Hydrogen Technologies and Applications

PRRE1003
Resources, Processes & Materials Engineering

LECTURE 12b

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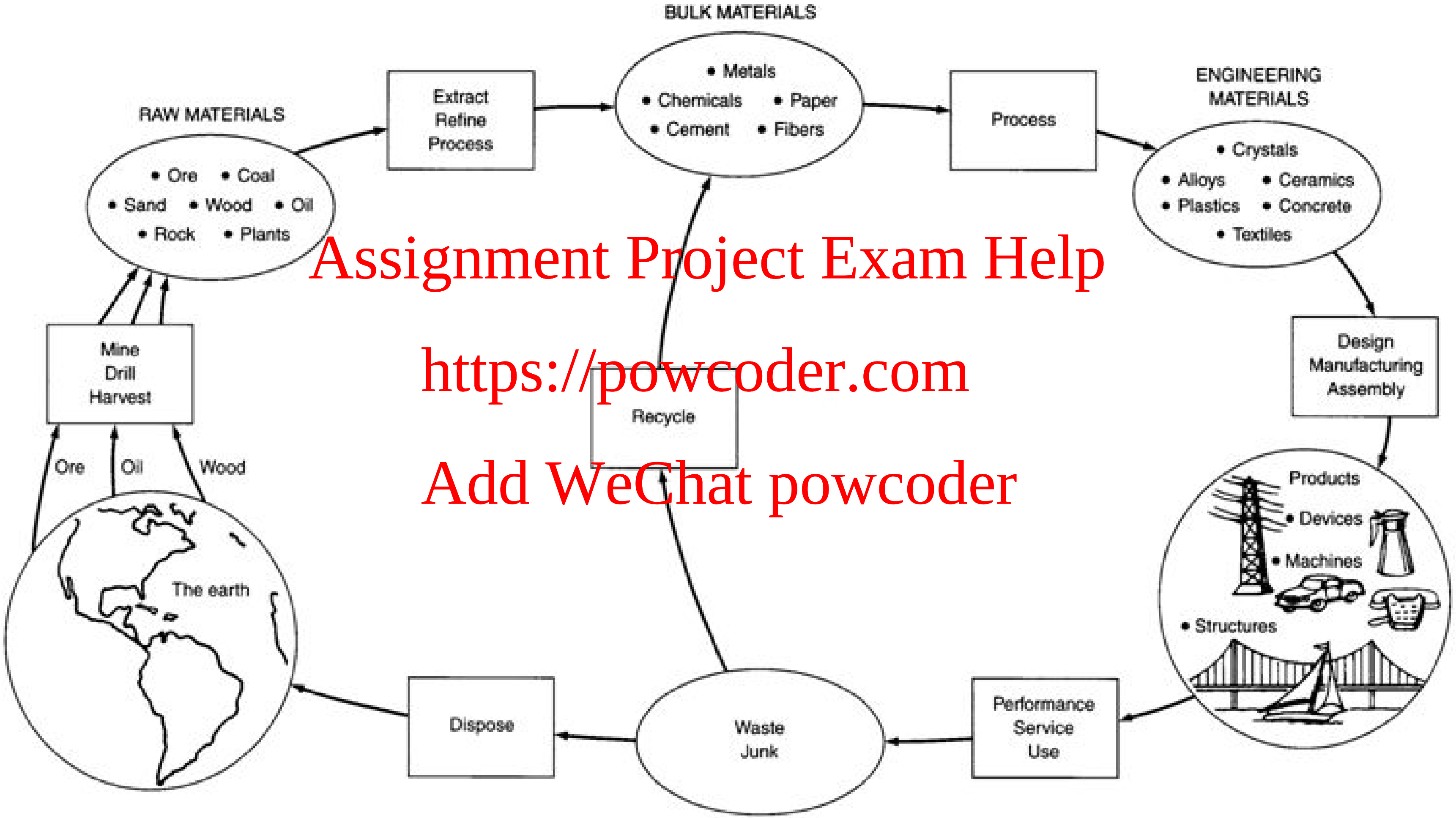
Electronic Warning Notice

Lecture focus



Reproduced from "Materials and Man's Needs", National Academy of Sciences, Washington D.C., 1974.

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Future Energy Exports (FEnEx) Cooperative Research Centre (CRC)

Lecture Outline

- Solar Power and Hydrogen
- Why Hydrogen?
- Hydrogen Storage Research Group (HSRG) Projects
- Conclusion

The Power of the Sun

- The World's current power consumption is 18.3 TW
- The incident solar power on the planet is 166 PW
- 30% of this is reflected back into space, and 19% is absorbed by clouds
- This leaves a balance of 85 PW available for terrestrial solar collectors
- 85 PW is well over 4500 times our current world consumption of 18.3 TW

Abbott *Proc. Of the IEEE* **98** (2010) 42 – 66.

