NTNU
Kunnskap for en bedre verden

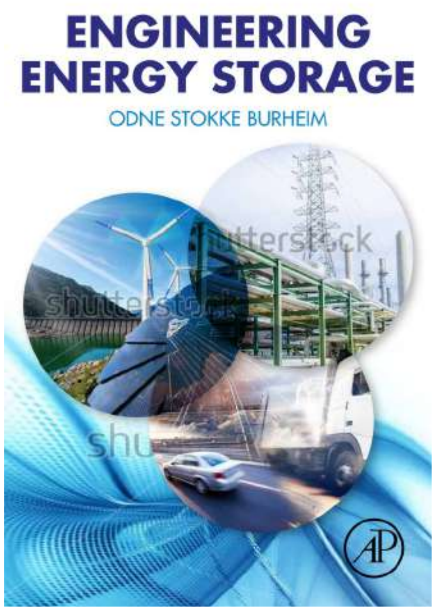
ENERSENSE

Hydrogen og Brenselcelleteknologi:

Hvor er vi nå?

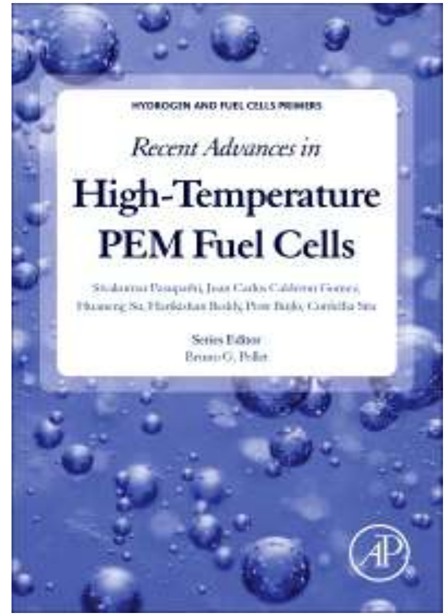
Professor Bruno G. Pollet
EPT, NTNU, Trondheim
rentnu.org

Odne S. Burheim



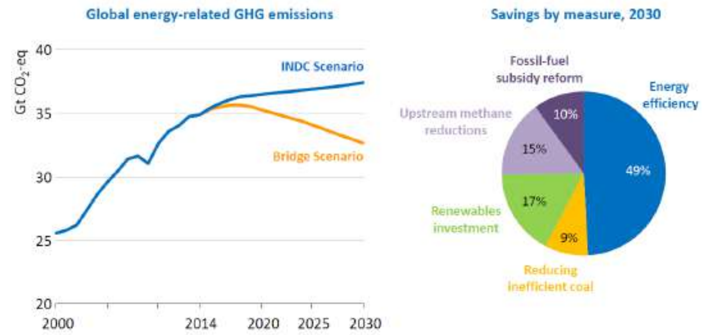
- Professor, Energy Storage
- Li-ion Batteries and PEM Fuel Cells
- Energy: Production, Consumption and Storage
- 7 Fellowships in Energy
- 5-6 in Electrochemical Energy Conversion

Bruno G. Pollet



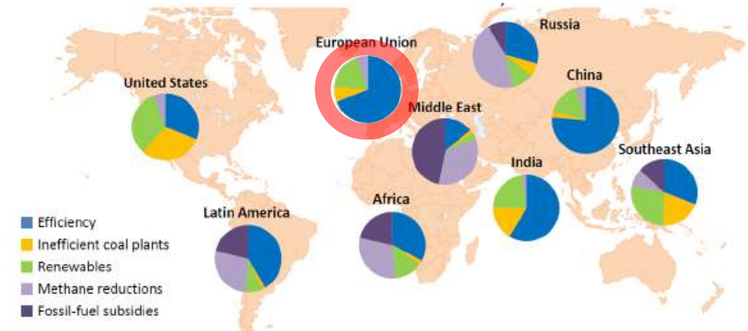
- Professor, Renewable Energy
- PEM Fuel Cells; Electrochemical Engineering
- Energy: Materials Development, Materials & System Manufacturing, System Integration
- Worked in industry (e.g. Johnson Matthey FC)
- Over 200 publications inc. 4 books

The *trinity nexus*



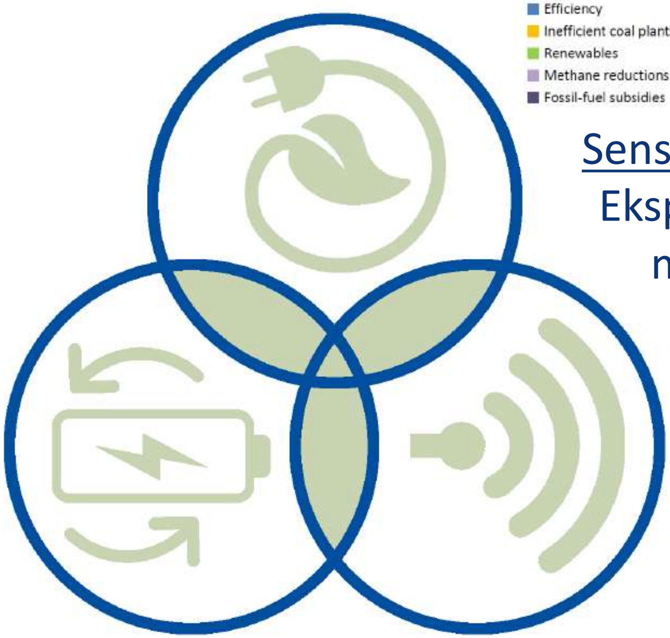
Energieffektivitet:

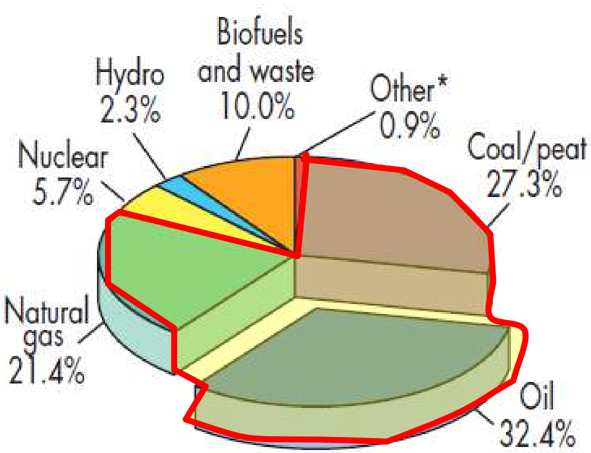
I europa må 2/3 av totalinnsatsen mot 2º-målet rettes mot energieffektivitet.



Sensor-instrumentering:

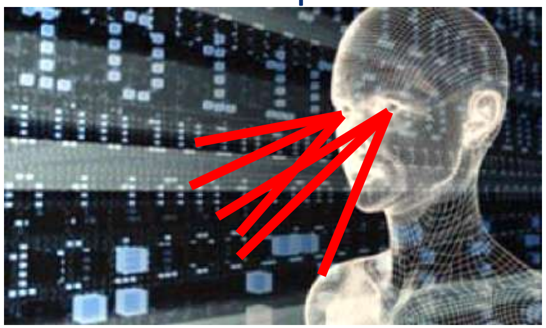
Eksperimentell dokumentasjon til modellering og beregninger.





12 717 Mtoe

Optiske sensorer



Energilagring:

80% av dagens energi må erstattes med fornybar energi – energi som må lagres i en annen form

ENERSENSE

What is *ENERSENSE*?

What makes *ENERSENSE* unique and important for NTNU

- ✓ *New & unique ideas:* We focus on the boundaries of energy storage, sensors instrumentation and energy efficiency
- ✓ *Quality:* Competence level programmes

  Assistant → Associate → Professor
- ✓ *New alliances*: Unite researchers from former HiST & former NTNU
- ✓ *External funding:* We get research grants externally

ENERSENSE

Background – June 2015

- History as a University College
- *ENERSENSE* is a catalyst, uniting NTNU-groups across mamy faculties – an interfacultary center
- Purpose: scientific, societally founded and beneficiary

Energy Storage

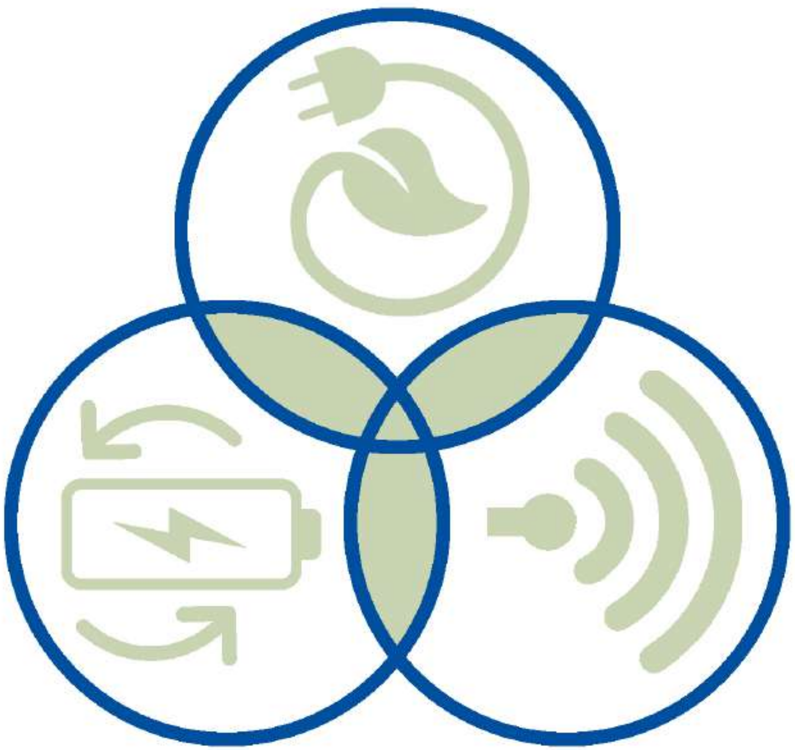
Energy Efficiency

Sensor Systems

Trinity inter-action output
The *Trinity Nexus*

- Interdisciplinary projects between the three fields:

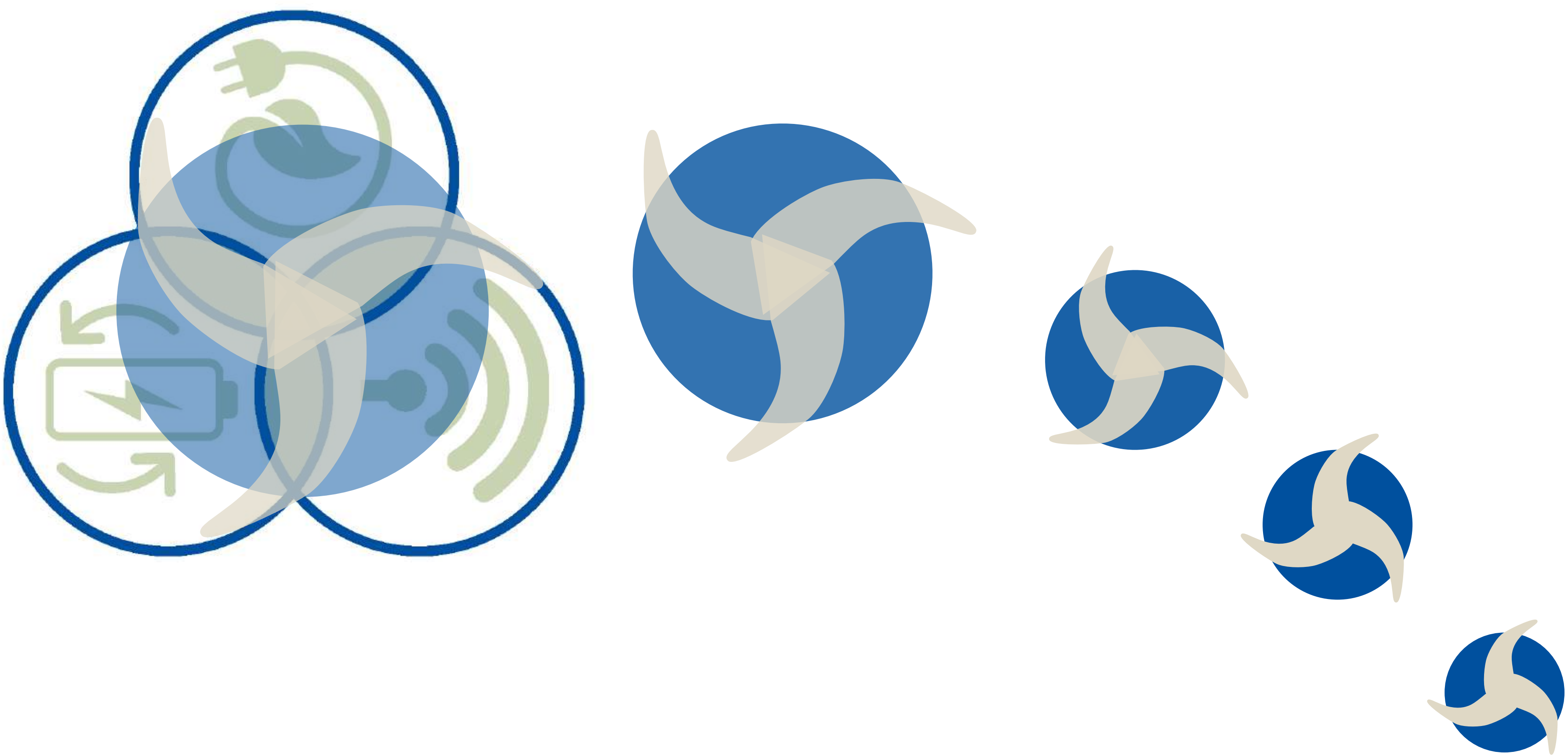
Energy Efficiency, Energy Storage and Sensors Instrumentation



