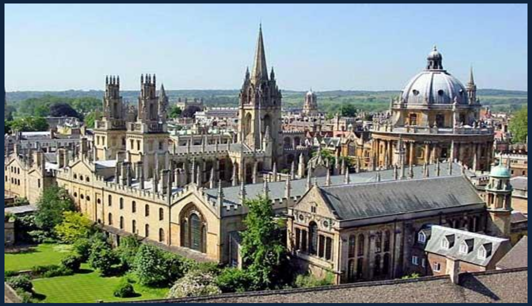
CO_2 Activation

New Catalysts for Polymerisation

مدينة الملك عبدالعزيز للعلوم والتقنية KACST

UNIVERSITY OF OXFORD

KOPRC
KACST - OXFORD
Petrochemical Research Centre



KOPRC II

Vapour Phase Synthesis of Propylene Oxide

New Generation High Performance Solid Acid Catalysts

with Cambridge

Microwave Assisted Processes

Direct Selective Oxidation of Light Hydrocarbons to Oxygenate

with Imperial College

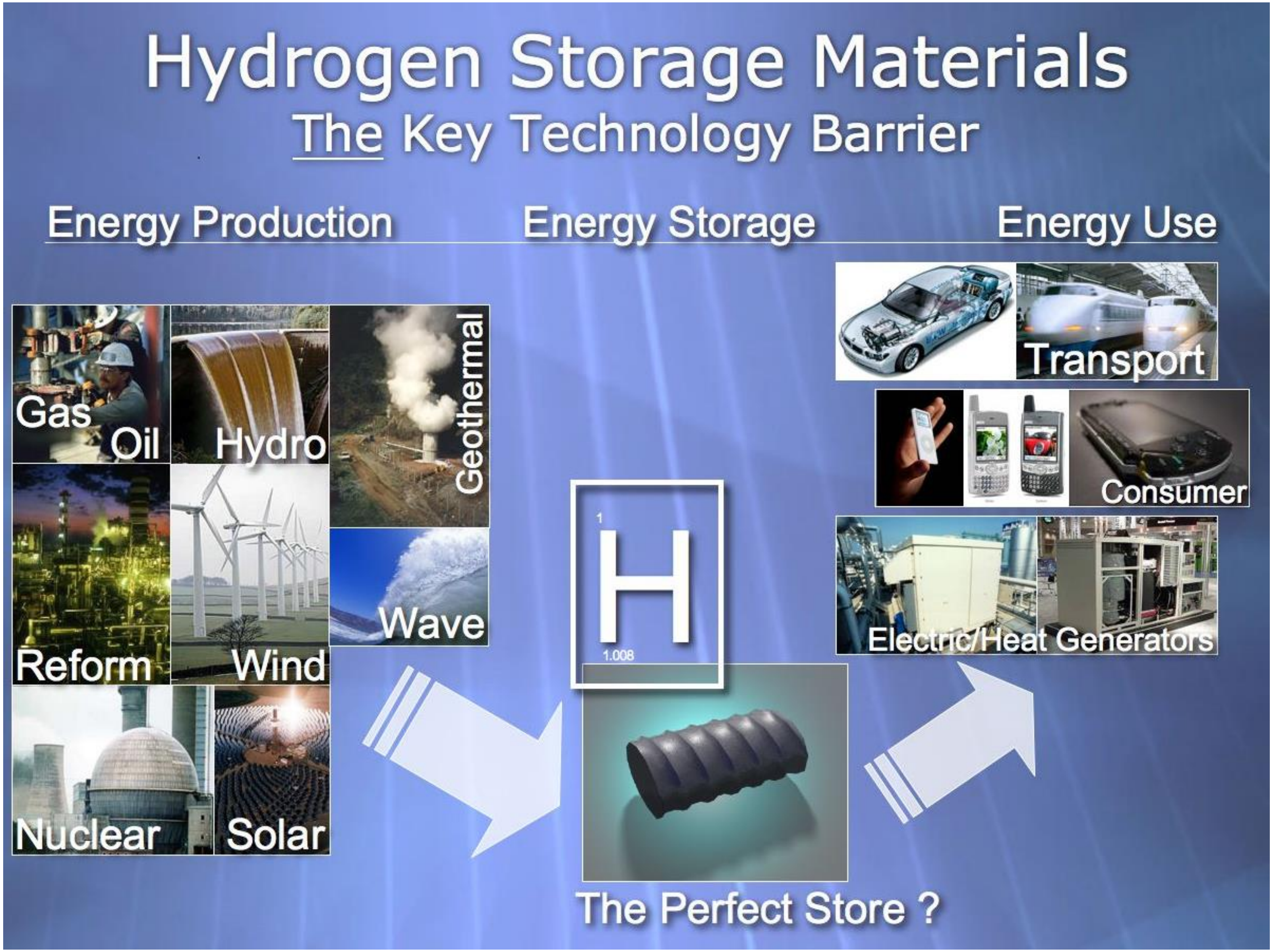
High Efficiency Nano-Gold Catalysts

with Cardiff

Clean Energy from Fossil Fuels

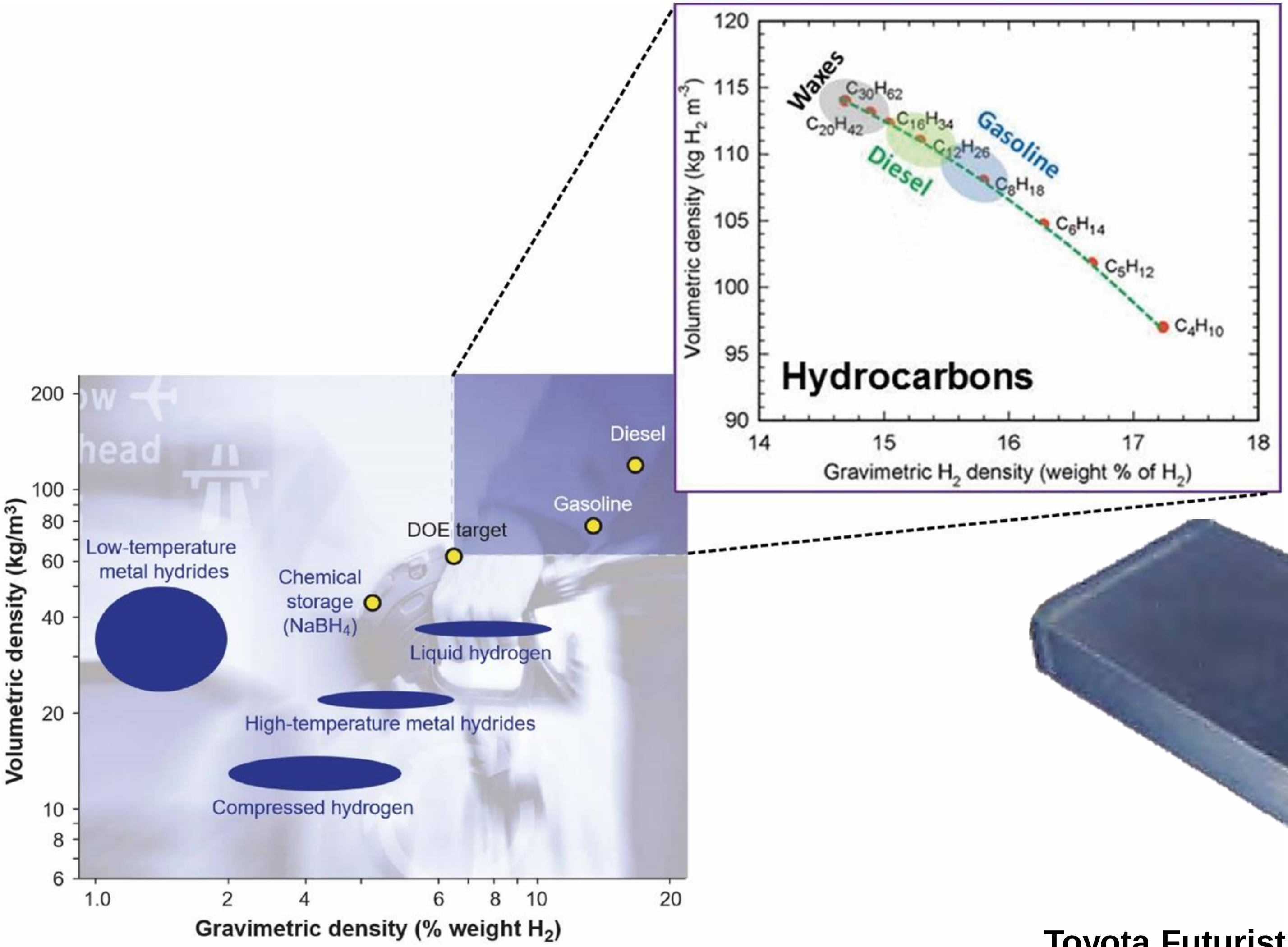
- Hydrogen and hydrocarbons production from crude and heavy oil;
- Minimal energy utilisation of CO_2 from refineries and power plants;
- Energy and sustainability economics through a complete Life Cycle Analysis: *“The Catalyst Sensitivity Index”*

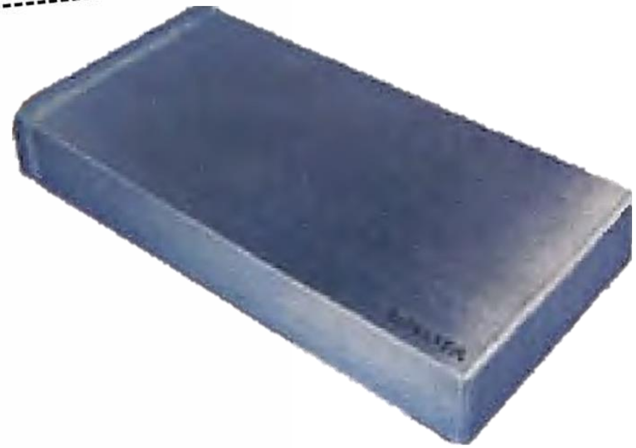
Hydrogen Storage Materials



W. Grochala and P. P. Edwards, *Chem Rev*. 2004, 104, 3, 1283-1316

Hydrogen from Fossil Fuels: The Perfect Store?