Solar Power vs other Renewable Sources

Energy source	Max. power	% of Tot. Solar
Total surface solar	85,000 TW	100%
Desert solar	7650 TW	9%
Ocean thermal	100 TW	0.12%
Wind	72 TW	0.08%
Geothermal	44 TW	0.05%
River hydroelectric	7 TW	0.008%
Biomass	7 TW	0.008%
Open ocean wave	7 TW	0.008%
Tidal wave	4 TW	0.003%
Coastal wave	3 TW	0.003%

Abbott *Proc. Of the IEEE* **98** (2010) 42 – 66.

- All other sources of renewable energy are less than 1% of solar.
- If we consider the solar power that hits the desert regions of the world, all other renewables still only amount to less than 3% of this power.

Solar Power as the Dominant Renewable Source

If we globally tap sunlight over only 1% of the incident area at only an energy conversion efficiency of 1%, this meets our current world energy consumption of 18.3 TW.

As 9% of the planet surface area is taken up by desert and efficiencies well over 1% are possible, in practice, this opens up many exciting future opportunities.

Specifically, we find solar thermal collection via parabolic reflectors where focussed sunlight heats steam to about 600° C to drive a turbine is the best available technology for generating electricity.

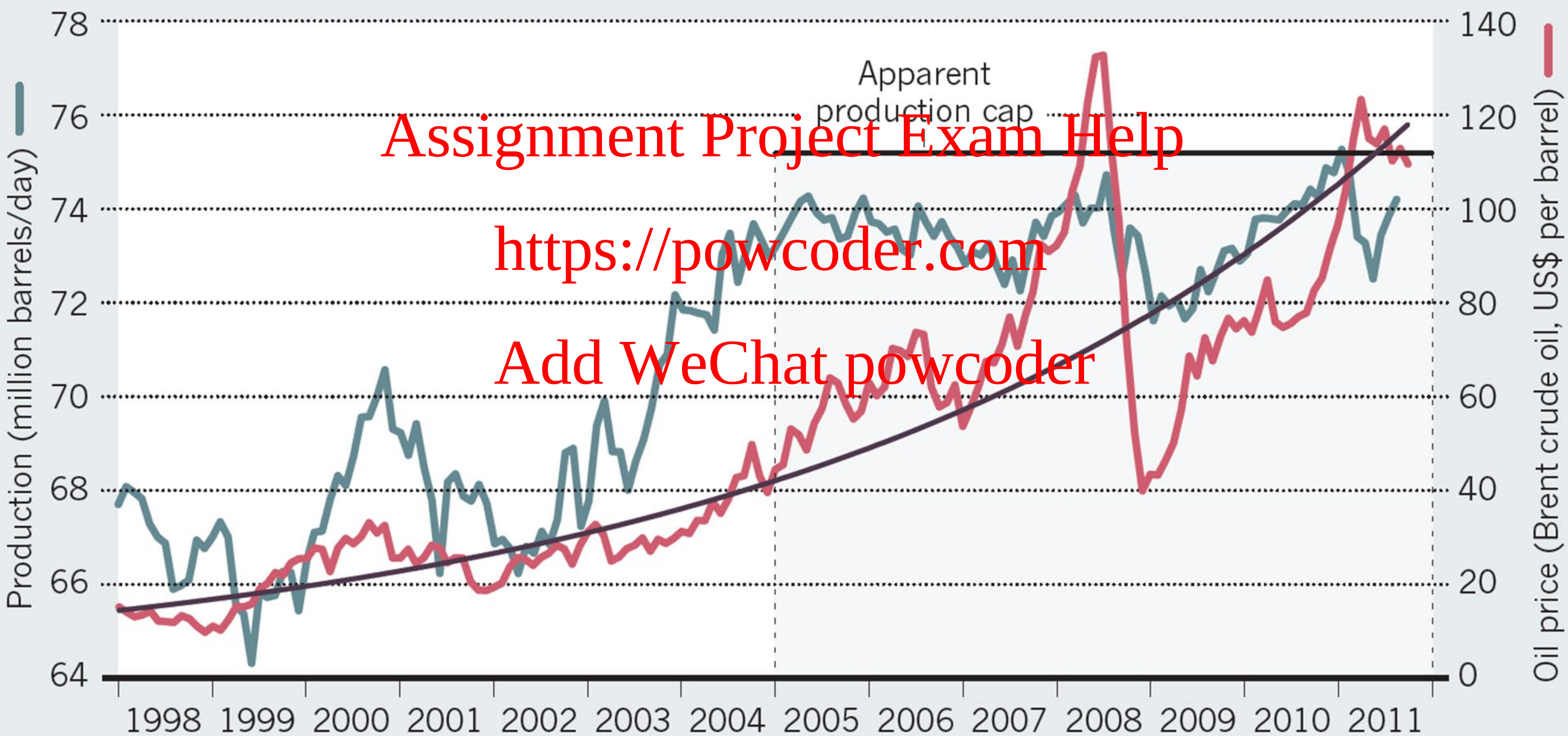
What is the solar thermal collector footprint?