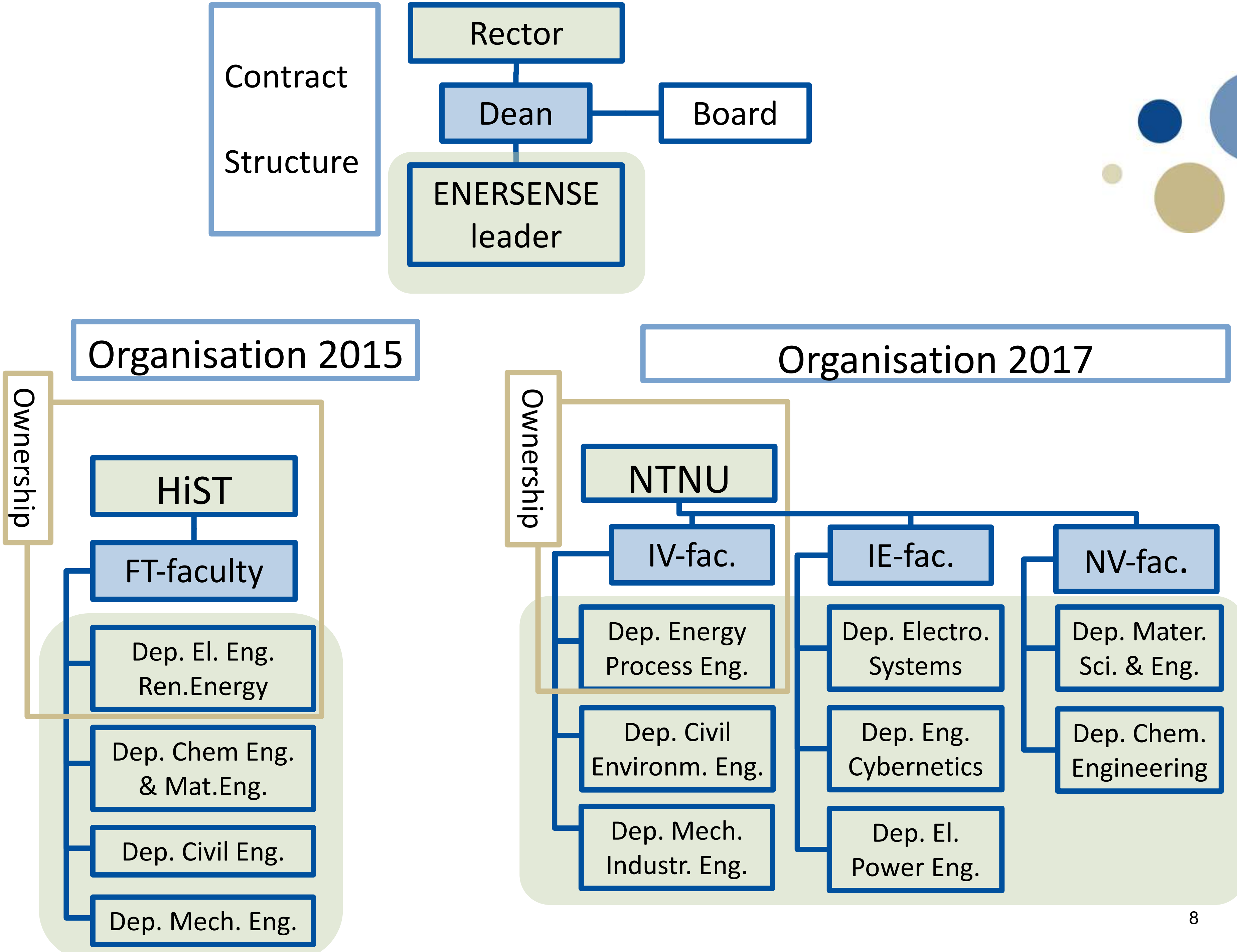
ENERSENSE

The *trinity nexus*

- Trinity inter-action output – **nye ideer spinner ut!**



ENERSENSE


Contract
Structure
Rector
Dean
Board
ENERSENSE leader
Organisation 2015
Ownership
HiST
FT-faculty
Dep. El. Eng. Ren.Energy
Dep. Chem Eng. & Mat.Eng.
Dep. Civil Eng.
Dep. Mech. Eng.
Organisation 2017
Ownership
NTNU
IV-fac.
IE-fac.
NV-fac.
Dep. Energy Process Eng.
Dep. Civil Environm. Eng.
Dep. Mech. Industr. Eng.
Dep. Electro. Systems
Dep. Eng. Cybernetics
Dep. El. Power Eng.
Dep. Mater. Sci. & Eng.
Dep. Chem. Engineering

Who participates within *ENERSENSE*?
3 Faculties & 7 Departments

IV-fakultetet:
- Odne Burheim (EPT)
- Tania Bracchi (EPT)
- Kristian Lien (EPT)
- Bruno G. Pollet (EPT)
- Magnus Thomassen (EPT)
- Håvard Karoliussen (EPT)
- Øivind Wilhelmsen (EPT/sintef)
- Bozena Hrynyszyn (BMT)
- Bjørn Austbø (MPT)
- Ola Ruch (MPT)

NV-fakultetet:
- Sondre Schnell (IMT)
- Frode Seland (IMT)
- Kristian Etienne Einarsrud (IMT)
- Iselin Grav Aakre (IMT)
- Magne Hillestad (IKPT)
- Erling Rytter (IKPT)

IE-fakultetet:
- Dag Roar Hjelme (El.Sys.)
- Dominik Osinski (El.sys.)
- Rolf K. Snilsberg (El.Sys)
- Fredrik Dessen (Kyb.)
- Håkon Grønning (El.Sys.)
- Pål Keim (Elkraft)

Other keywords:
- Young team - a future team (many less than 40)
- An NTNU strategic project within engineering science
- 14 PDF and PhDs – as of fall 2017
- We support international efforts and exchanges
- CANOPENER is an early achievement
- REN-BTL, HyBIG, PoreLab, and others too

ENERSENSE

5 granted areas...

CANOPENER 2017
19th - 23rd June, Trondheim, Norway

2. *Høgskolestyret vedtar følgende rammer for tildeling:*

Forskningsmiljø	Årlig tildeling for perioden 2015-2023*	Rekrutteringsstilling er tildelt 2015 gjeldende fra 01.01.2016	Rekrutteringsstilling er tildelt 2015 gjeldende fra 01.01.2019
a. ENERSENSE	3 mill	2	2
b. Helse i kontekst	3 mill	2	2
c. Literacy	1.5 mill	2	2
d. Regulering og styring	1.5 mill	2***	2
e. OPTiMAT	1.5 mill**	2	2

SFF 2017: Porelab - kontekst

Porous Media Laboratory (*PoreLab*)

WP5: Thermodynamic Driving Forces, Øivind Wilhelmsen

WP7: Applications: Porous Layers for PEM Fuel Cells and CO_2 sequestration

the ENERSENSE group at NTNU gives broad experimental support on fuel cell testing.

ENERSENSE

Past & Current Collaborators

Batteries and fuel cells

Johnson Matthey Fuel Cells
the power within
Rolls-Royce
Johnson Matthey
TATA
GM
AIRBUS
AN EADS COMPANY
EADS
Eskom
DAIMLER
e·on
AREVA
acal energy
Clean affordable power
Unilever
IMPALA PLATINUM
EDF ENERGY
AIR PRODUCTS
AIR LIQUIDE
Intelligent Energy
BAXI INNOTECH
fuel cell heating
ANGLO AMERICAN
BALLARD
PUTTING FUEL CELLS TO WORK
UTC Power
A United Technologies Company
Bac2
Conductive Composites
MICRO CAB
ITM POWER
Energy Storage | Clean Fuel

Past & Current Collaborators

Batteries and fuel cells

UFRGS

Argonne NATIONAL LABORATORY

IFE

University of Yamanashi
Fuel Cell Nanomaterials Center

cnrs

INRIA

cea

Newcastle University

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

HiST TRONDHEIM

中山大學 SUN YAT-SEN UNIVERSITY

CHINESE ACADEMY OF SCIENCES

KAIST
KOREA ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY
한국과학기술원
SINCE 1971

UCL

Los Alamos NATIONAL LABORATORY

Queen's UNIVERSITY

中國科学院
CHINESE ACADEMY OF SCIENCES

AALBORG UNIVERSITY DENMARK

ZSW

Technical University of Denmark

DTU

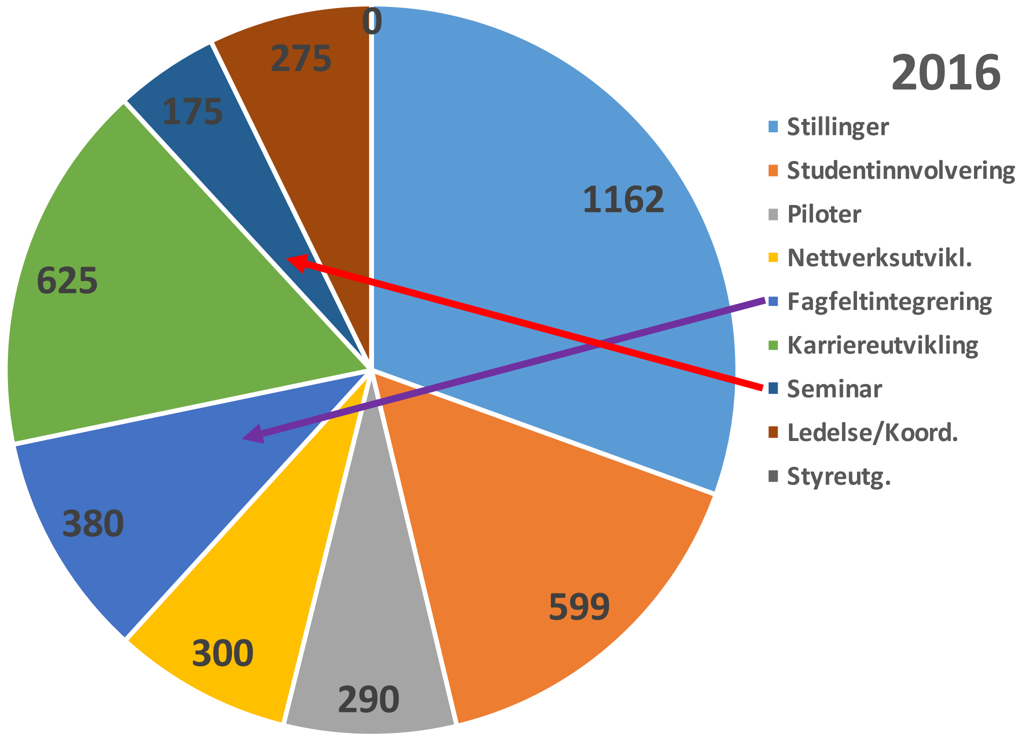
University of ULSTER

جامعة الملك عبدالله للعلوم والتقنية
King Abdullah University of Science and Technology

Catalysis for Energy Conversion

Budsjett & måloppnåelse

- Årlig 3Mkr fra Rektor
- Årlig 800 kkr fra Dekan
- 2 RSO stillinger i 2016 og 2 i 2020



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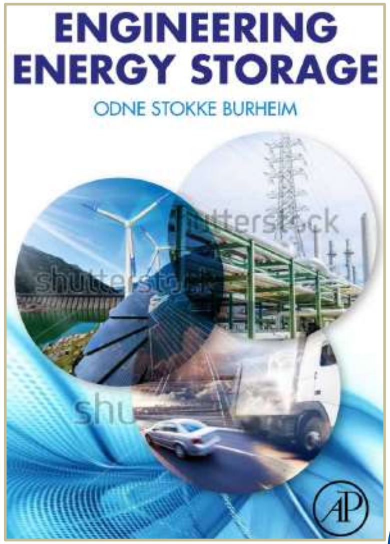
Energy Efficiency & Storage

- **Industry transport:**
  - Biogas
    - ***Skogn industry: Liquid biogas***
    - ***Biogas as «Hydrogen-carrier»***
    - **Samarbeid:** Biokraft AS, Purac, Cambi, Ecopro, AtB, Avinor, STFK, NTFK, CENBIO / NUMB, Trønder-energi, NTE, Statkraft, AGA
- **Buildings:**
  - ***nZEB***
    - Automatisation

- **ENGINGEERING ENERGY STORAGE**



ENERSENSE

Effektiv Energigbruk

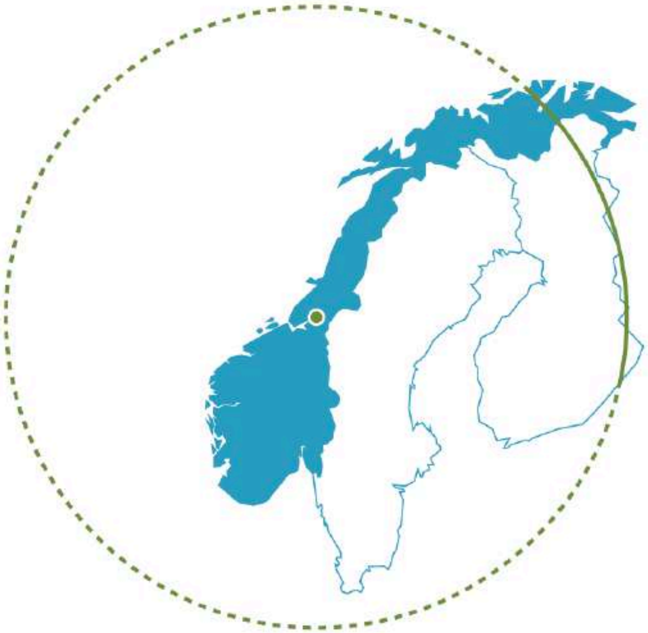
- **Industri / Transport:**
  - **Biogass Flytende vs komprimert**

DAGENS BIOGASSMARKED

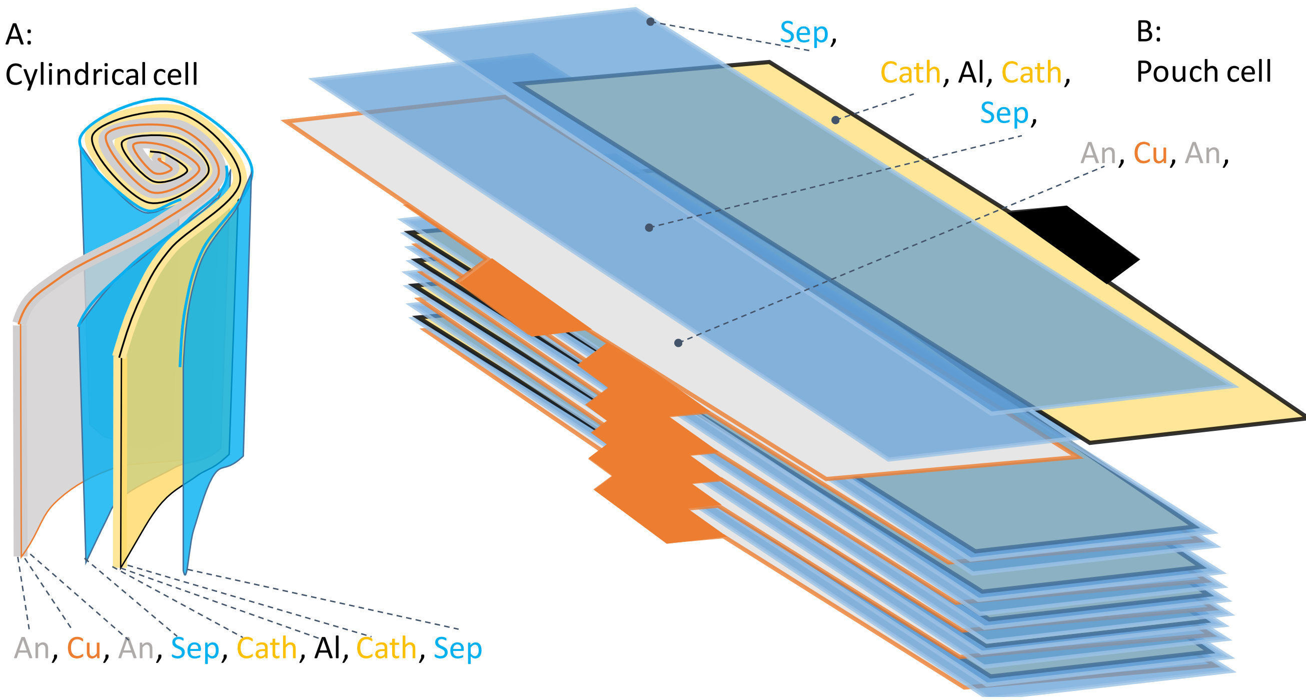
BIOKRAFT ENDRER MARKEDET – "GAME CHANGER"