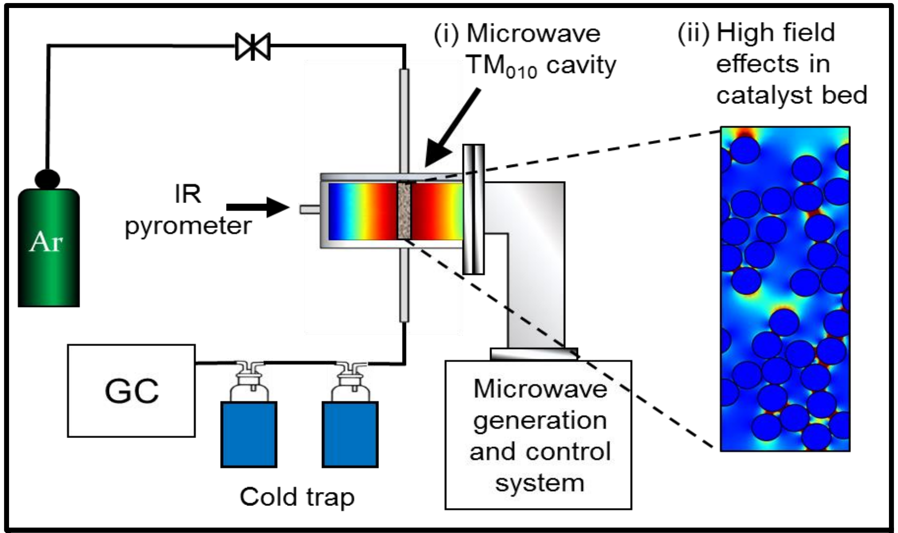


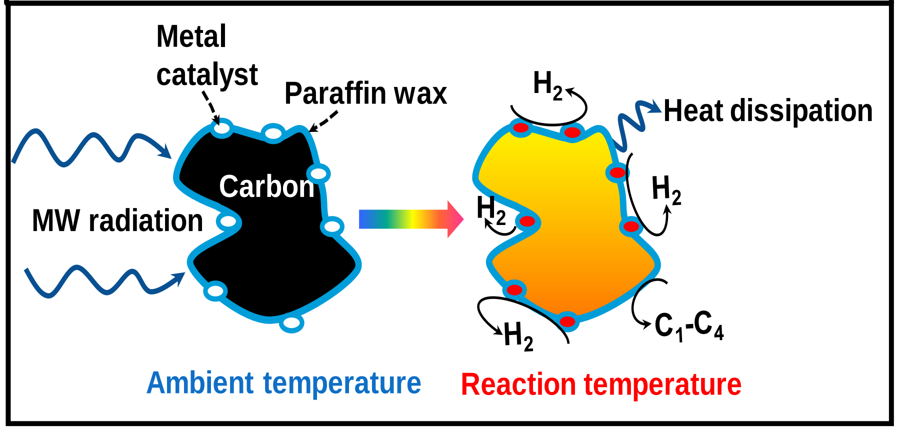


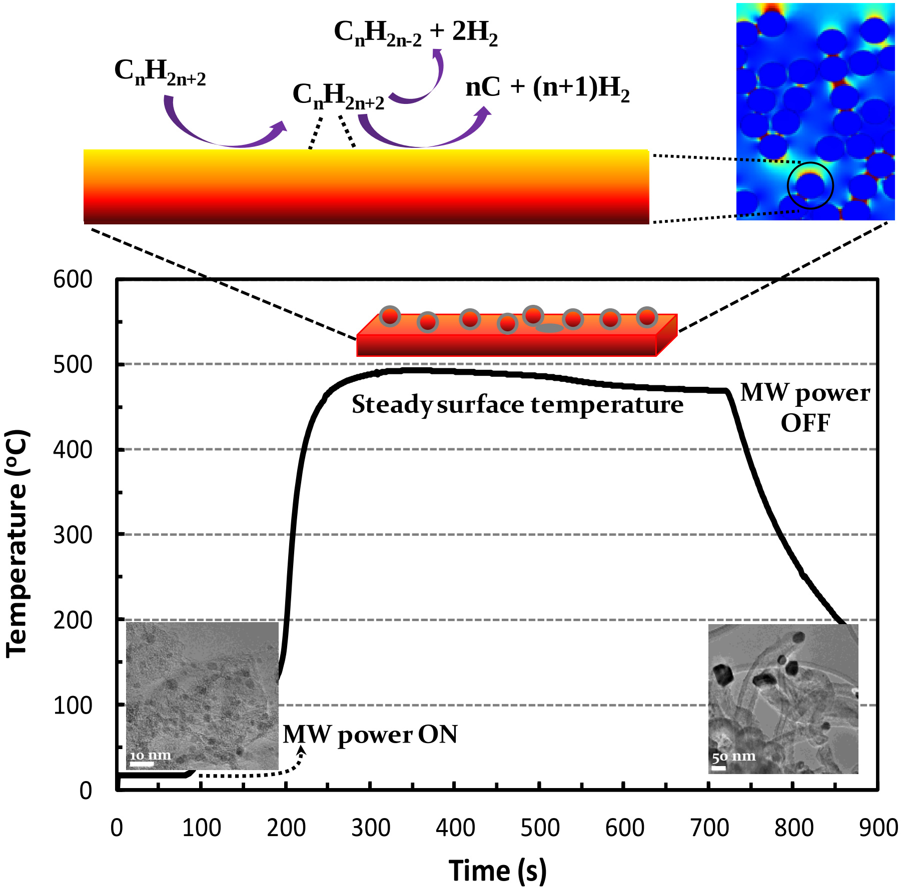
Toyota Futuristic Hydrogen Store

S. Gonzalez-Cortes, *et al.*, *Nature Scientific Reports*, **6**, 35315 (2016)
X. Jie, *et al.*, *Angew. Chem. Int. Ed.*, 2017, **56**, 10170-10173

Microwave irradiation and catalytic decomposition of hydrocarbons

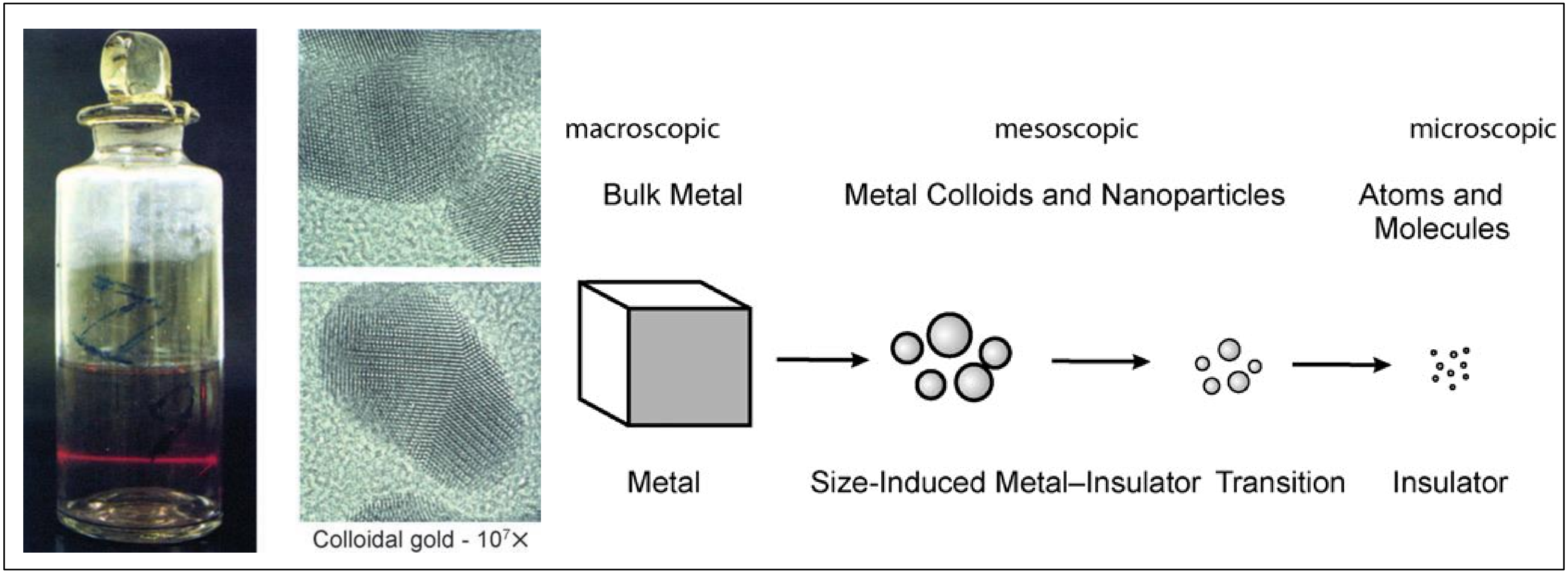






S. Gonzalez-Cortes, *et al., Nature Scientific Reports* 6, 35315 (2016)

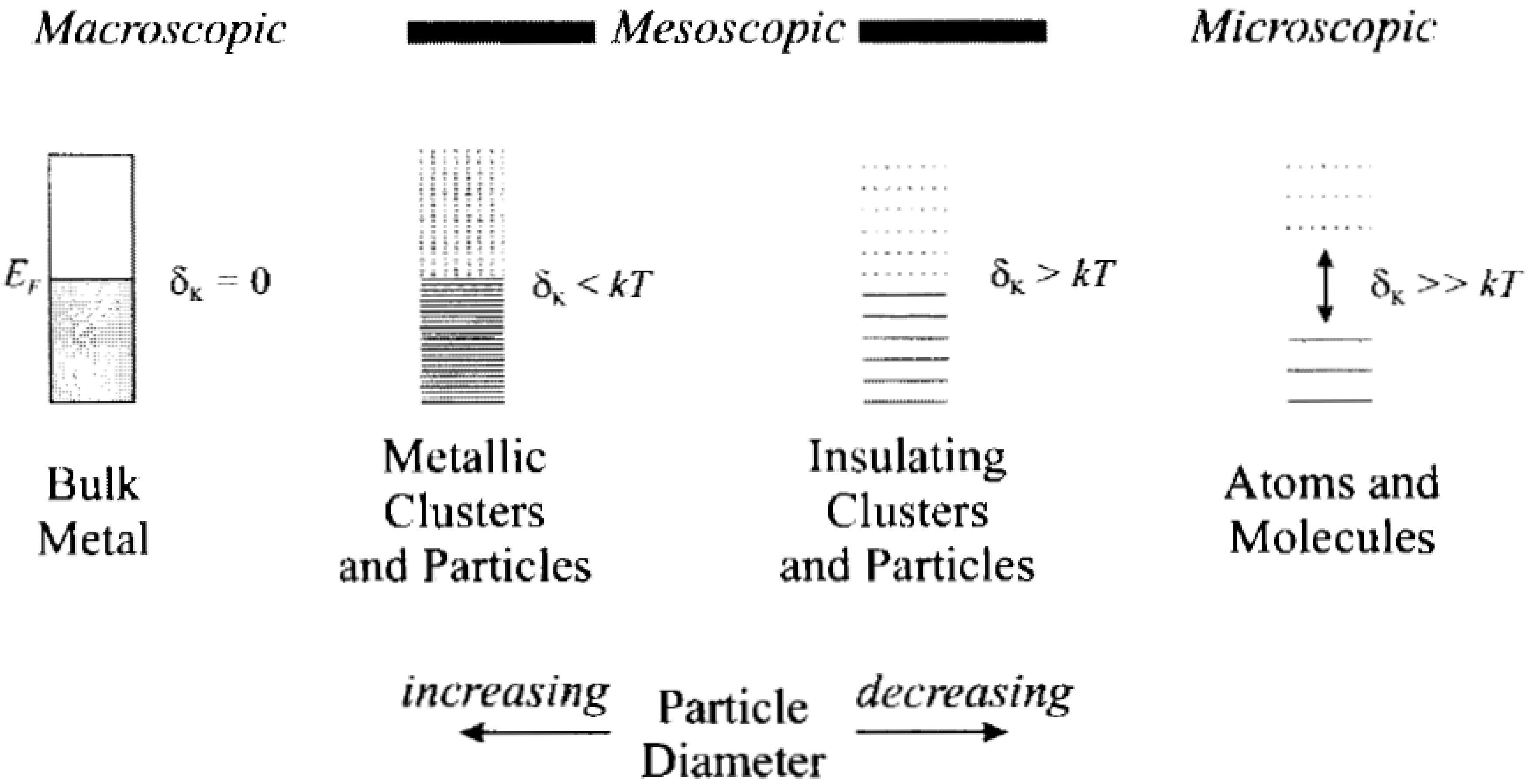
Divided Metals:
The Size-Induced Metal-Insulator Transition