CBG

LBG



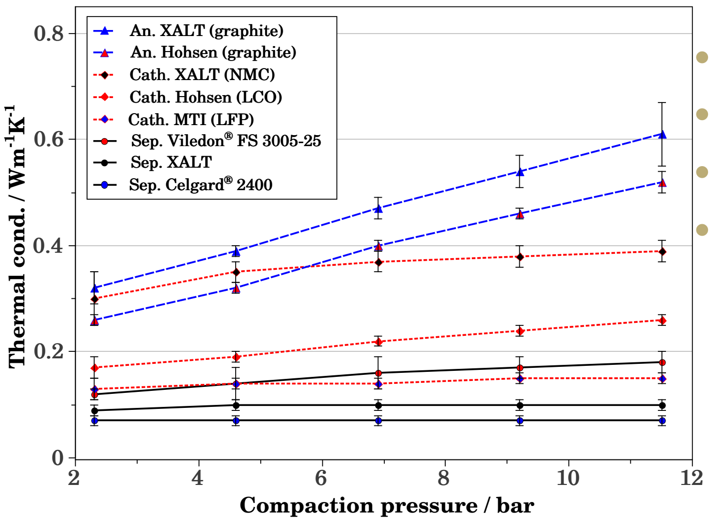
Anodes, cathodes and separators are: rolled in cylindrical batteries (A) ; stacked in poach cells (B)

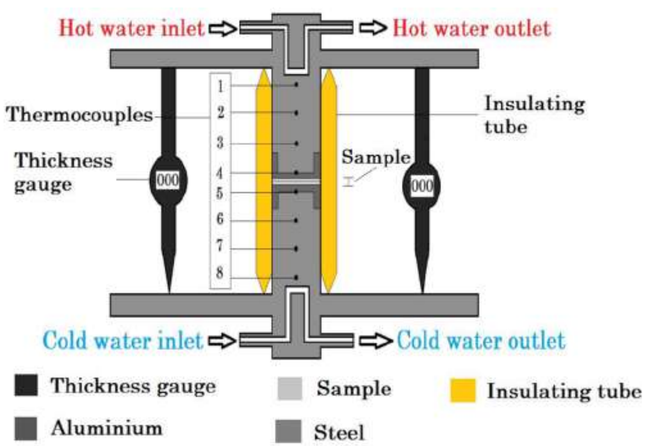


Batteries and fuel cells

Materials development | Cell assemblies & manufacturing | **Systems engineering** | Ageing & life assessment

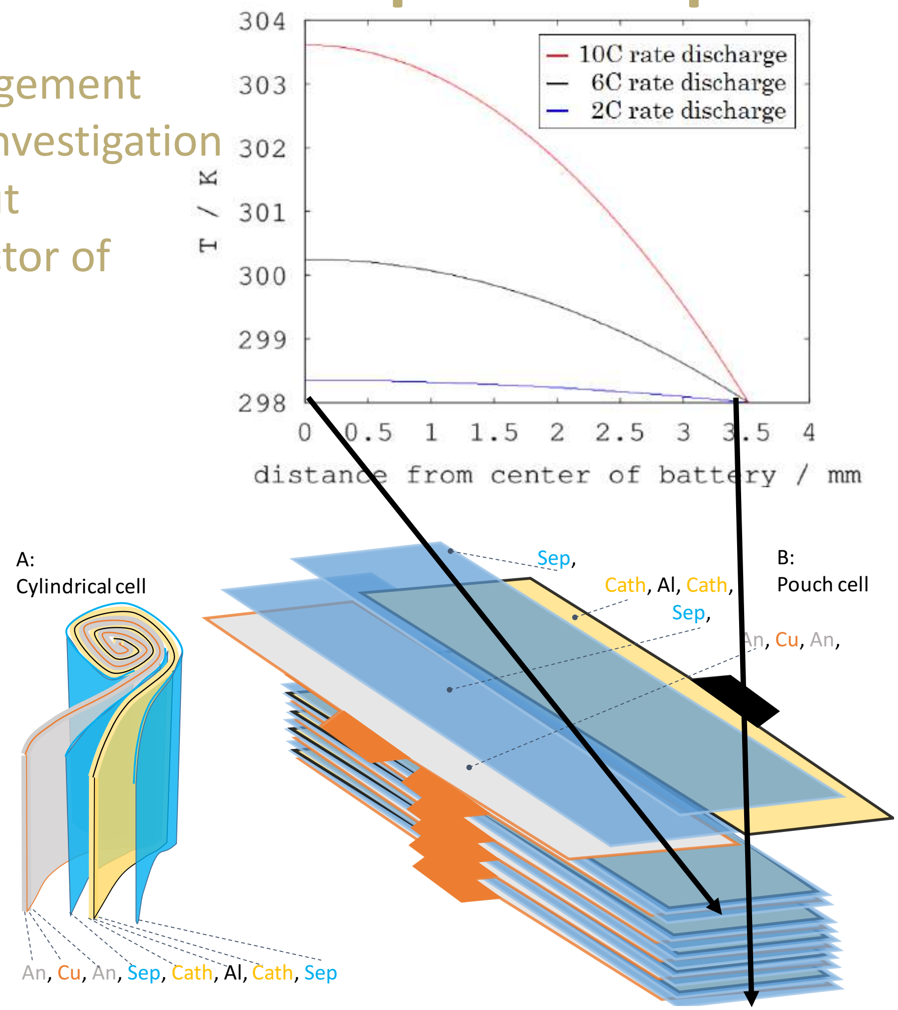
Thermal conductivity





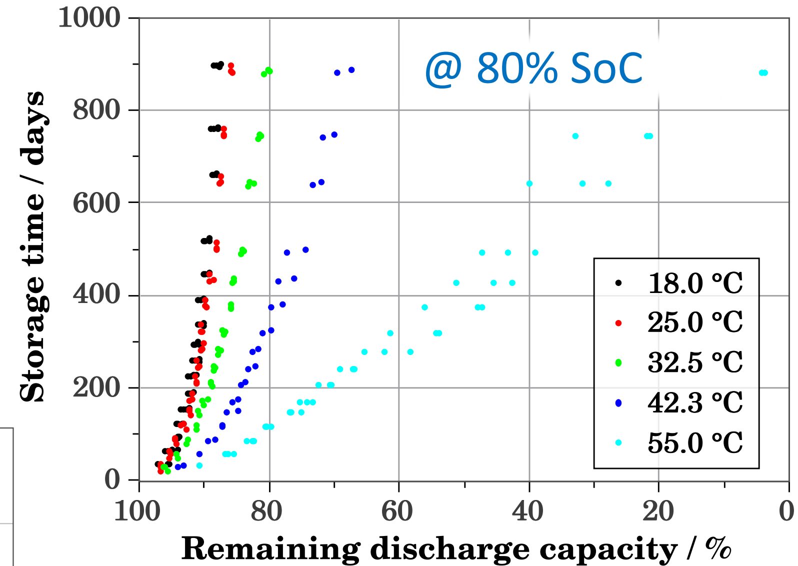
- Heat management
- Electrode investigation
- Model input
- Range a factor of **20 times**!

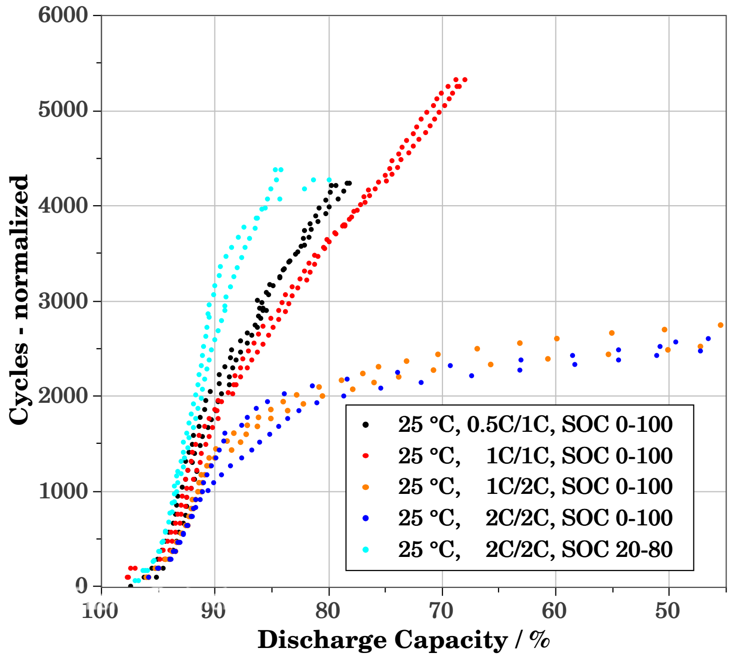
Internal temperature profile

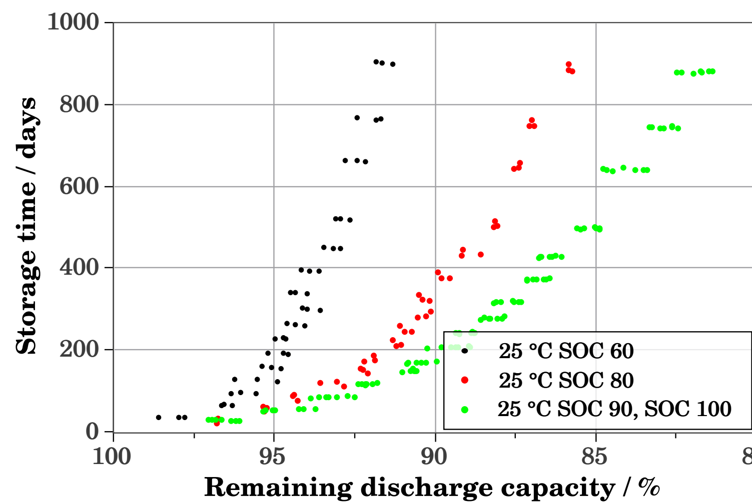


Ageing effects

1. Temperature accelerate ageing
2. Discharge rate is important
3. Charging is less important
4. Models derived – battery specific







Global Issues

CO_2 & global warming

Improved fuel efficiency and non carbon fuels favoured

'Business-as-usual' energy scenario could lead to catastrophic Climate Change by the late 21st century!

Around a 1/3 of CO_2 emission from transport in the UK

Energy demand

To exceed **30,000 TWh** by 2030!

Oil production to peak in 2010-2020 (?)

Most oil produced from a fewer giant fields - production from these fields will peak around 2015

➔ 2007 Oil Reserves stand at 1237.9 billion barrels (BP estimate)

➔ This will encourage alternative fuels (in theory!)

Population growth ....

Longer life expectancy ➔ rise in world population from 6.3 Billion to 9 Billion over next 45 years is inevitable!

➔ Improved pollution standards required just to keep up!

Challenges for the Energy Sector

- Climate change & security of supply issues must be addressed very quickly!

- EU primary energy resources [fossil fuels e.g. Oil(35%)/NG (39%)/Coal(15%) inc. renewable energy (2%) & nuclear (9%)] are diminishing → affordable, available & low carbon energy is required

- The EU is currently reliant upon 3 main energy vectors (carriers) = Petroleum Products/NG/Electricity

FACTS about Hydrogen

Energy in 1 gallon of Petrol ≈ 1 kg of Hydrogen

Efficiencies:

Petrol ICEs = 18-20%; Hydrogen ICEs = 25%; Hydrogen Fuel Cell Vehicles = 60%

3 X better than today's petrol fuelled engines!!!

➔ Amount of energy produced by hydrogen per unit weight of fuel is about 3 X the amount of energy contained in an equal weight of petrol & almost 7 X that of coal! Energy Content: 60,958 Btu/lb – highest energy content of all fuels on a weight basis

Hydrogen energy density per volume is quite low at STP

Volumetric energy density can be increased by storing the hydrogen under increased pressure or storing it at extremely low temperatures as a liquid

FACTS about Hydrogen

Uses Today and Future

- **Today**: chemical processing, petroleum industry, fats and oils, metals, electronics, space flight, utilities, glass manufacturing, etc…
- **Future**: stationary power, portable power, and transportation

Production

- **Today:** mainly through reformation of fossil fuels (e.g. 100,000 tons of H_2 produced from NG)
- Industrial by-product
- **Future:** from Renewable as well as fossil fuels with carbon sequestration

Recent worldwide hydrogen production totals

Origin	%
Natural gas	48
Oil	30
Coal	18
Electrolysis	4

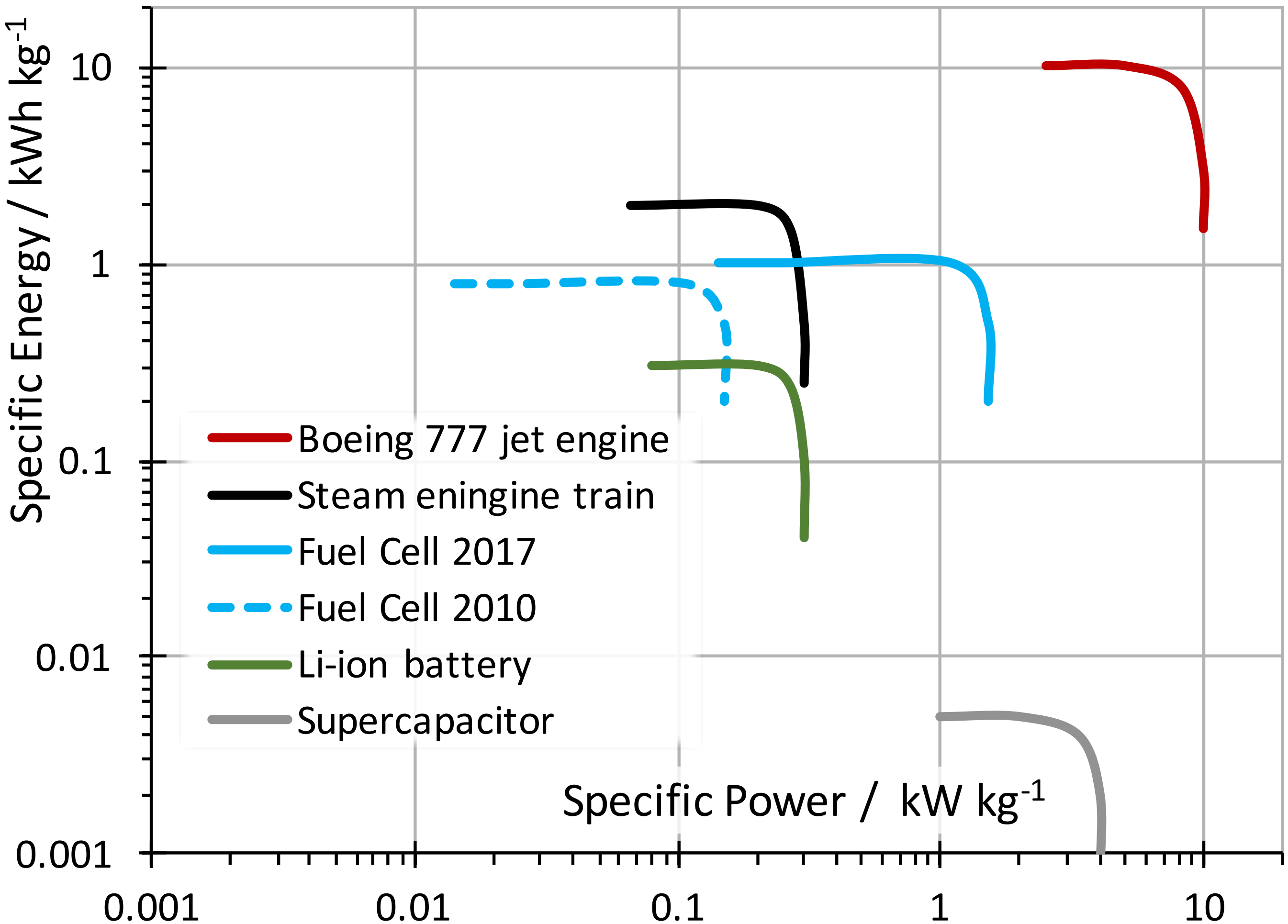
FACTS about Hydrogen

How much hydrogen is used each year?

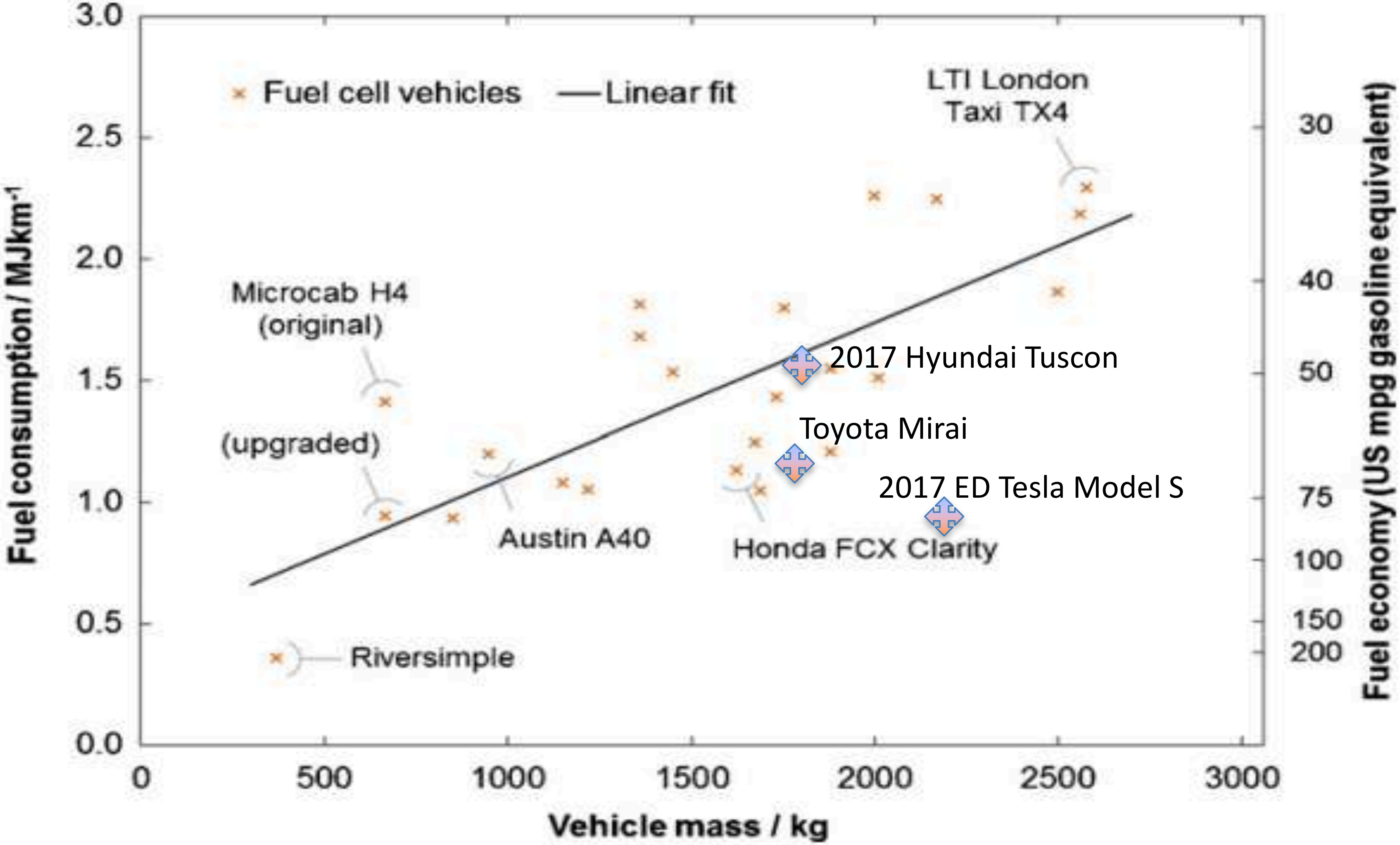
- **>50m tons** of hydrogen per year consumed globally
- **>60m tons** of produced hydrogen globally (forecast = 200,000 tons by 2030)
- **60%** of this becomes feedstock for ammonia production and subsequent use in fertilizer
- Petroleum refining consumes another **23%** to remove sulfur
- Another **9%** is used to manufacture methanol
- Remainder goes for chemical, metallurgical & space purposes

Energy Storage – Where are we now?

- Fuel cells – range, acceleration and fast fueling
- Batteries – efficiency and electric compatibility
- Fuel cells – evolving in performance & cost into 2020's



Energy Consumption – Where are we now?

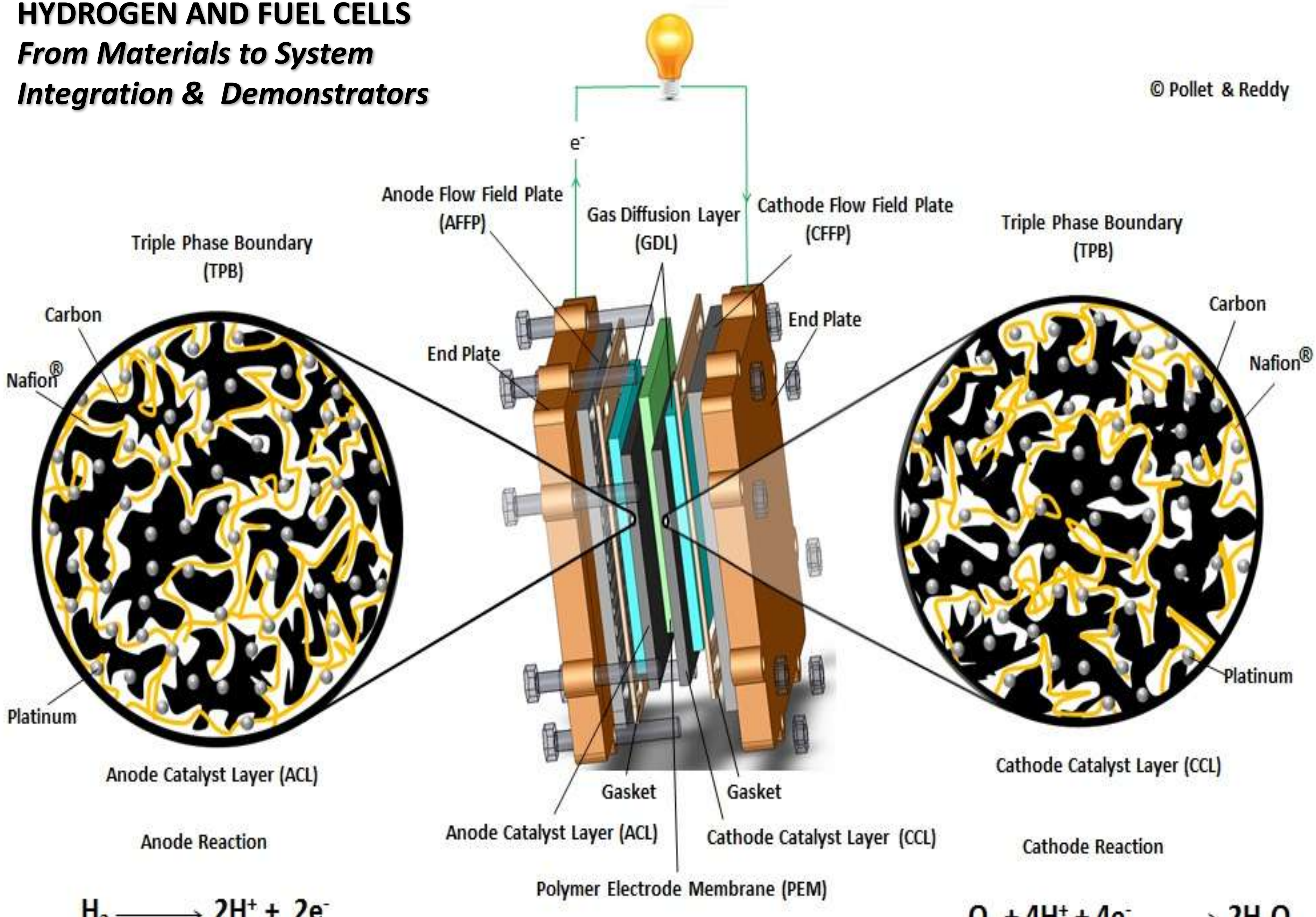


Energy consumption (MJ km^{-1}) measured from 'real-world' testing of 23 hydrogen fuel cell vehicles, plotted against vehicle mass (kg)

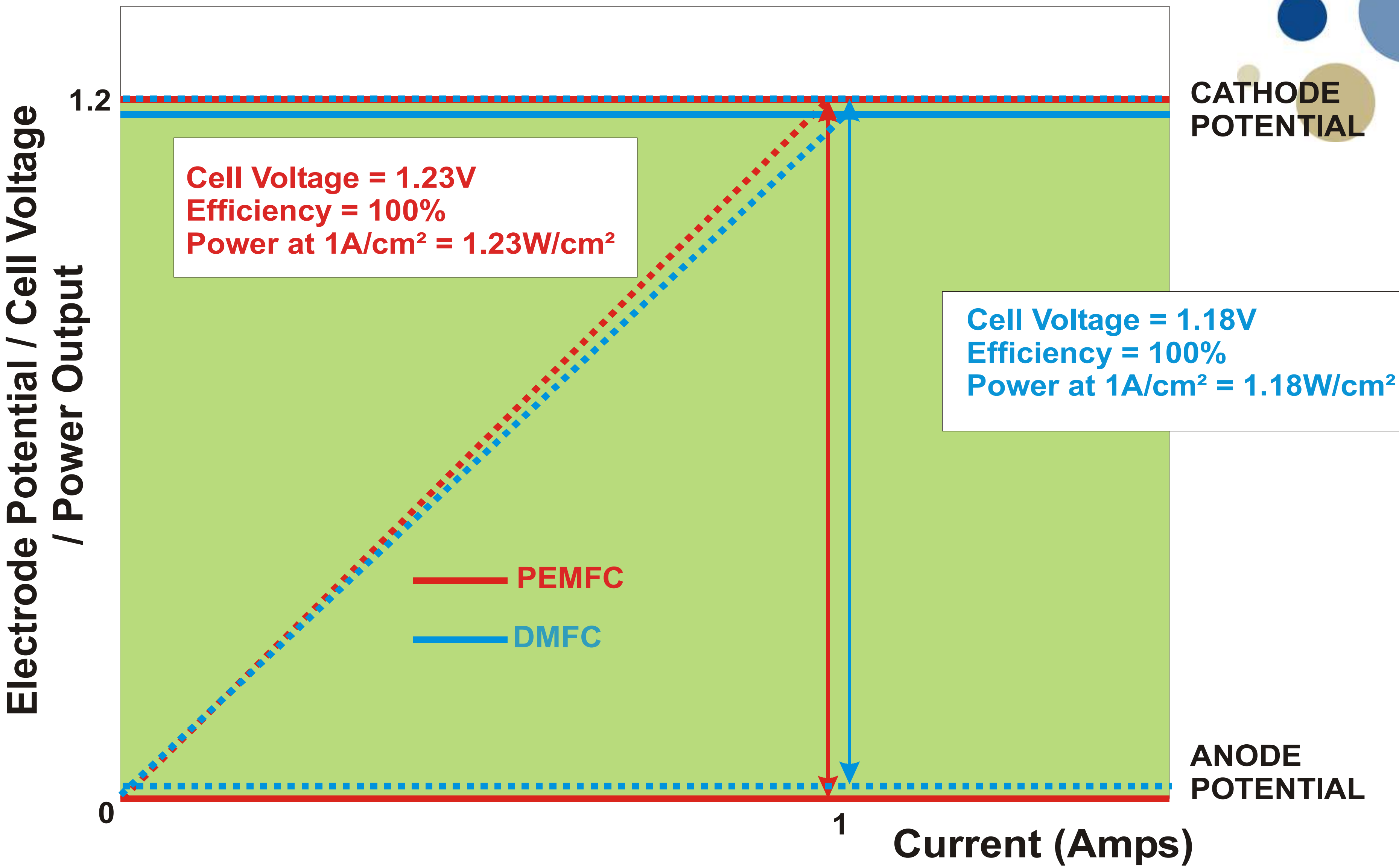
Pollet BG, Staffell I, Shang JL. Current status of hybrid, battery and fuel cell electric vehicles-From electrochemistry to market prospects. Electrochim. Acta 2012; 84:235-49

Courtesy: University of the Western Cape

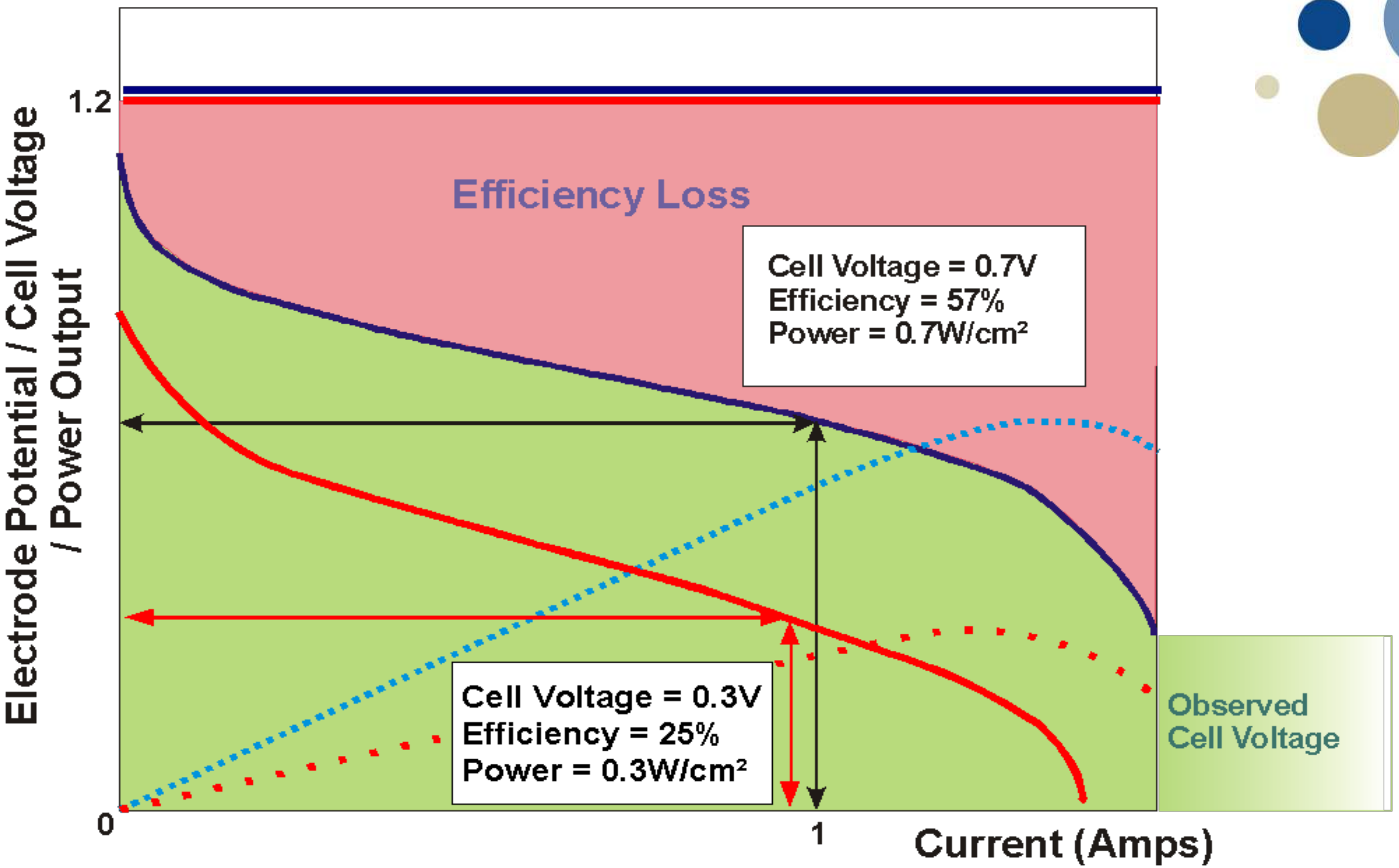
HYDROGEN AND FUEL CELLS
From Materials to System Integration & Demonstrators



An ideal PEM Fuel Cell



A 'real' PEM Fuel Cell

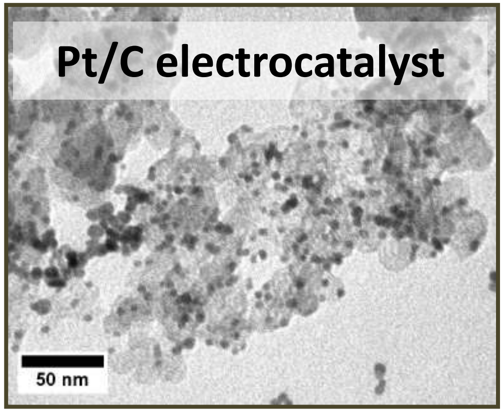


Cost – ~£20/g (~kr 220/g)

For 100 kW stack at a loading of 0.40 g_{Pt}/kW [0.05 $mg.cm^{-2}$ at anode & 0.35 $mg.cm^{-2}$ at cathode] require:

40g of Pt = **£800 (~kr 8,700)**!