P. P. Edwards and J. M. Thomas, *Angew. Chem. Int. Ed*. 2007, 46, 5480-5486

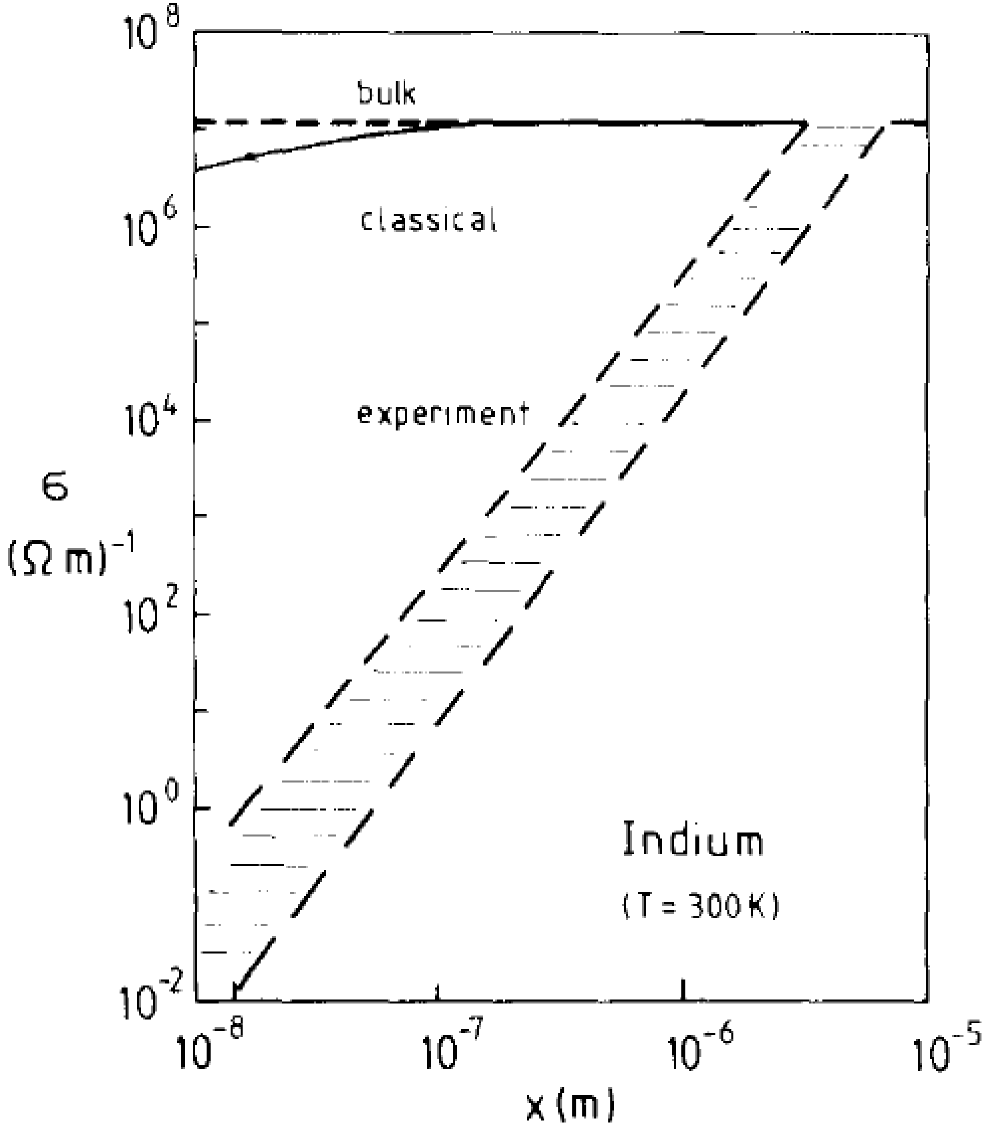
M. Faraday, *Phil.Trans. R. Soc.London,* 1857, 147, 145 -181

The Size-Induced Metal-Insulator Transition: Evolution of the Kubo Gap



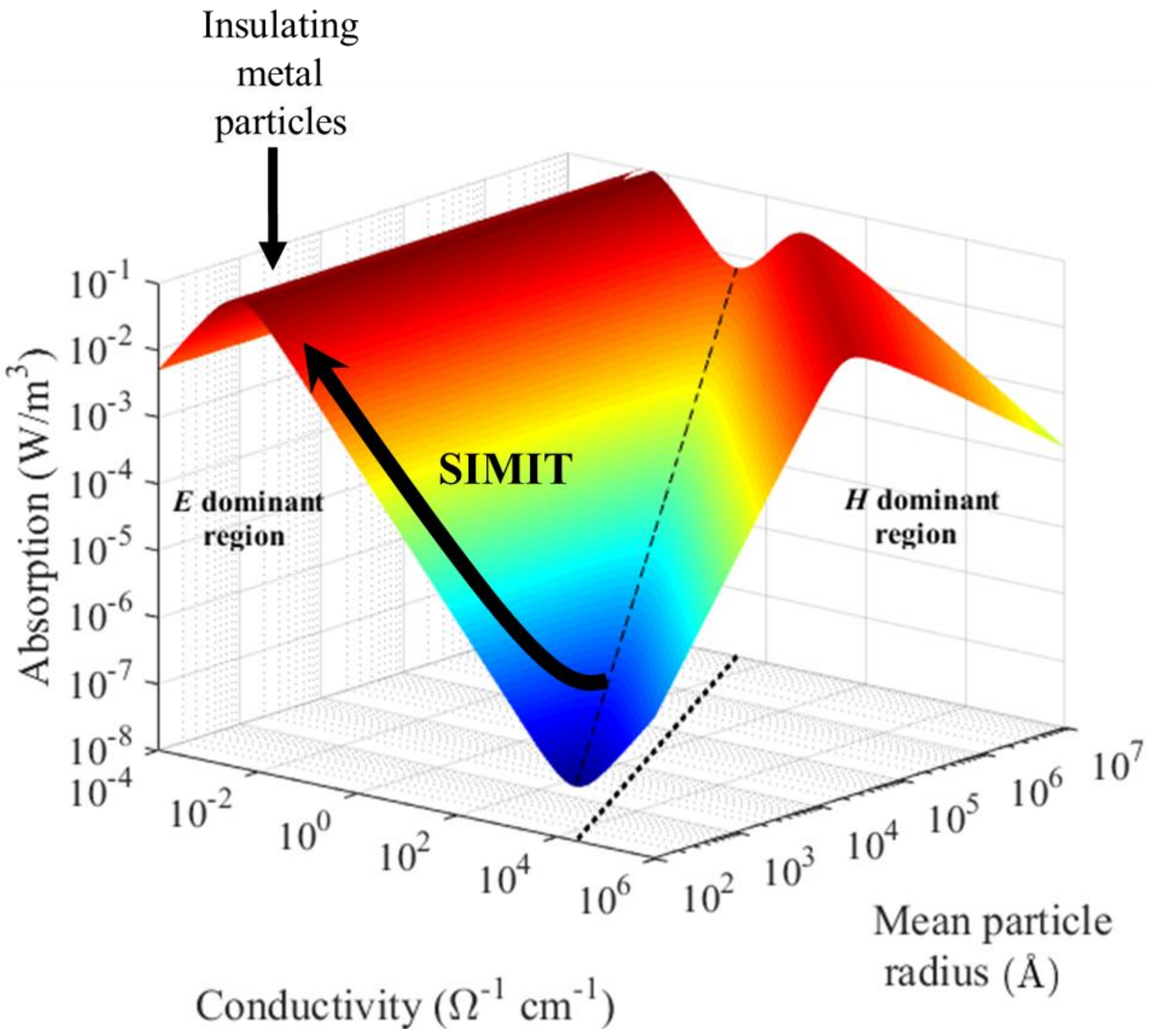
R. Kubo, *J. Phys. Soc. Japan,* 1962, 17, 975

The Size-Induced Metal-Insulator Transition in Indium Metal



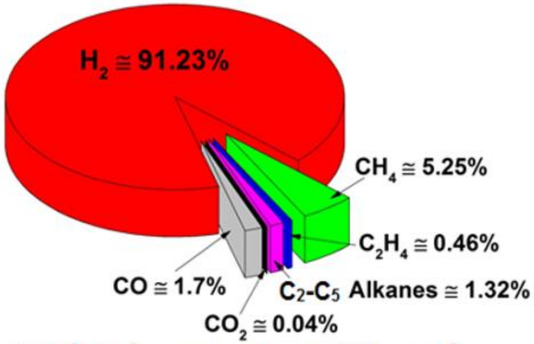
G. Nimtz, *et al., J. Crystal Growth,* 1988, 16., 66

The Size-Induced Metal-Insulator Transition: Electromagnetic Absorption



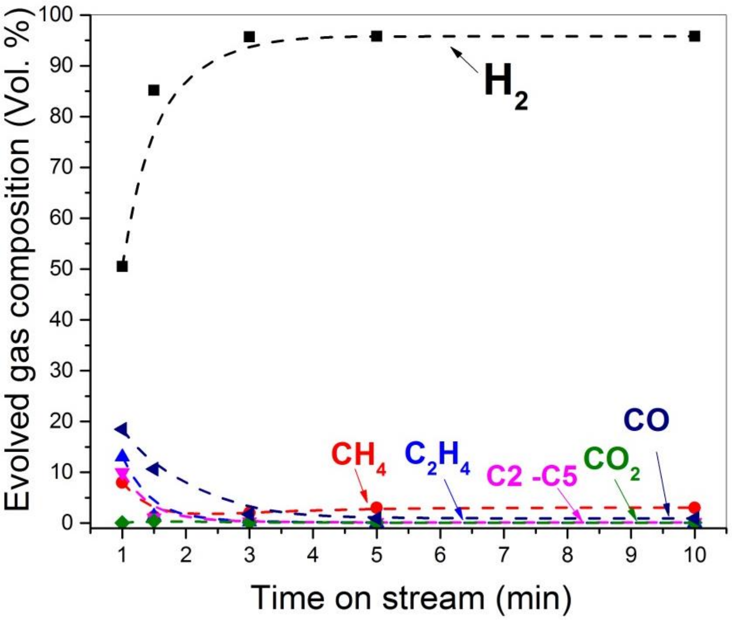
A. Porch, D. Slocombe and P. P. Edwards, *Phys. Chem. Chem. Phys.,* 2013, **15**, 2757-2763

Decarbonizing Diesel



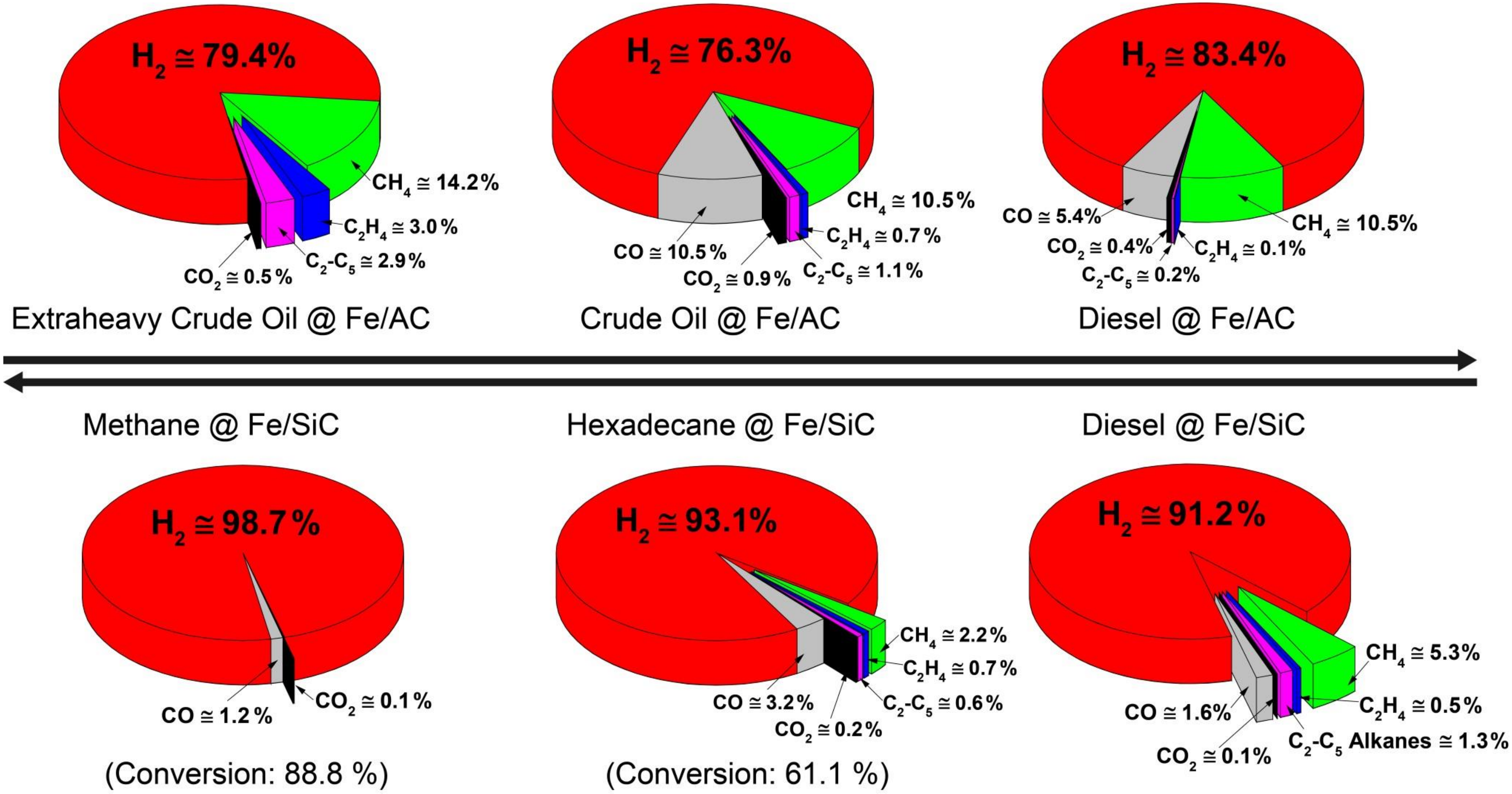
Evolved gas composition of Diesel @ Fe/SiC sample

$$\text{Diesel} \xrightarrow[\text{Microwave 2.45 GHz}]{\text{[Catalyst]}} C + H_2$$