Objective: decreasing Pt loading by **10 fold**

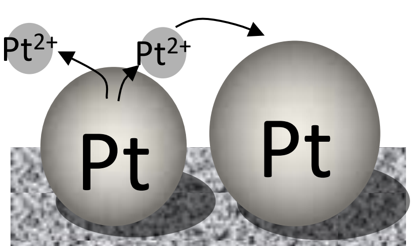


Availability ➔ Scarcity

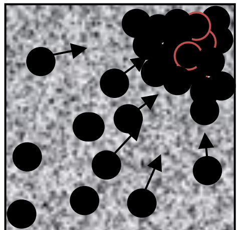
- Worldwide Pt reserves ~ 30,000-100,000 tons
- Annual production rate ~ 30 tons / year
- Commodity market: supply & demand

Durability

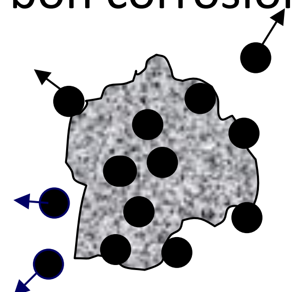
Pt dissolution



Aggregation & sintering



Carbon corrosion



B.G. Pollet, Platinum Metals Review, Volume 57, Issue 2, April 2013, Pages 137-142

Batteries and **fuel cells**

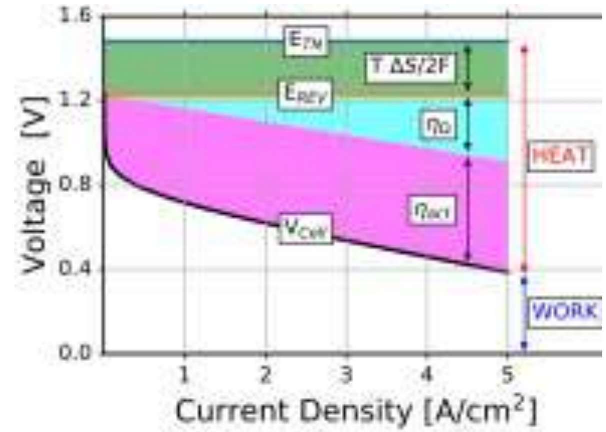
Materials development | Cell assemblies & manufacturing | **Systems engineering** | Ageing & life assessment

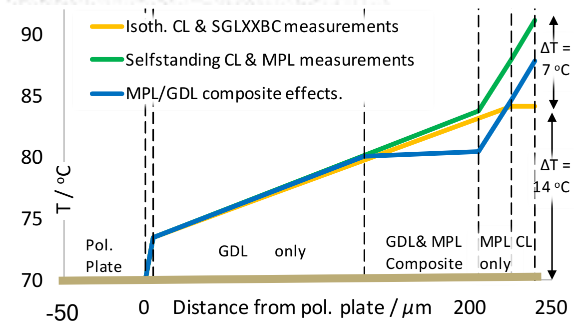
High conversion rates means more heat

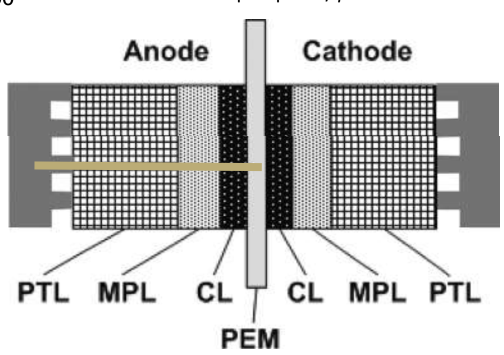
In turn stronger temperature gradients

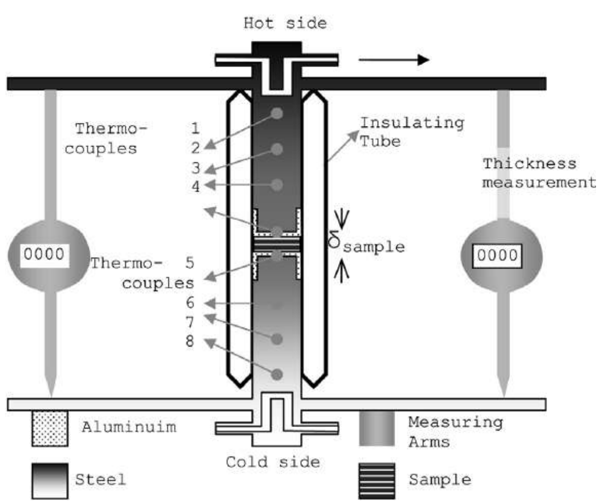
We measure thermal conductivity

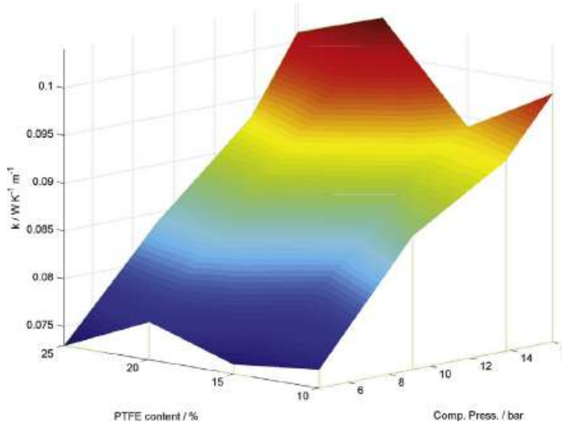
Change pressure and water content







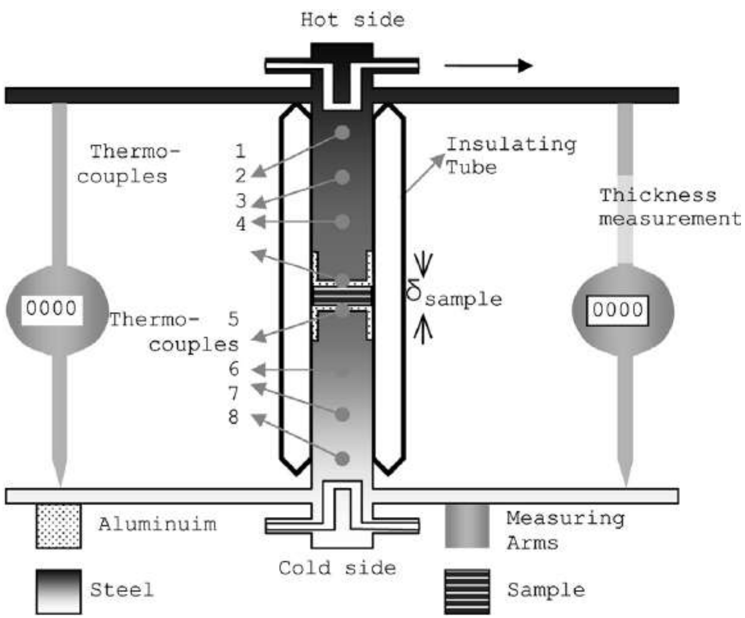


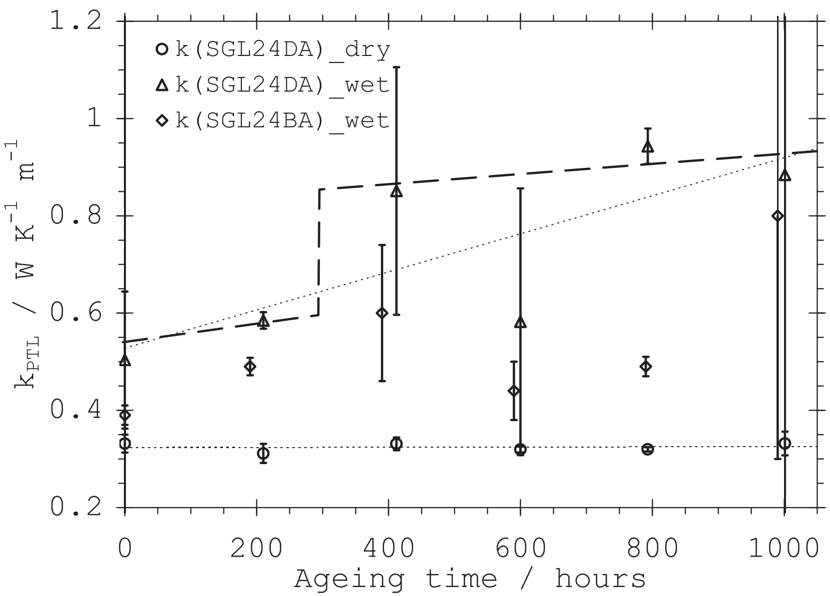


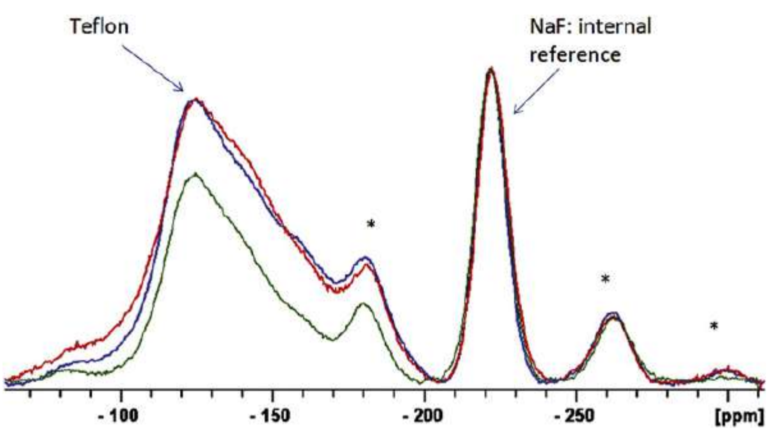
Batteries and **fuel cells**

Materials development | Cell assemblies & manufacturing | Systems engineering | Ageing & life assessment

Ageing removes Teflon
Water retention increases
Thermal conductivity increases





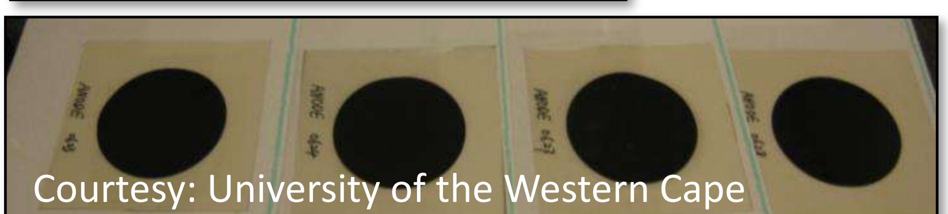


Batteries and **fuel cells**

Materials development → **Cell assemblies & manufacturing** → Systems engineering → Demonstrators

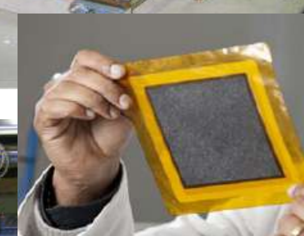
Assembly line development

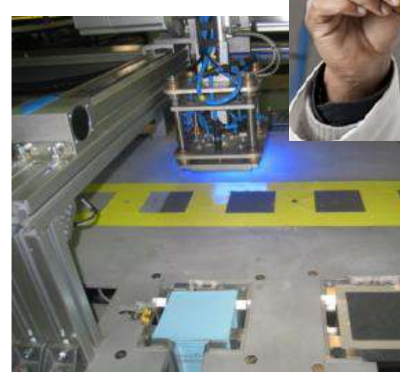
Low Temperature MEA

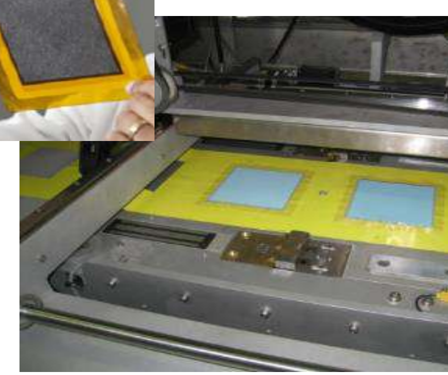


Courtesy: University of the Western Cape

High Temperature MEA



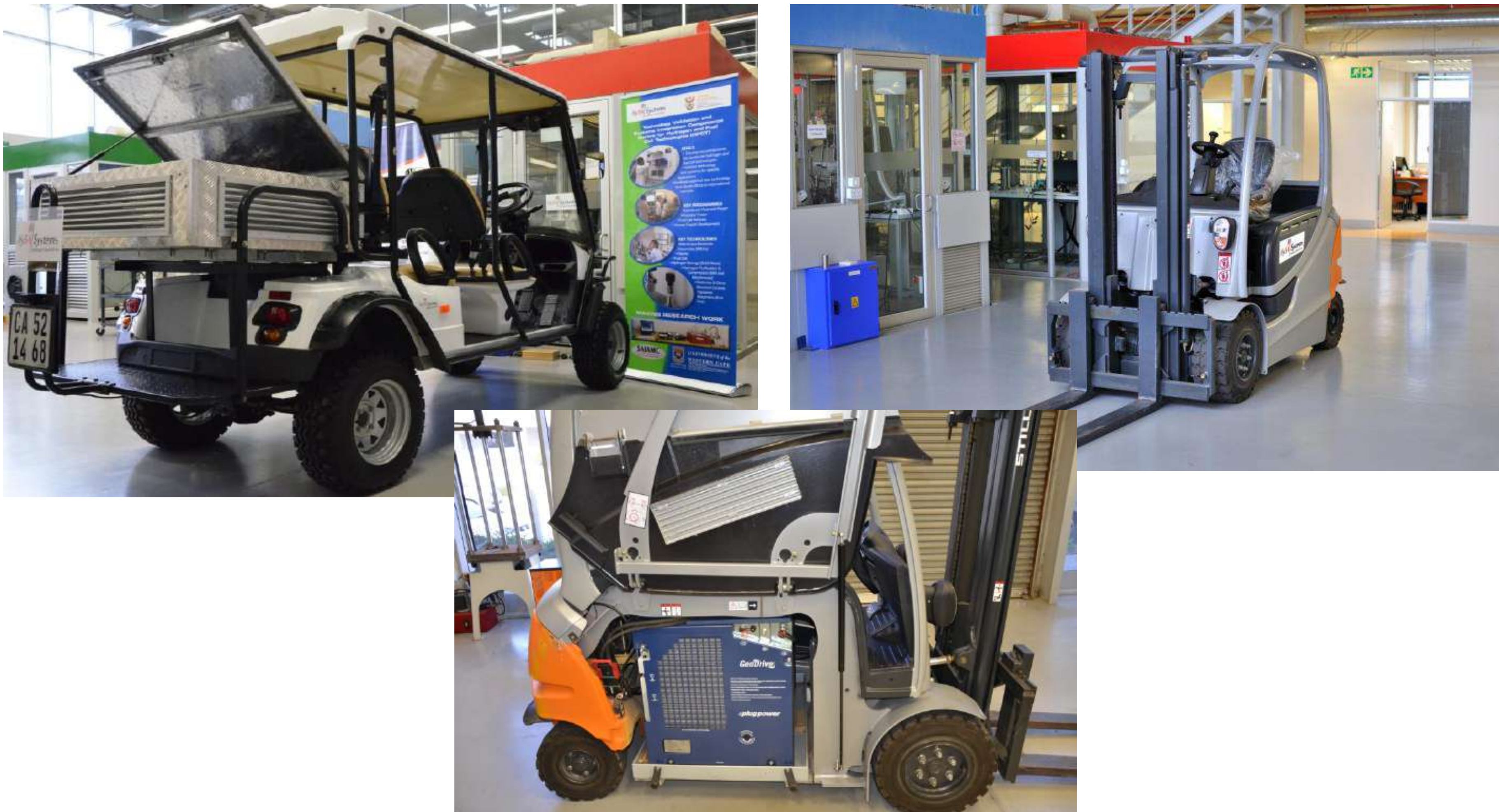




Batteries and **fuel cells**

Materials development → Cell assemblies & manufacturing → Systems engineering → Demonstrators