Catalysts	Gravimetric Density (kg-H_2/kg)	Volumetric Density (kg-H_2/m^3)
DoE target	7.5	70
Fe/SiC	8.59	71.45
Ni/SiC	9.04	75.22
FeNi/SiC	8.10	67.40

Hydrogen Energy from Fossil Fuels



Extraheavy Crude Oil @ Fe/AC

Crude Oil @ Fe/AC

Diesel @ Fe/AC

Methane @ Fe/SiC

Hexadecane @ Fe/SiC

Diesel @ Fe/SiC

(Conversion: 88.8 %)

(Conversion: 61.1 %)

Earth, Mankind and Energy

Carlo Rubbia

Life long Member of the Senate of the Italian Republic

GSSI, Gran Sasso Science Institute, L'Aquila, Italy

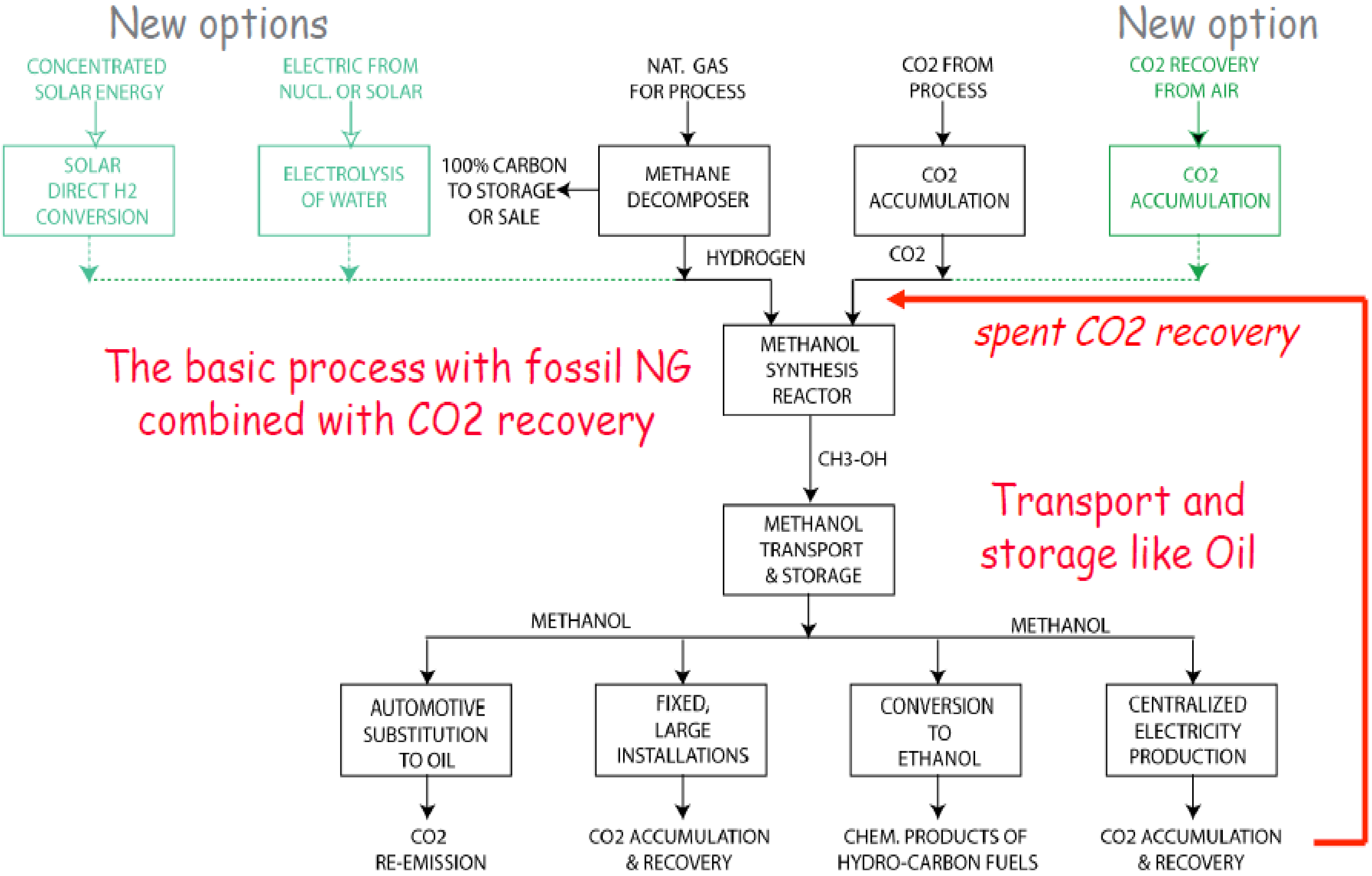
Foreign Member of the Royal Society

Conclusions…

- In addition to the progress with Renewables, the continued production of energy from fossils is mandatory.
- According to an old saying, "The end of stone age did not occur because of the lack of stones". Likewise, in my view, at the end of the Coal exploitation era, there will be still huge amounts of Coal left.
- Methane decarburation (TDM, $CH_4 \rightarrow 2H_2+C$) in association with NG may become a valid alternative to Renewable Energies since having removed the CO_2, it has the capability of becoming another safe primary energy source adequate for centuries.
- Both as a H_2 gas or a liquid with Methanol and already "spent CO_2" it can be made environmentally acceptable with a minimal footprint and without costly new infrastructures.
- *Provided the emissions of CO_2 can be economically removed with black carbon and our simple method, why should it not be vastly used in the future without environmental drawbacks ?*

Carlo Rubbia (May 2017)

Transforming CO_2 from a liability to an asset



New options

CONCENTRATED SOLAR ENERGY

SOLAR DIRECT H2 CONVERSION

ELECTRIC FROM NUCL. OR SOLAR

ELECTROLYSIS OF WATER

NAT. GAS FOR PROCESS

METHANE DECOMPOSER

100% CARBON TO STORAGE OR SALE

HYDROGEN

CO2 FROM PROCESS

CO2 ACCUMULATION

CO2

New option

CO2 RECOVERY FROM AIR

CO2 ACCUMULATION

METHANOL SYNTHESIS REACTOR

spent CO2 recovery

The basic process with fossil NG combined with CO2 recovery

CH3-OH

METHANOL TRANSPORT & STORAGE

Transport and storage like Oil

METHANOL

METHANOL

AUTOMOTIVE SUBSTITUTION TO OIL

CO2 RE-EMISSION

FIXED, LARGE INSTALLATIONS

CO2 ACCUMULATION & RECOVERY

CONVERSION TO ETHANOL

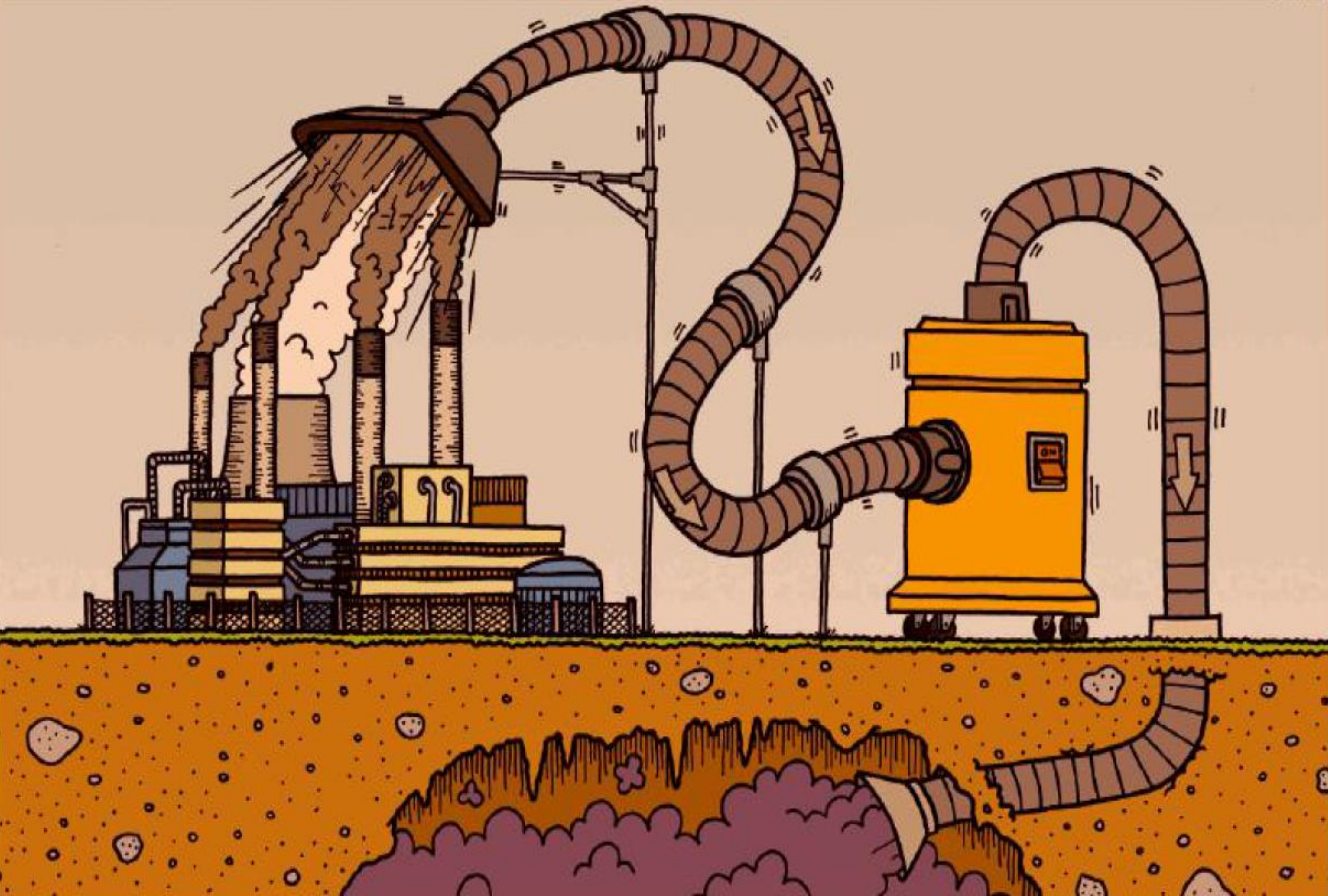
CHEM. PRODUCTS OF HYDRO-CARBON FUELS

CENTRALIZED ELECTRICITY PRODUCTION

CO2 ACCUMULATION & RECOVERY

Carlo Rubbia (May 2017)

Miracle Machine or White Elephant?



Buried Trouble

NATURE|Vol 463|18 February 2010

NEWS FEATURE

BURIED TROUBLE

Protesters saying “no to CO_2” are just one roadblock facing carbon sequestration — a strategy that could help prevent dangerous climate change. **Richard Van Noorden** investigates.