Hydrogen Fuel Cell/Battery Electric Utility Vehicles



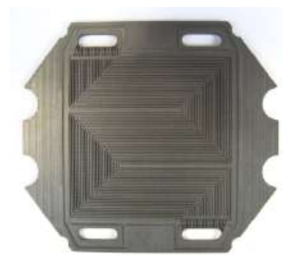
Batteries and fuel cells

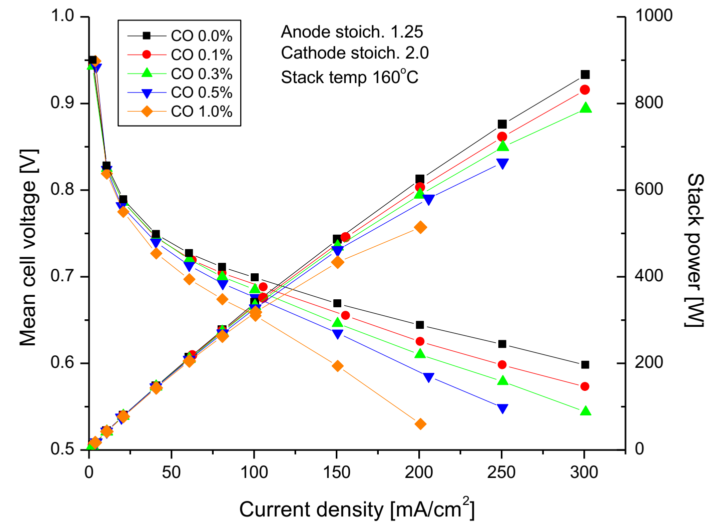
Materials development

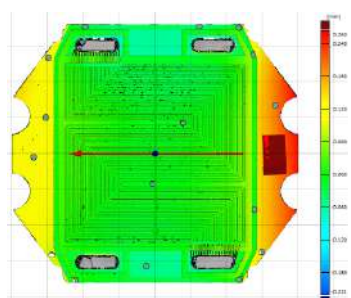
Cell assemblies & manufacturing

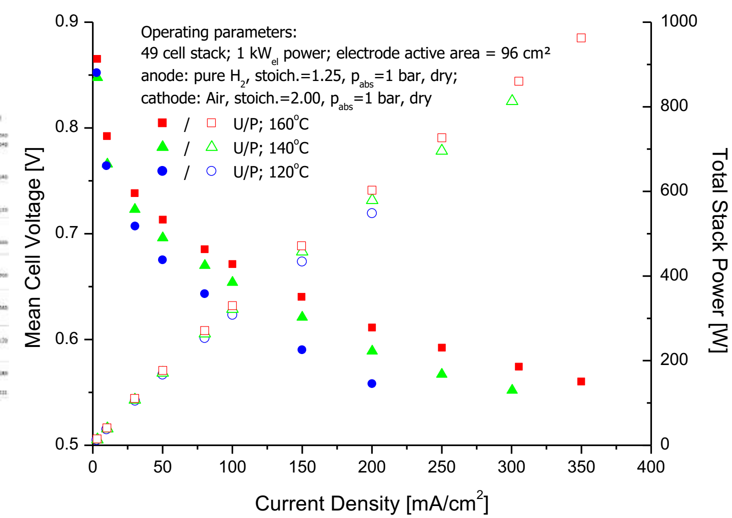
Systems engineering

Ageing & life assessment





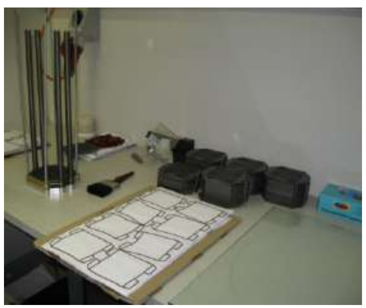


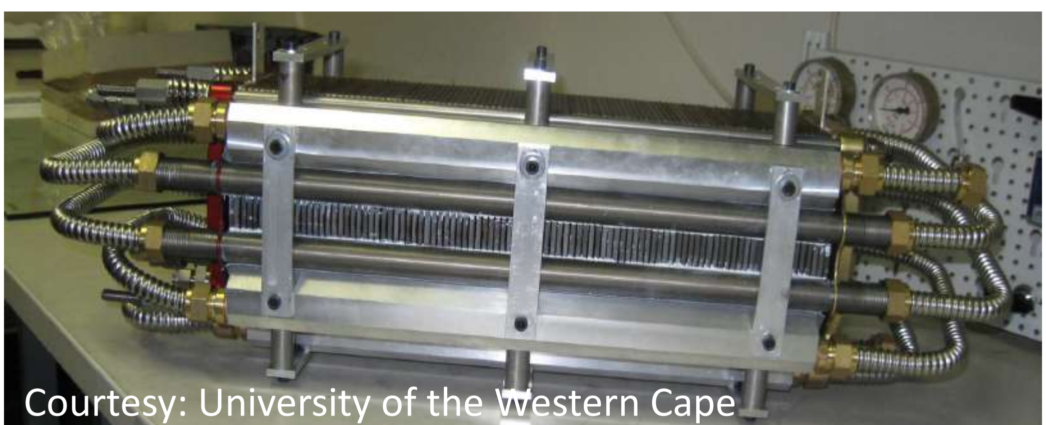


Batteries and **fuel cells**

Materials development → **Cell assemblies & manufacturing** → Systems engineering → Ageing & life assessment

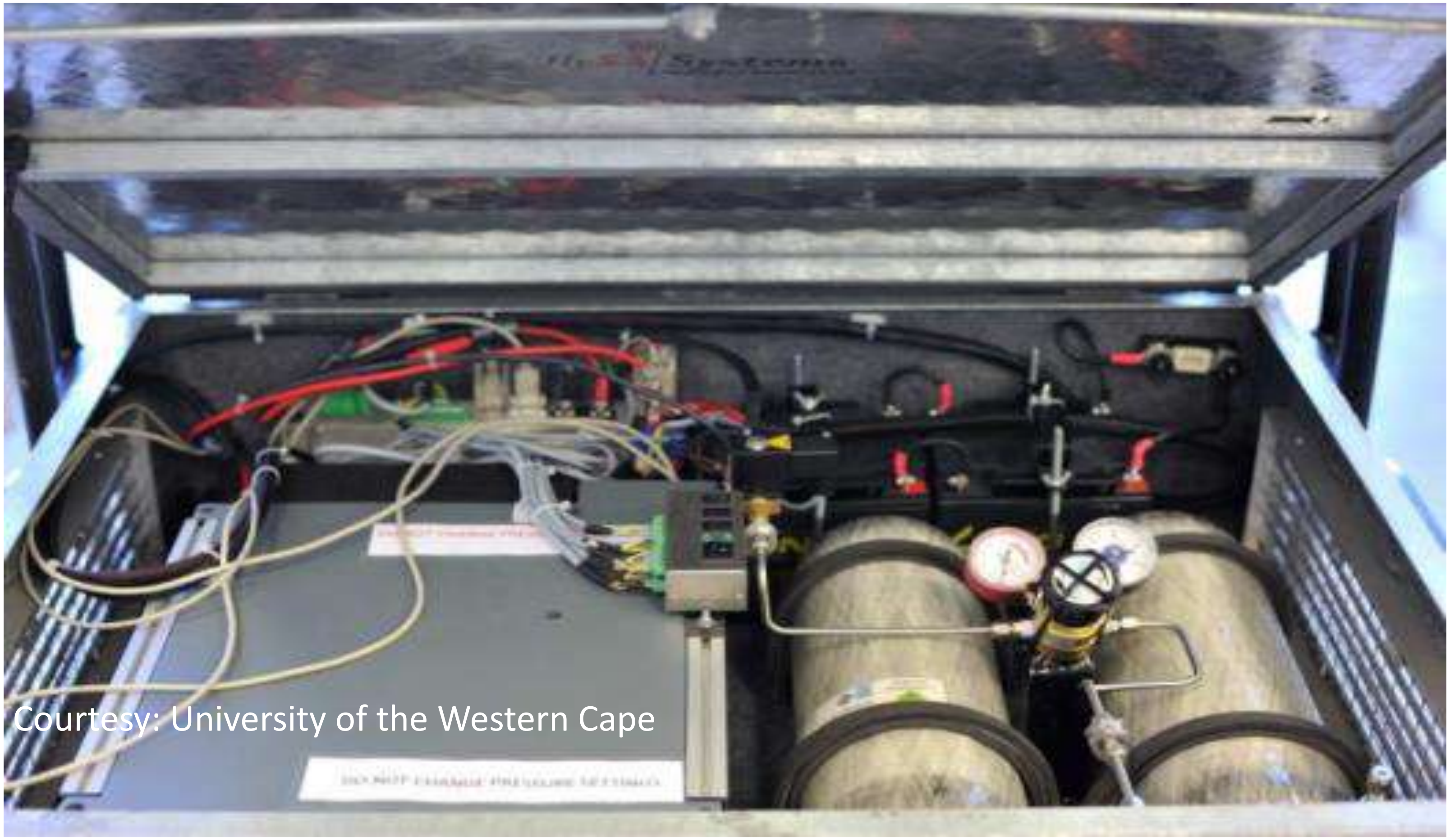
PEMFC Stack Development





Courtesy: University of the Western Cape

"Hybrid" Power Module


Courtesy: University of the Western Cape

Materials development → Cell assemblies & manufacturing → Systems engineering → Demonstrators

Hydrogen Fuel Cell/Battery Electric Urban Vehicles (Range Extender)

Courtesy: University of Birmingham

Materials development — Cell assemblies & manufacturing — Systems engineering — Demonstrators

Hydrogen Fuel Cell/Battery Electric Boat

- **Norwegian Fuel Cell and Hydrogen Centre (Sintef, IFE, og NTNU)**
- ***SafeLiLife*** **– Secure long-life batteries in the shipping industry under Nordic conditions (IFE, FFI, NTNU, HiST, Rolls-Royce Marin, ZEM A/S, FMC Kongsberg SUBSEA, DNV GL og ABB).**

NORWEGIAN FUEL CELL AND HYDROGEN CENTRE
LOW TEMPERATURE FUEL CELLS & ELECTROLYSERS
FUEL CELL & ELECTROLYSER SYSTEMS

Contents lists available at SciVerse ScienceDirect

Electrochimica Acta

journal homepage: www.elsevier.com/locate/electacta

Review

Current status of hybrid, battery and fuel cell electric vehicles: From electrochemistry to market prospects

Bruno G. Pollet[a,*,1], Iain Staffell[b], Jin Lei Shang[c]

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Hydrogen

ABSTRACT

Decarbonising transport is proving to be one of today's major challenges for the global automotive industry due to many factors such as the increase in greenhouse gas and particulate emissions affecting not only the climate but also humans, the increase in pollution, rapid oil depletion, issues with energy security and dependency from foreign sources and population growth. For more than a century, our society has been dependent upon oil, and major breakthroughs in low- and ultra-low carbon technologies and vehicles are urgently required. This review paper highlights the current status of hybrid, battery and fuel cell electric vehicles from an electrochemical and market point of view. The review paper also discusses the advantages and disadvantages of using each technology in the automotive industry and the impact of these technologies on consumers.