The Carbon Dioxide Economy: CO_2 as a new feedstock

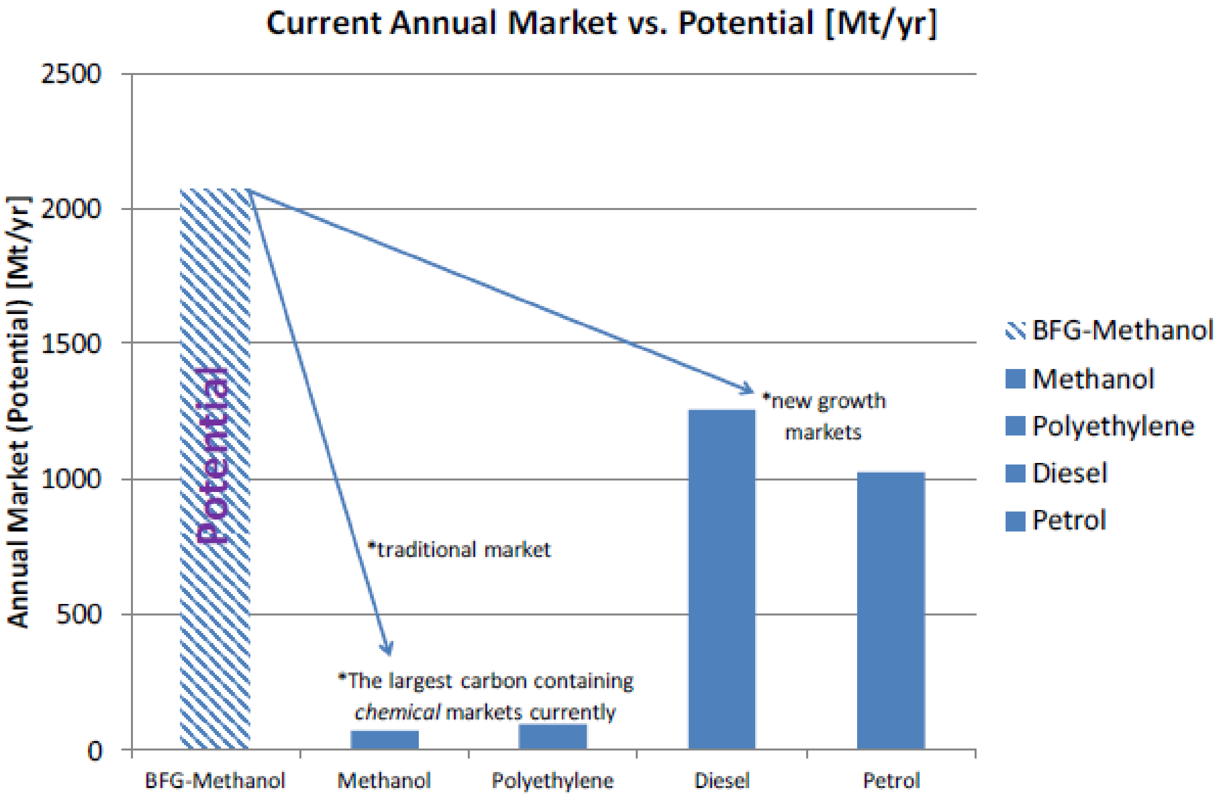
The Top 10 emerging technologies for 2012

6. Utilisation of carbon dioxide as a resource

World Economic Forum (2011) Abu Dhabi

CO_2 re-use: which product?

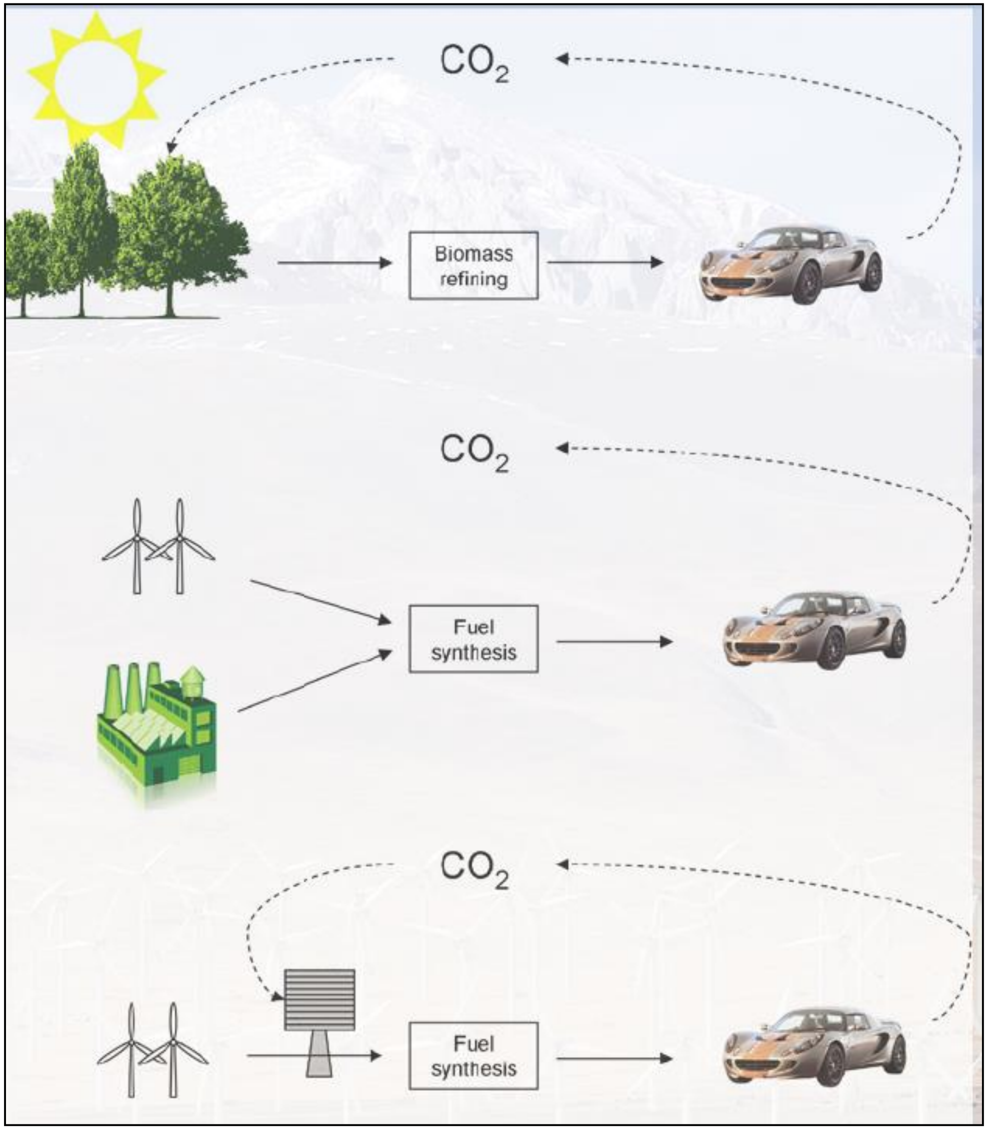
- Annual global CO_2-production in steel industry vs current annual markets



➡ Fuel market as growth market

Frans van Berkel, ECN NL, ICCDU 2016

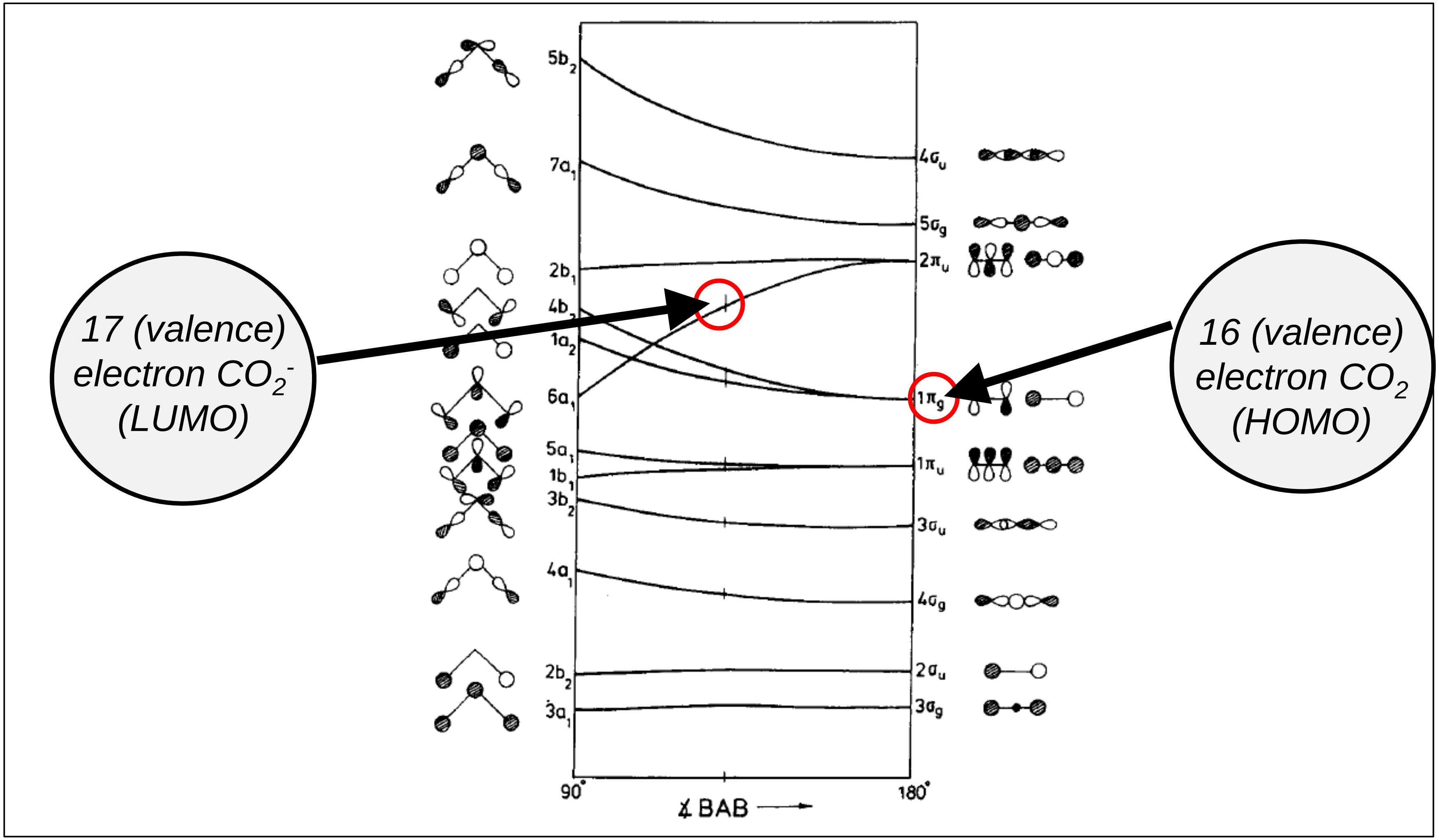
Carbon-neutral fuels



R. J. Pearson and J. Turner, P. P. Edwards, Lotus Engineering, *ProActive Issue 44, Spring 2012*

Bonding and the activation/reduction of CO_2

Walsh diagram of CO_2 orbital energies



17 (valence) electron CO_2^- (LUMO)

16 (valence) electron CO_2 (HOMO)

Electron transfer into CO_2 LUMO is the key to CO_2 activation and utilisation

H.-J. Freund, M. W. Roberts, *Surface Science Reports*, 25, 225-273 (1996)

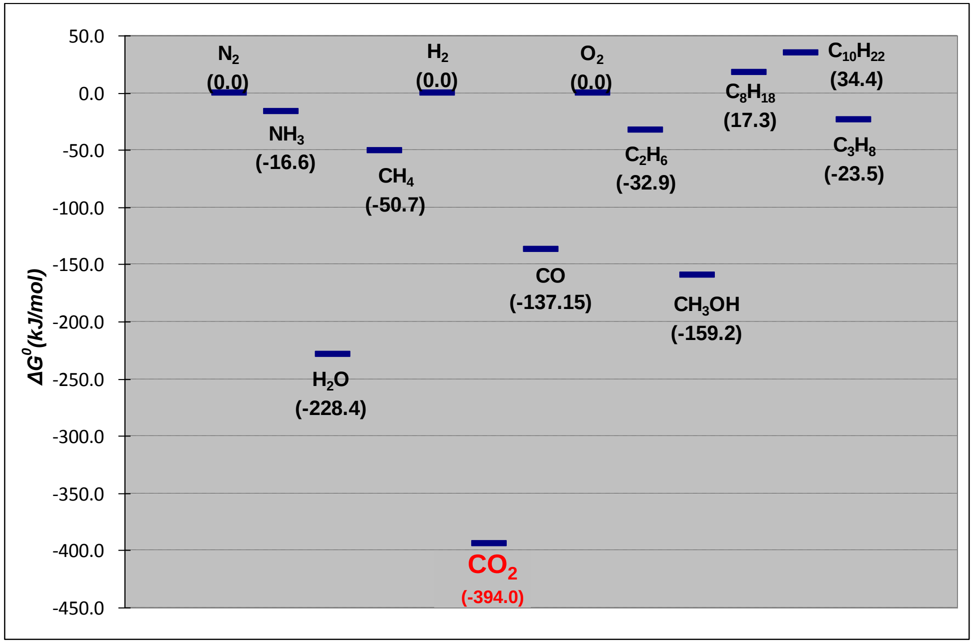
“Chemical” reduction of CO_2

Thermodynamics of CO_2 conversion: *Lessons I*

- CO_2 is a stable molecule
- Conversion of CO_2 involves endothernic, reduction reactions