Market Drivers

- **Decarbonisation**
- **Climate change**
- **Energy Decentralisation**
- **Reduced water use**

Snapshot

- Fuel cell industry is slowly growing in volume
- >200 companies (stacks & systems)
- ~50% might have products by 2020
- Industry has consolidated (many buy-outs – joining forces!)
- Some companies driven by Policies (Japan)
- Majority funding around focused on RD&D
- Leading countries: Japan, South Korea, China & Germany
- Japan very serious about H2E (especially after Fukushima Daiichi)

Snapshot

- >400 MW shipped globally in 2015
- >1GW of shipped over 10 years vs. >10GW for PV pa
- >US$1b revenue from sale of FC systems in 2015
- Hydrogen infrastructure underway, although slow
- Majority of investment still comes from private capital and government subsidies (mainly project or R&D funding)
- PEM & SO FC dominate the market
- Huge gap between R&D labs & commercial market
- Huge gap between revenues & profits
- Large gap between ‘cost to make’ & ‘sell price’

Stationary

- Suffering from a slow down!
- Not enough highly marketable products
- High CAPEX vs. long-term payback vs. lifetime issues
- FC systems cost target of **US$ 5,000/kW** by 2030
- Sluggish growth in the telecoms, CHP, Prime Power (PP) and ResCHP
- ~150MWs shipped in 2015 for PP and ca. >50MWs for ResCHP
- >5m households with HFC CHPs by 2030 (Japan)

Journal of Power Sources 293 (2015) 312–328

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Review

Current status of fuel cell based combined heat and power systems for residential sector

Harikishan R. Ellamla [a,*], Iain Staffell [b], Piotr Bujlo [a], Bruno G. Pollet [a], Sivakumar Pasupathi [a]

[a] Hydrogen South Africa (HySA) Systems and Validation Centre, SAIAMC, University of the Western Cape, Robert Sobukwe Road, Bellville, 7535, Cape Town, South Africa

[b] Imperial College Business School, Imperial College London, London, SW7 2AZ, United Kingdom

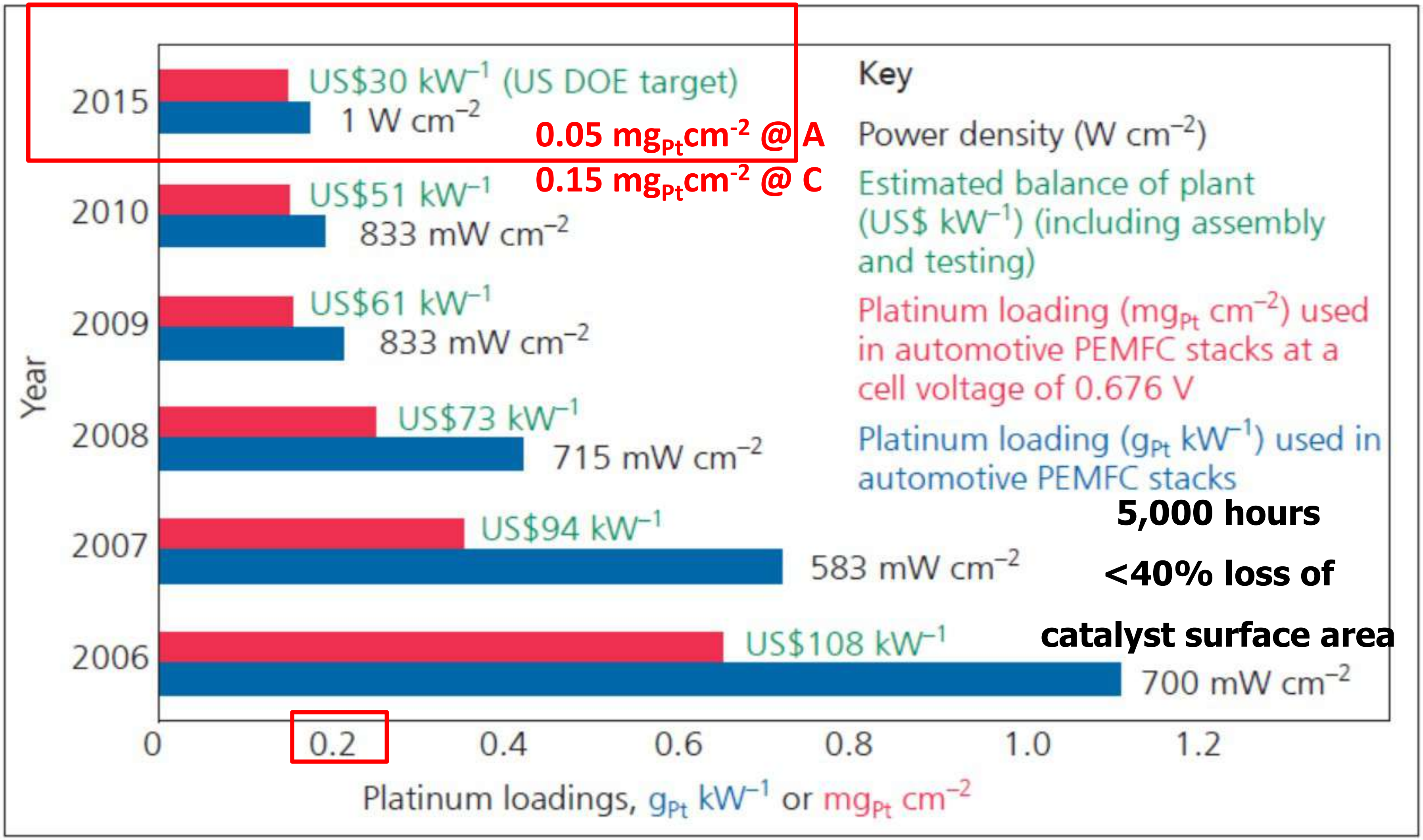
HIGHLIGHTS

- Status of micro FC-CHP system activities in different countries is described.
- Technical potential of PEMFC and SOFC technology is presented.
- FC-CHP system main components are characterised and analysed.
- By doubling the production 25% price reduction of micro FC-CHP system is possible.
- LT-PEMFC and SOFC is dominant but HT-PEMFC has potential for FC-CHP application.

Transport

- >800k HFCVs by 2030 (Japan)
- >25,000 HFC buses by 2030 (South Korea)
- Seeing some new business models (market penetration) e.g. car clubs, car sharing, PAYG etc
- Automotive FC cost stiil high although prices more attractive than 10 years ago!

TECHNOLOGY TARGETS



B.G. Pollet, Platinum Metals Review, Volume 57, Issue 2, April 2013, Pages 137-142

OBJECTIVES

Cost

Durability

US Dept. Of Energy targets

Total Pt loading

$0.2\ mg.cm^{-2}$

$0.2\ g.kW^{-1}$

5,000 hours

<40% loss of catalyst surface area

Improve catalyst activity

Mass activity

$mA.mg_{Pt}^{-1}$

Specific activity

$\mu A.cm_{Pt}^{-2}$

Improve catalyst utilisation

N_{active}/N_{total}

N=no. of catalyst particles

Inhibit degradation mechanisms

'The platinum industry has the potential to meet a scenario where HFCVs achieve 50% market penetration by 2050, while an 80% scenario could exceed the expansion capabilities of the industry. Recycled platinum from the transportation sector will be an increasingly critical source of supply'

Hydrogen in transport – where are we now?

With the growing volatility of oil prices, *Fleet News* looks at one possible fuel of the future

By Dr Bruno G Pollet, head of the Proton Exchange Membrane Fuel Cell Research Group, Centre for Hydrogen and Fuel Cell Research, University of Birmingham

Decarbonising transport is proving to be one of the largest research and development projects of the early 21st century.

Motor vehicles are one of the greatest purchases that a person will make, with around 800 million vehicles in use worldwide.

The motor industry is therefore one of the largest global forces, employing millions of people and generating a value chain in excess of £2.5 trillion per year. A consequence of this colossal industry is that road transportation emits 4.6 billion tonnes of CO_2 per year, approximately 17% of mankind's greenhouse gas emissions.

The ever-increasing demand for personal mobility and near total dependence on liquid hydrocarbons means that emissions reductions from this sector will be particularly difficult.

The development of alternative fuels to petrol and diesel has been ongoing since the 1970s, initially in response to the oil shocks and concerns over urban air pollution. Efforts have gained momentum more recently as the volatility of oil prices and stability of supplies, not to mention the consequences of global climate change have risen up political agendas the world over.

'Hydrogen is regarded as a sustainable fuel of the future'

Hydrogen fuel cell vehicles (HFCV)

Major global automotive manufacturers such as Honda (FCX Clarity – *below*), Nissan (FCV X-trail) and Daimler-Chrysler have invested significant amounts on R&D for fuel cell vehicles.

Some prototypes using a proton exchange membrane fuel cells stack up to 100kW at a cost of £250,000 have ended up having a total vehicle cost of up to £1.7 million.

However, recently Toyota has announced a price tag of £30,000 for its first hydrogen fuel cell vehicle.

Nevertheless, there are three main problems associated with fuel cell vehicles:

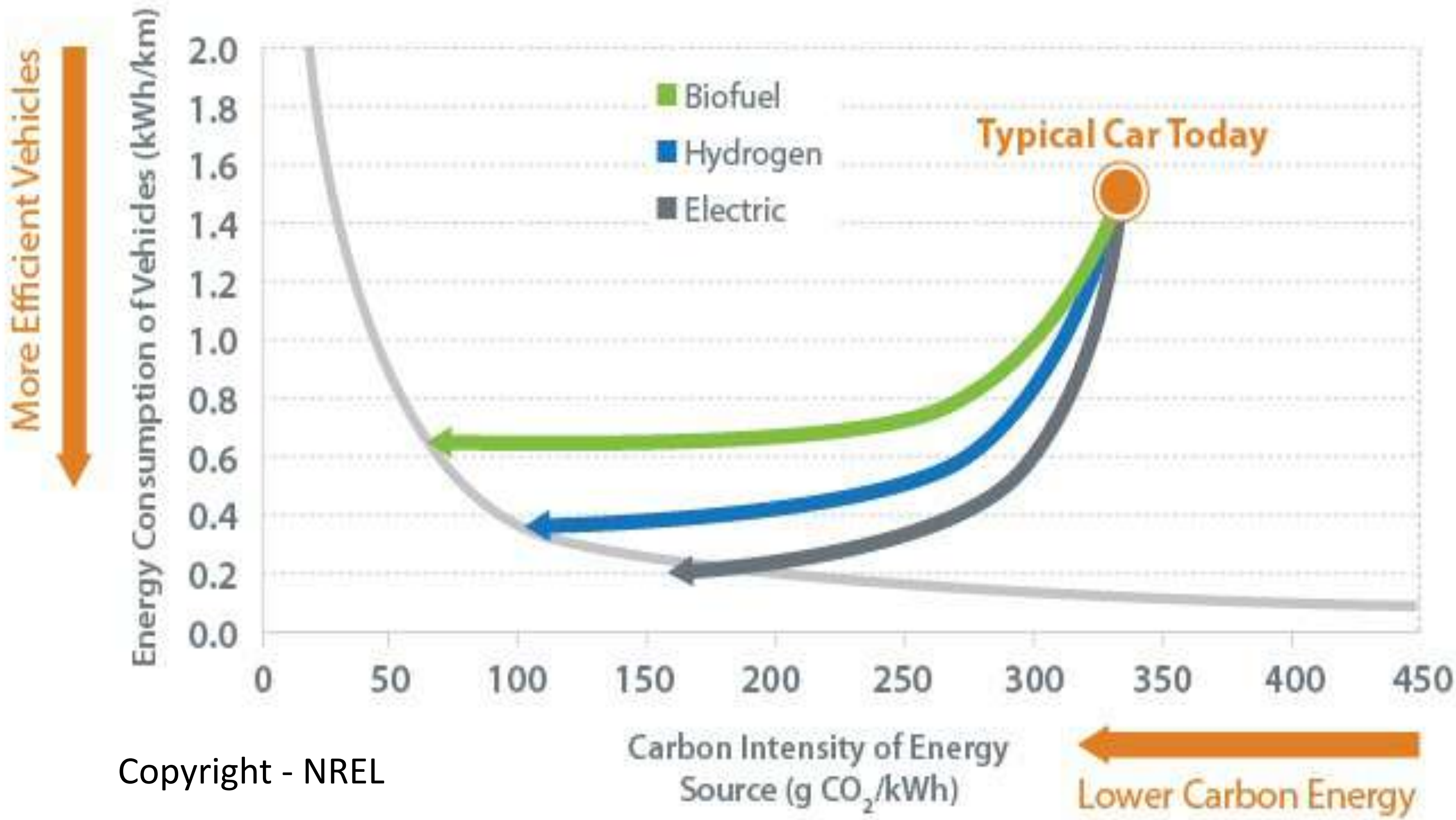
» There are insufficient demonstration vehicles in the field to give adequate statistics on performance and cost in 'real-world' situations

» Vehicles are custom made and too costly for the consumer who typically only wishes to spend around £10,000 for a 'green' vehicle

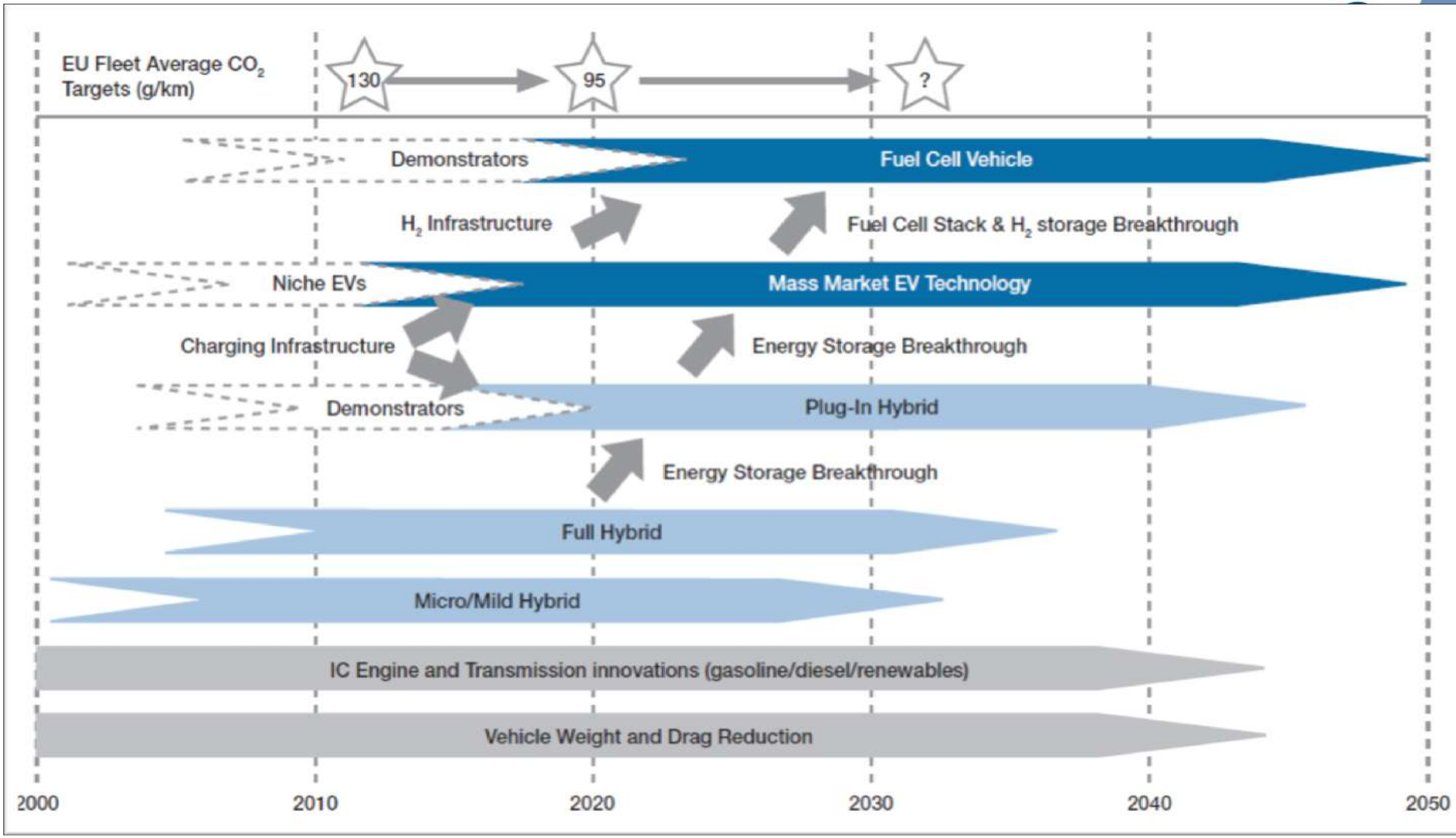
» Difficulty meeting existing legislation

Another major obstacle to the widespread deployment of fuel cell vehicles is the availability of component materials.

For example, if 600 million fuel cell vehicles running at 100kW were produced worldwide, around 40,000 tons of platinum would be required, which is far more than the estimated global resources. In other words, the platinum industry has the potential to meet a scenario where fuel cell vehicles achieve 50% market penetration by 2050, while 80% could exceed the expansion capabilities of the industry (based on a US Department of Energy research R&D target of 0.6g/kW with a goal of 0.2g/kW by 2015).