BUT

- All chemical reactions are driven by *differences* in Gibbs Free Energy between products and reactants
- Many large-scale industrial processes are based on endothermic reactions.
- Endothermic reactions set the target and the scale for Solar Thermal Energy Processes



$$CH_4 + H_2O = CO + 3H_2$$

$$\Delta H = +206 \text{ kj/mol } CO_2$$

$$CH_4 + CO_2 = 2CO + 2H_2O$$

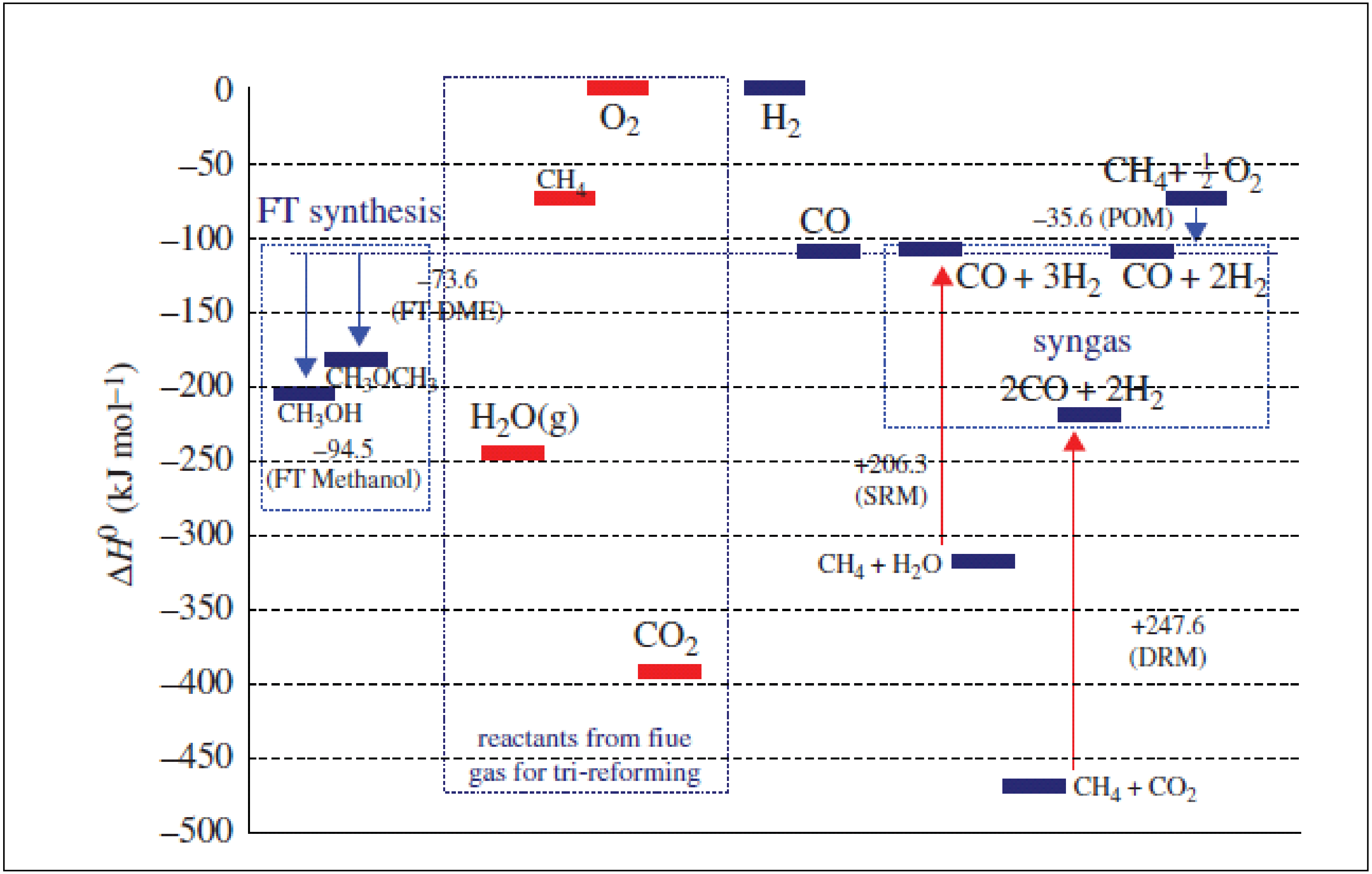
$$\Delta H = +247 \text{ kj/mol } CO_2$$

Z. Jiang, T. Xiao, V. L. Kuznetsov and P. P. Edwards, *Phil. Trans. R. Soc. A,* 2010, 368, 3343-3364

Dry reforming puts CO_2 to work

C&E News, 25 April 2016

The Tri-Reforming Process

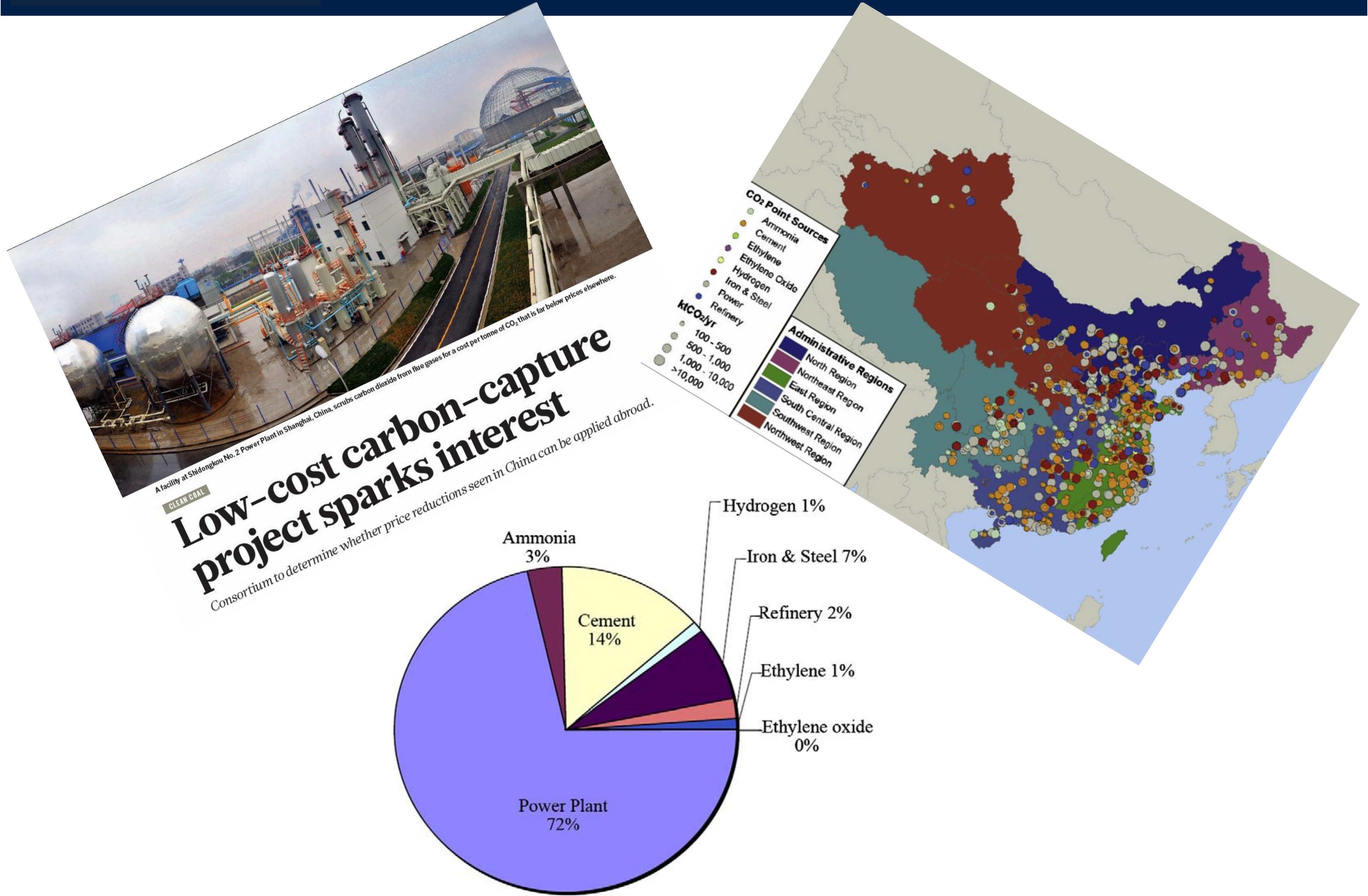


Z. Jiang, T. Xiao, V. L. Kuznetsov and P. P. Edwards, *Phil. Trans. R. Soc. A,* (2010), **368**, *3343-3364*

Potential for Flue Gas Reforming

Chunshan Song (Penn State)

CO_2 Capture, Storage and Utilisation in China



A facility at Shidongkou No. 2 Power Plant in Shanghai, China, scrubs carbon dioxide from flue gases for a cost per tonne of CO_2 that is far below prices elsewhere.

CLEAN COAL

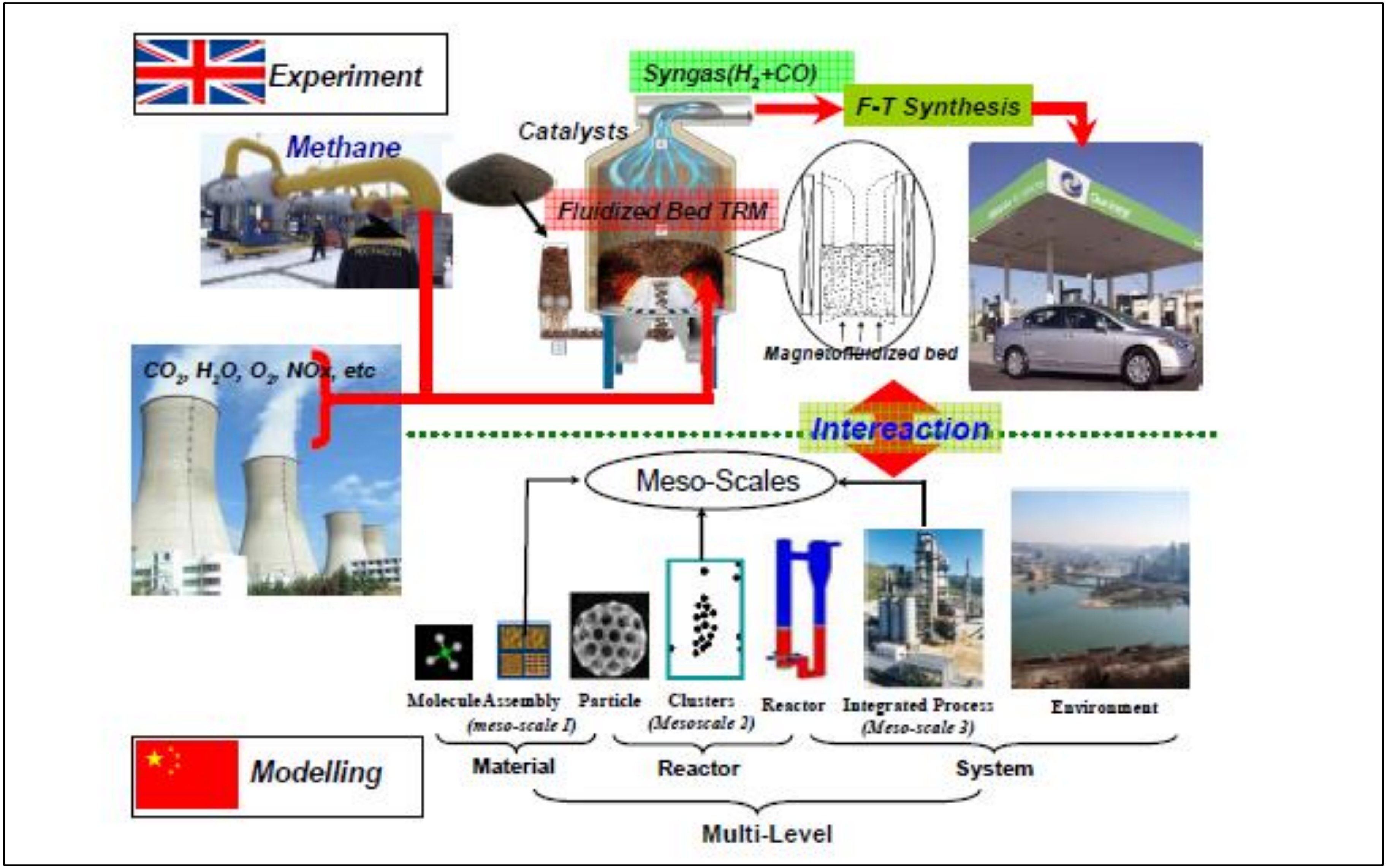
Low-cost carbon-capture project sparks interest

Consortium to determine whether price reductions seen in China can be applied abroad.