More Efficient Vehicles
Energy Consumption of Vehicles (kWh/km)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Biofuel
Hydrogen
Electric
Typical Car Today
0
50
100
150
200
250
300
350
400
450
Carbon Intensity of Energy Source (g CO_2/kWh)
Lower Carbon Energy



Courtesy: NREL & EU JTI

Electrochimica Acta 84 (2012) 235–249

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Portable

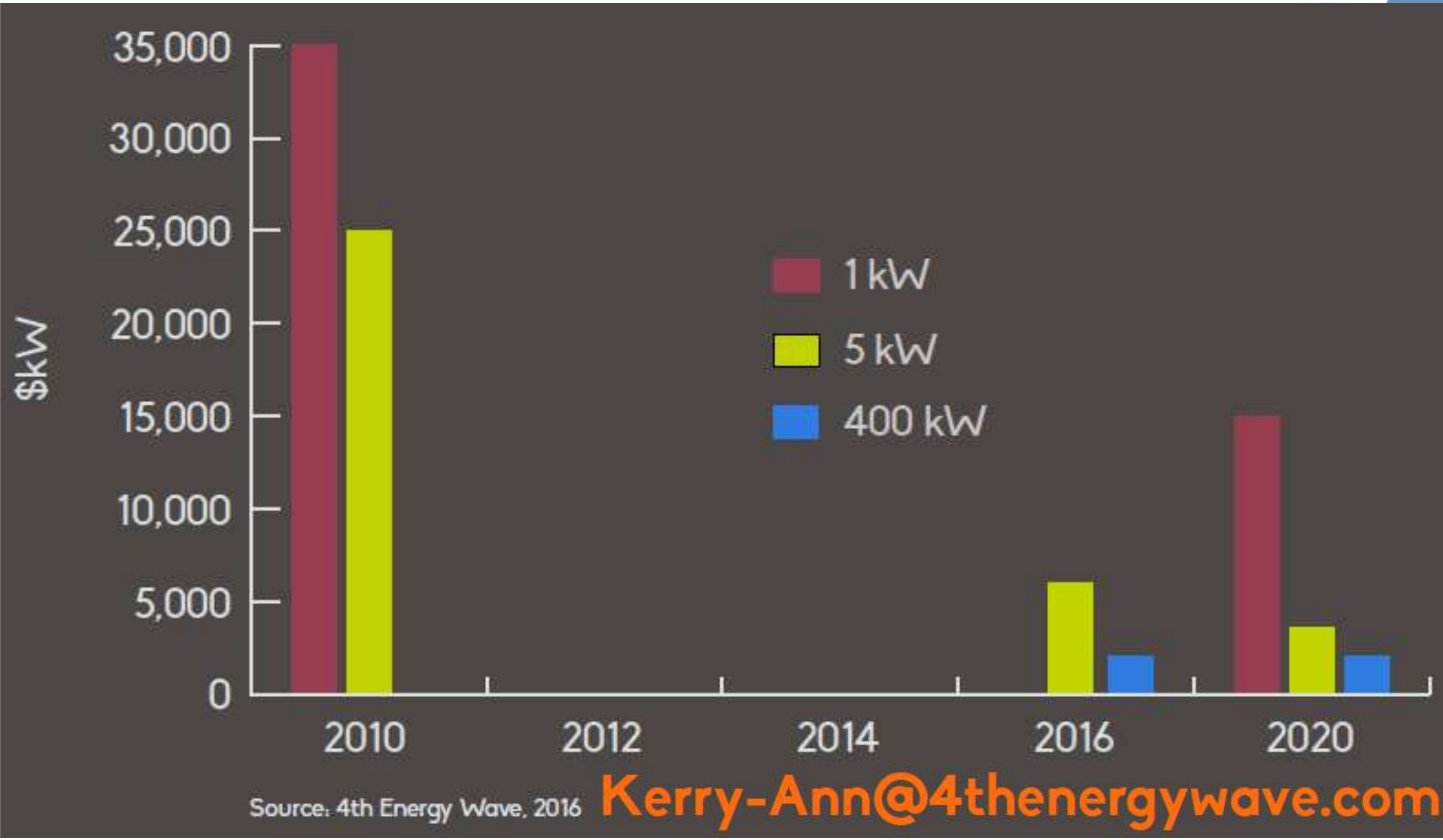
- Also suffering from a slow down!
- Li-ion battery smart phone chargers dominating the portable market
- Some companies focusing on defense and oil & gas markets
- Although Europe strong in that market!

Hydrogen Refuelling

- California, Germany, Norway & Japan are deploying H2 refuellers
- Norway is leading! with all major cities having H2R by 2020
- >300 H2 refuelling stations by 2030 (Japan)

PEMFC Historical/Forecast CAPEX Cost

SOFC Historical/Forecast CAPEX Cost



Hydrogen Generation

- Still dominated by Water PEM Electrolysers (MW)
- 2^{nd} Alkaline Electrolysers (MW)
- Other technologies e.g. Solid Oxide Electrolysers still under development!

Market opportunities

- **Stationary** - Remote hospitals, water treatment & desalination plants and data centres (large energy demand)

- **Transport** – Heavy duty e.g. buses, trucks, trams, light rail & mining vehicles (expected to mature & profitable by 2020)

- **Portable** - Military

Biogas Intensification & Upgrading

Innovative Methods for Biogas Generation and Upgrading by the Addition of Hydrogen to Anaerobic Reactor

- **Biogas** is now seen as an alternative fuel in emerging renewable energy strategies in Europe, motivated by the EU target of achieving 20% renewable energy by 2020

- **Biogas** generation offers many benefits as various organic wastes and by-products can be converted to a useful energy carrier product biogas

- **Biogas** is a primarily mixture of CH_4 (50–75%) and CO_2 (25–50%) produced by a portfolio of different bacteria

- Several methods have been suggested for the intensification of biogas productivity, for example the facilitation of biomass decomposition by means of various pre-treatments, modification of the composition of the bacterial community, or various **Anaerobic Digestion (AD)** phases in separate reactors

BIOMETHANE & HYDROGEN GENERATION

Biogas Intensification & Upgrading

Innovative Methods for Biogas Generation and Upgrading by the Addition of Hydrogen to Anaerobic Reactor

- Upgrading of biogas to CH_4 content higher than 90% not only increases the heating value but also reduces corrosion caused by acid gas in turns extending the biogas utilisation as a useful renewable energy source.

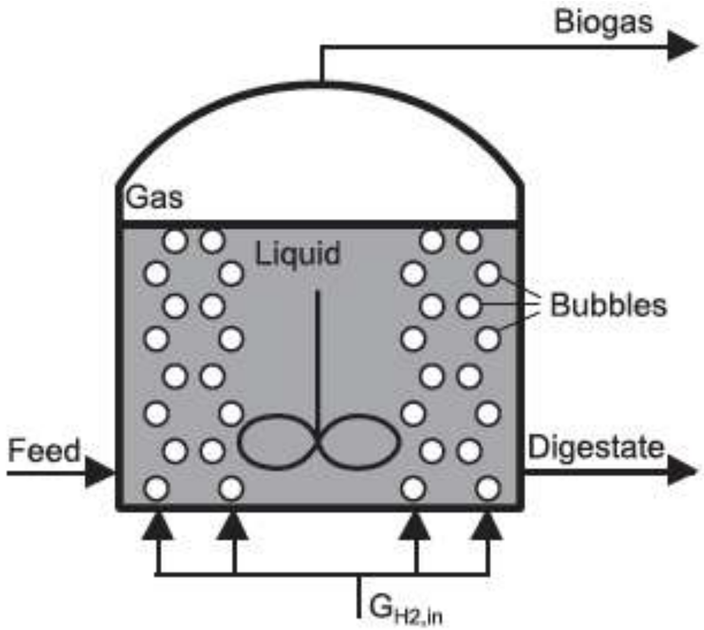
- Many methods for upgrading biogas, for example, water washing, pressure swing adsorption, polyglycol adsorption and chemical treatments, all aiming to remove CO_2 from the biogas

- **PROBLEM**: the initial capex and running costs of the above technologies are relatively high and not effective in separating carbon dioxide and methane

- **SOLUTION**: **Hydrogen** is used to effectively convert CO_2 to CH_4 using anaerobic microorganisms (hydrogenotrophic methanogens e.g. *Enterobacter cloacae*).

Fotoniske sensorer kan muliggjøre bedre systemer for overvåkning og kontroll av bioprosesser

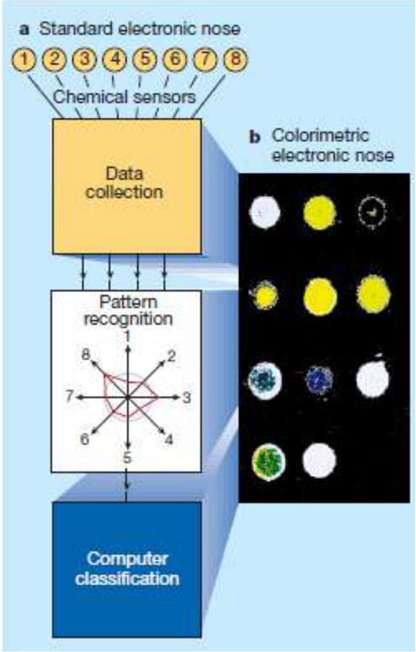
Prosjekt: Bioreaktor monitorering (HyBiG)



Bioreaktor med hydrogen input for redusert CO_2 innhold i biogass

Løst hydrogen og flyktige fettsyrer er gode indikatorer for tilstand i bioreaktor.

Optisk nese for deteksjon av spesifikke komponenter i komplekse media



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Future

- Some FC technologies mature enough
- Need public and governments acceptance
- Cost must be reduced in order to compete with existing ESD technologies
- Power-to-Gas (P2G) will grow
- Need to grow the H2 infrastructure

“The Sensor Revolution” NSF, USA (2005)

- 80’tallet => **PCer**
  - Databehandling tilgjengelig for alle
- 90’tallet => **Internet**
  - Alle sammenkoblet gjennom et verdensomspennende datanettverk
- ………
- Nå => Sensorer
  - Verdens elektroniske nervesystem
    - Koble Internett til den fysiske verden vi lever
  - Sensorer monitorerer våre omgivelser på måter vi knapt kan forestille oss
    - Noe er allerede her. Resten kommer snart!

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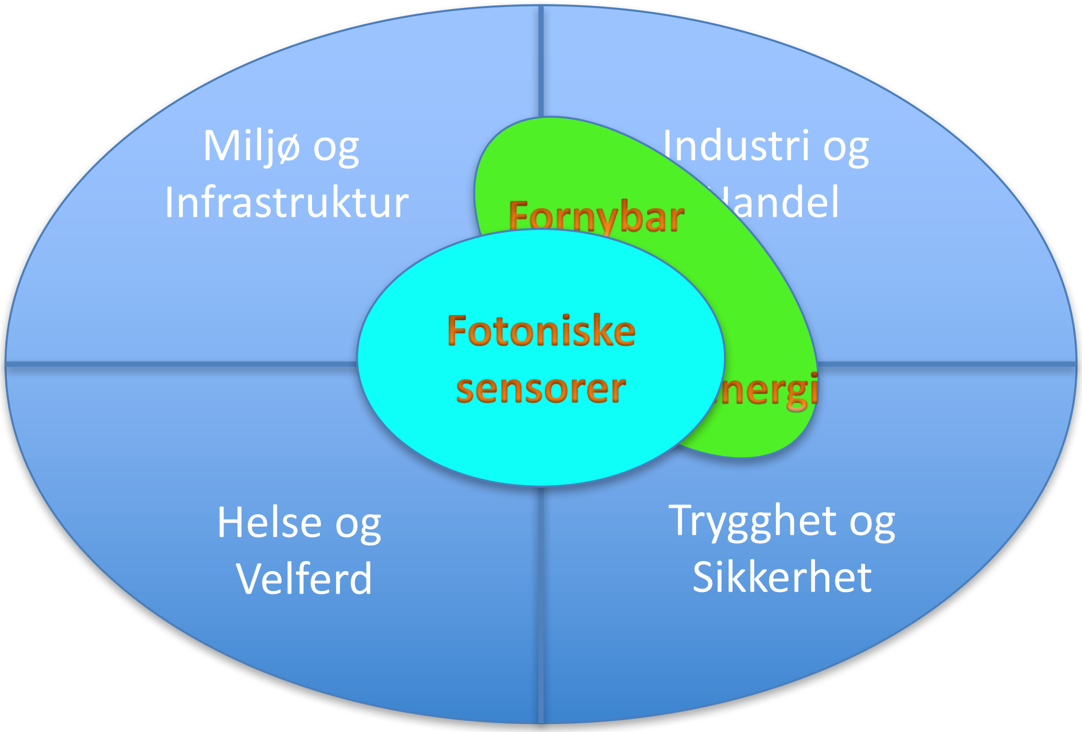
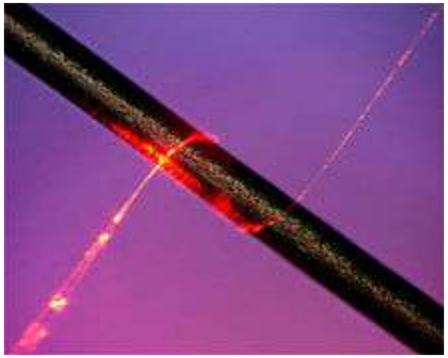
Sensorer – anvendelser og teknologi





Optisk mikrofiber
rundt et hårstrå

ENERSENSE

Market Hydrogen and Fuel Cell Reports

Dr. Kerry-Ann Adamson

Kerry-ann@4thenergywave.com

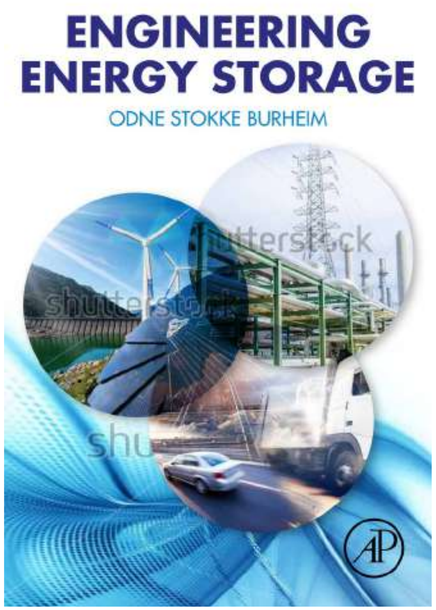
NTNU
Kunnskap for en bedre verden

ENERSENSE

Any Questions?

- ✓ Electrochemical Systems for Energy Storage
- ✓ Knowledge Development and Knowledge Dissemination
- ✓ Li-ion Batteries, Flow Batteries & Fuel Cells
- ✓ Energy and Process Engineering
- ✓ Thermal Aspects & Ageing

Odne S. Burheim



BATTERY, HYDROGEN & FUEL CELLS

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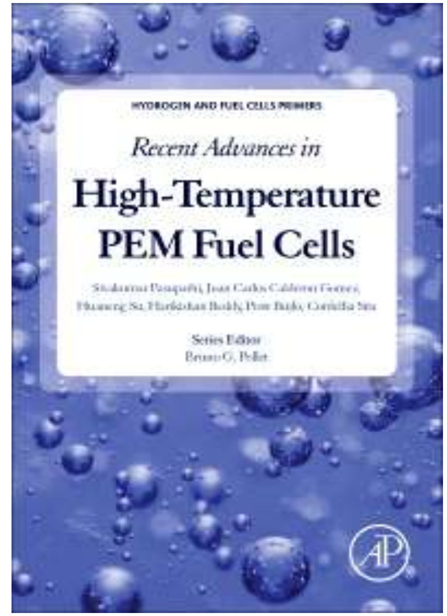

HYDROGEN, FUEL CELLS & ELECTROCHEMISTRY

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