L. Li et al., *Fuel,* 108 (2013) 112–130)

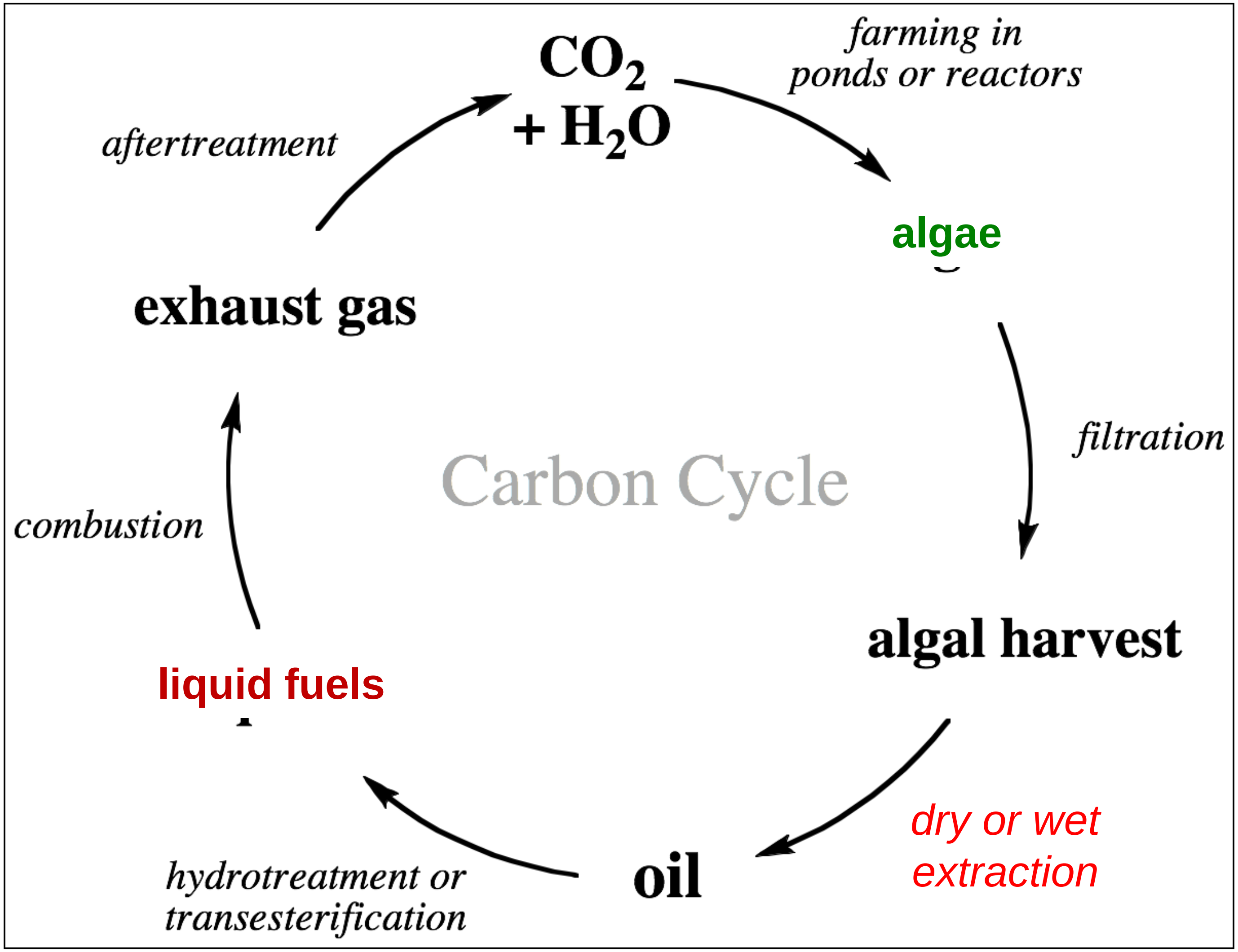
Scenarios: The critical role of the meso-scale

From chemistry to chemical engineering



J. Li, J. Houghton and P. P. Edwards and T. Xiao

Linking Catalyst Performance to Carbon Footprints: Life Cycle Analysis: Carbon Cycle: Algae-to-Biodiesel



Carbon Cycle

CO_2 + H_2O

farming in ponds or reactors

algae

filtration

algal harvest

dry or wet extraction

oil

hydrotreatment or transesterification

liquid fuels

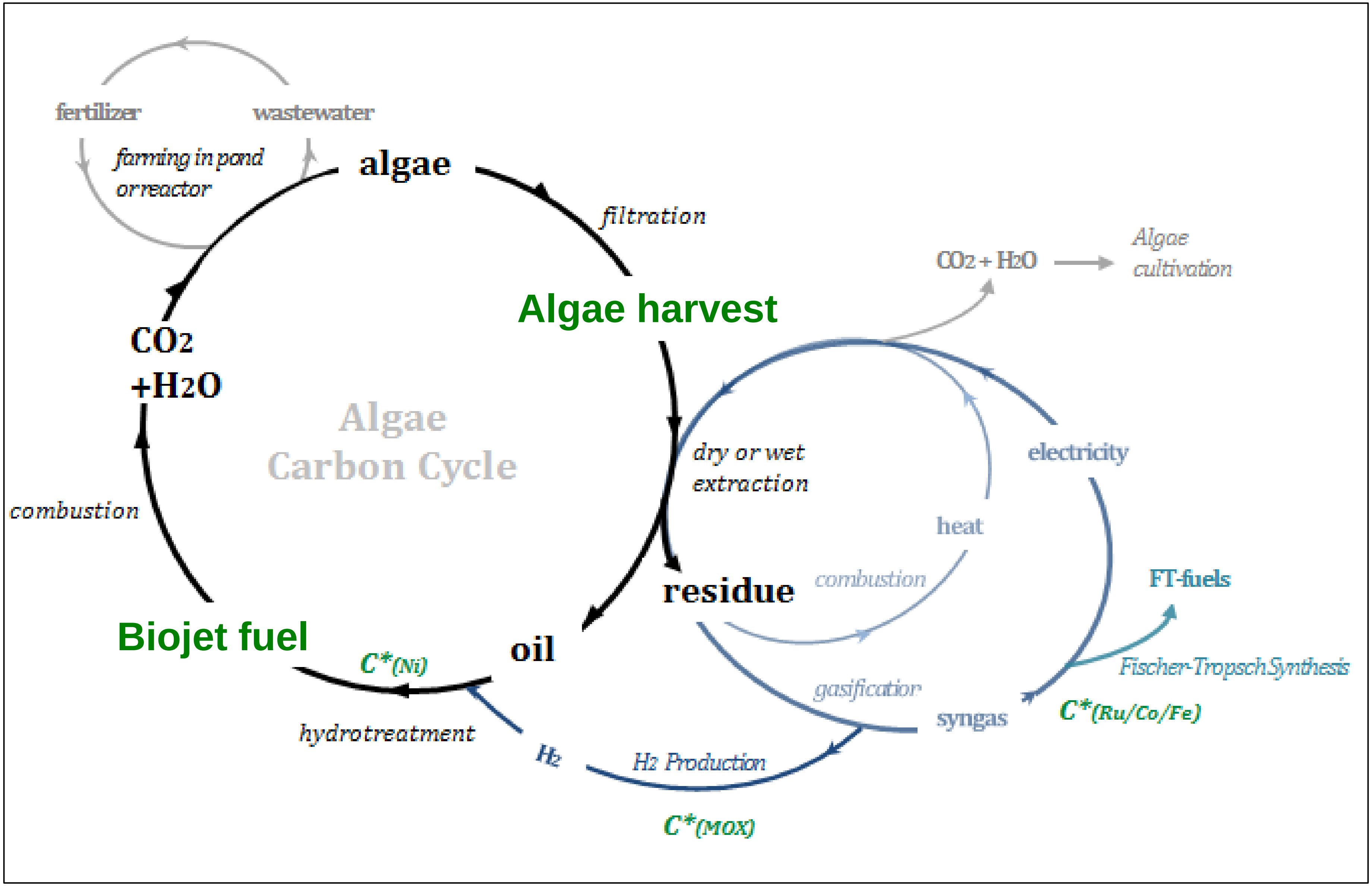
combustion

exhaust gas

aftertreatment

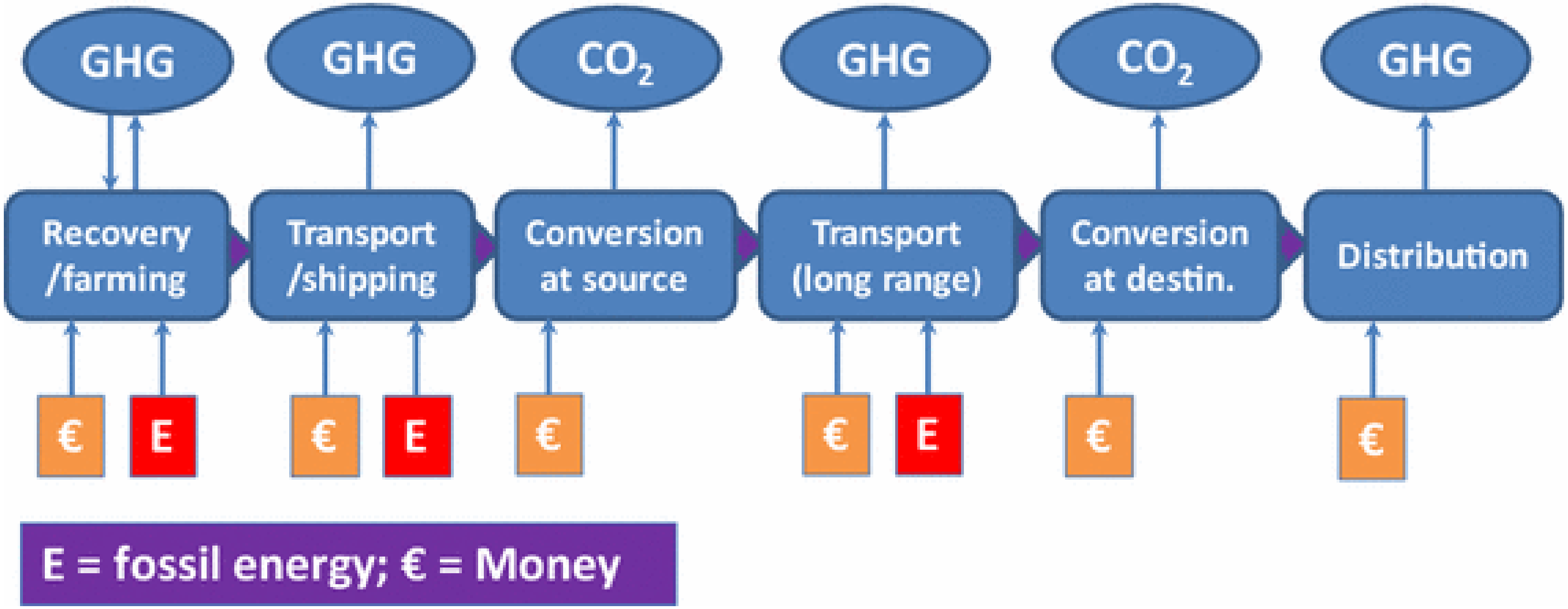
T. Shrivani, X. Y. Yan, O. R. Inderwildi, D. A. King, P.P. Edwards, *Energy & Environmental Science* (2011), 4, 3773-3778

The importance of Catalysis for the Algae Fuel Carbon Cycle



T. Shrivani, X. Yan, O. Inderwildi, D. A. King, P.P. Edwards (2012)

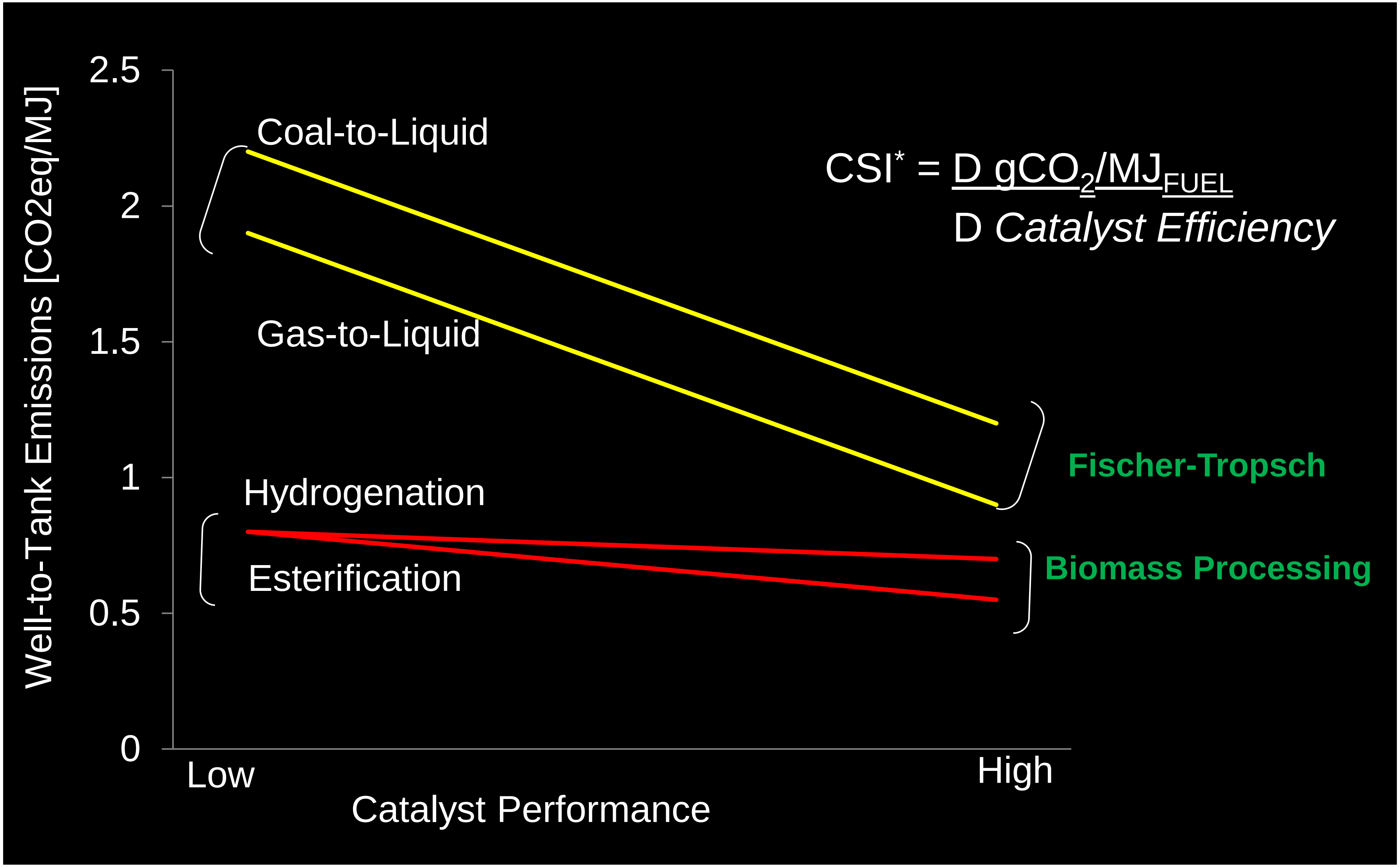
Life Cycle Analysis of a complete energy process



E = fossil energy; € = Money

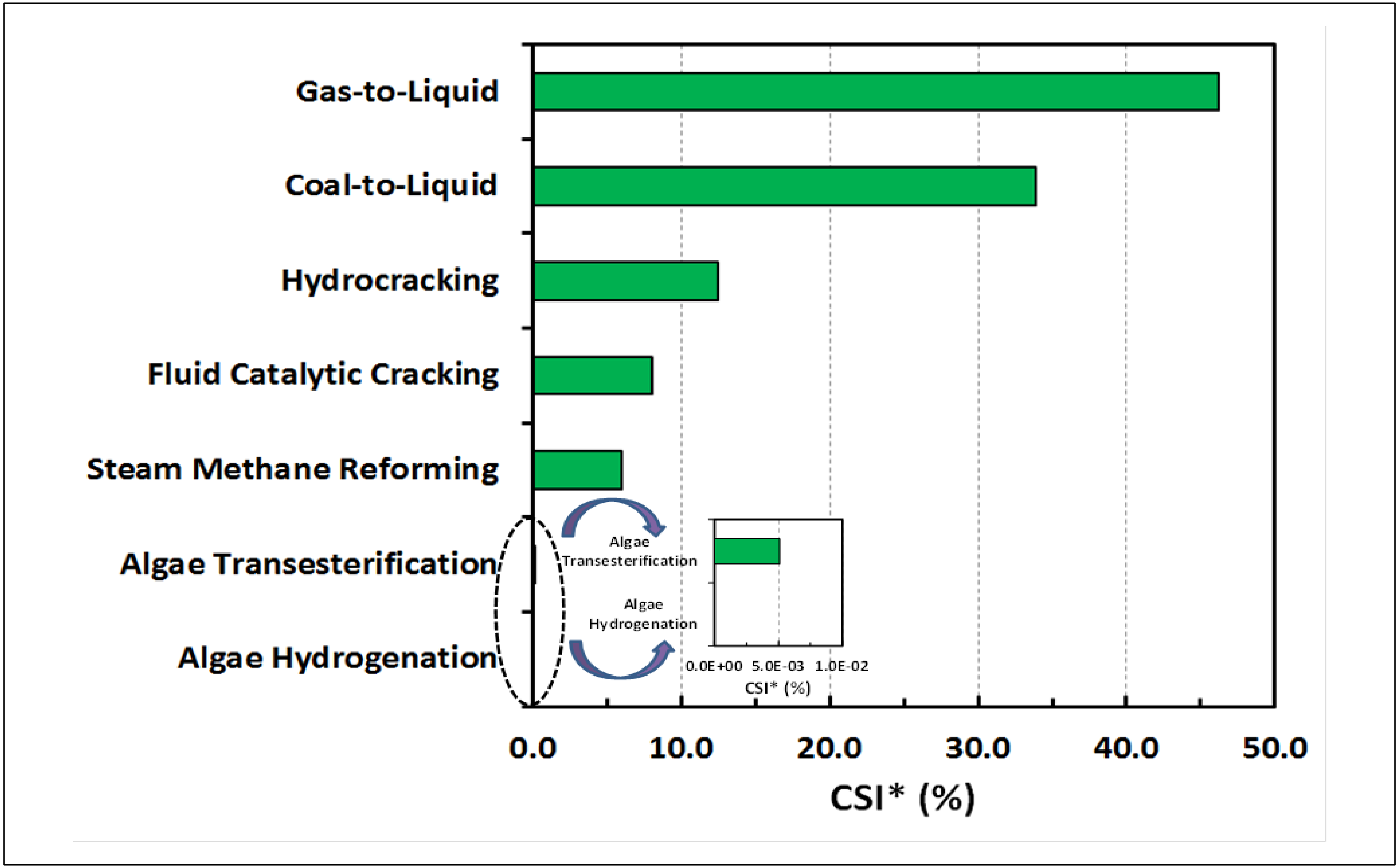
T. Xiao, T. Shrivani, O. Inderwildi, S. Gonzalez-Cortes, H. Almegren, D. A. King, P. P. Edwards, *Topics in Catalysis*, 2015, **58**, 10, 682

The Catalyst Sensitivity Index: Quantifying the Sensitivity of the Carbon Footprint of any Process on Catalyst Efficiency



T. Xiao, T. Shrivani, O. Inderwildi, S. Gonzalez-Cortes, H. Almegren, D. A. King, P. P. Edwards, *Topics in Catalysis*, 2015, **58**, 10, 682

The Catalyst Sensitivity Index:
Various catalytic processes involving fuel production and conversion



T. Xiao, T. Shrivani, O. Inderwildi, S. Gonzalez-Cortes, H. Almegren, D. A. King, P. P. Edwards, *Topics in Catalysis*, 2015, **58**, 10, 682

▶ Humanity faces a choice between two futures: doing nothing to curb emissions (which poses huge climate risks) and bringing them under control (which has costs but also benefits).

A Plan to Keep Carbon in Check

Getting a grip on greenhouse gases is daunting but doable. The technologies already exist. But there is no time to lose

BY ROBERT H. SOCOLOW AND STEPHEN W. PACALA

OVERVIEW

- Humanity can emit only so much carbon dioxide into the atmosphere before the climate enters a state unknown in recent geologic history and goes haywire. Climate scientists typically see the risks growing rapidly as CO_2 levels approach a doubling of their pre-18th-century value.
- To make the problem manageable, the required reduction in emissions can be broken down into "wedges"—an incremental reduction of a size that matches available technology.

Retreating glaciers, stronger hurricanes, hotter summers, thinner polar bears: the ominous harbingers of global warming are driving companies and governments to work toward an unprecedented change in the historical pattern of fossil-fuel use. Faster and faster, year after year for two centuries, human beings have been transferring carbon to the atmosphere from below the surface of the earth. Today the world's coal, oil and natural gas industries dig up and pump out about seven billion tons of carbon a year, and society burns nearly all of it, releasing carbon dioxide (CO_2). Ever more people are convinced that prudence dictates a reversal of the present course of rising CO_2 emissions.

The boundary separating the truly dangerous consequences of emissions from the merely unwise is probably located near (but below) a doubling of the concentration of CO_2 that was in the atmosphere in the 18th century, before the Industrial Revolution began. Every increase in concentration carries new risks, but avoiding that danger zone would reduce the likelihood of triggering major, irreversible climate changes, such as the disappearance of the Greenland ice cap. Two years ago the two of us provided a simple framework to relate future CO_2 emissions to this goal.

We contrasted two 50-year futures. In one future, the emissions rate continues to grow at the pace of the past 30 years for the next 50 years, reaching 14 billion tons of carbon a year in 2056. (Higher or lower rates are, of course, plausible.) At that point, a tripling of preindustrial carbon concentrations would be very difficult to avoid, even with concerted efforts to decarbonize the world's energy systems over the following 100 years. In the other future, emissions are frozen at the present value of seven billion tons a year for the next 50 years and then reduced by about half over the following 50 years. In this way, a doubling of CO_2 levels can be avoided. The difference between these 50-year emission paths—one ramping up and one flattening out—we called the stabilization triangle [*see box on page 52*].

To hold global emissions constant while the world's economy continues to grow is a daunting task. Over the past 30 years, as the gross world

KENN BROWN

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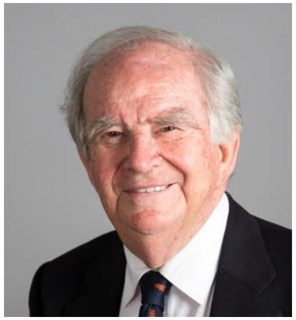
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Sir David King


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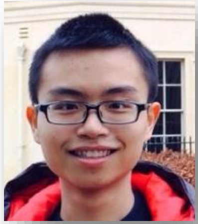
Afrah Aldawsari


Benzhen Yao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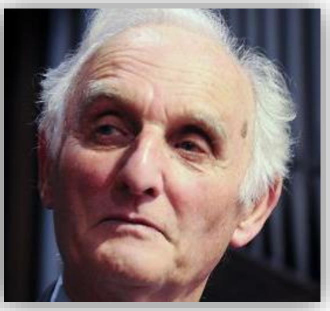
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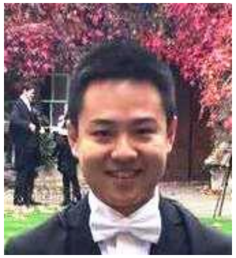
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