Worst case scenario 1300 km × 1300 km. With less pessimistic assumptions only 500 km × 500 km (approx. 1% of the land area of the Worlds hot deserts) would be required.

Abbott *Proc. Of the IEEE* **98** (2010) 42 – 66.

OIL PRODUCTION HITS A CEILING

Production followed demand until 2005, when it levelled off despite continued price increases. There seems to be a production 'cap' at about 75 million barrels per day.



Murray, J. and King, D. 'Oil's tipping point has past', 26 January 2012, Nature 481 pp. 433-435.

Solar vs Fossil Fuels

- At the current rate of consumption of reasonably recoverable reserves [1, 2]
- Coal reserves will run out in 130 years,
- Natural gas in 60 years,
- Oil in 40 - 50 years.
- We cannot continue to burn oil to secure long-term viability of our future, we need to conserve oil for lubricating the machines of the world for years to come
- Oil is used for lubricants, dyes, plastics, and synthetic rubber; natural gas is an important desiccant in industry and is used in ammonia, glass and plastics production; and coal products are used to make creosote oil, benzene, toluene, ammonium nitrate, soap, aspirin, and solvents.
- Oil, coal and natural gas are a precious resource that humankind cannot afford to burn anymore.

> "I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that."
>
> Thomas Edison (1931) in conversation with Henry Ford and Harvey Firestone

[1] World Coal Institute www.worldcoal.org
[2] Abbott Proc. Of the IEEE 98 (2010) 42 – 66.

Solar vs Nuclear Fission & Fusion

- At the current rate of consumption with conventional reactors, there are only 80 years of world uranium resources at reasonable recovery cost levels.[1, 2]

- Nuclear power currently only supplies about 5.7% of the world's total energy, thus if we hypothetically supplied the whole world's energy needs with nuclear power there would be only 5 years of supply.

- Why does it make sense for humankind to foot the risks and costs of nuclear power, for such a short-term return?

- To supply the Worlds 18.3 TW of power with nuclear fission alone would require 18,300 1 GW reactors.

- To supply the Worlds energy needs for 1 year with nuclear fusion one would require 2290 tonnes of D_2 and 68,700 tonnes of Li.

- Given that Li has several competing industrial uses the viability of nuclear fusion is ≈ 100 years.

[1] World Nuclear Association (www.world-nuclear.org)

[2] Abbott Proc. Of the IEEE 98 (2010) 42 – 66.

Solar Photovoltaic vs CST

Silicon photovoltaic (PV) solar cells

- 500 km x 500 km to supply 18.3 TW (World consumption)
- 0.17 g/cm^2 of arsenic → 425 million tons As → (World reserves @ 3 million tons)
- Other varieties of solar cells → rare earth metals → world reserves stretched

Concentrating solar thermal (CST)

- 500 km x 500 km to supply 18.3 TW → Low-tech → using mirrors to provide heat
- Heat → Electricity using heat engine (i.e. Steam Engine, Stirling engine etc.)

Abbott Proc. Of the IEEE 98 (2010) 42 – 66.

Solar Hydrogen Economy

- Electricity is produced using CST and PV
- Solar farms are linked by cable to desalination plants for large scale electrolysis to produce hydrogen
- Hydrogen is used as the dominant transport fuel and for night time power use.
- In the long term a Solar Hydrogen economy makes sense, because there is so much available power
- Conversion losses can be compensated for by adding more solar collectors.
- In the long term we have no choice, but to move almost entirely to a Solar-Hydrogen Economy

Abbott Proc. Of the IEEE 98 (2010) 42 – 66.

Solar-Hydrogen vs the Rest

Energy source	Max. power	% of Tot. Solar
Total surface solar	85,000 TW	100%
Desert solar	7650 TW	9%
Ocean thermal	100 TW	0.12%
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Coastal wave	3 TW	0.003%

D. Abbott, Proceedings of the IEEE, 98 (2010) 42-66.

World uses 18.3 TW of power

To sustain this we only have a finite utility time for our resources

Energy source	Utility time
Solar-hydrogen	1-billion years
Nuclear fusion	100 years
Coal	35 years
Gas	14 years
Oil	14 years
Nuclear fission	5 years

"I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that."

Thomas Edison (1931) in conversation with Henry Ford and Harvey Firestone

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Facts about Hydrogen

- Hydrogen is the most abundant element in the universe and makes up 75 % of all known mass in the universe.
- Hydrogen is the lightest element in the universe. The hydrogen atom (H) has one proton and one electron and it exists at STP in a molecular form (H_2) as a gas.
- If hydrogen is burnt with oxygen it forms water.
- Hydrogen is colorless, has no odor or taste and is non-toxic. It is highly flammable, but will not ignite unless an oxidizer and ignition source are present.
- Hydrogen has an autoignition temperature of 585 °C in air
- The flammability range of hydrogen is between 4 – 77% H_2 to air volume ratio.
- The ignition energy of hydrogen is 0.02 MJ.

Why Hydrogen?

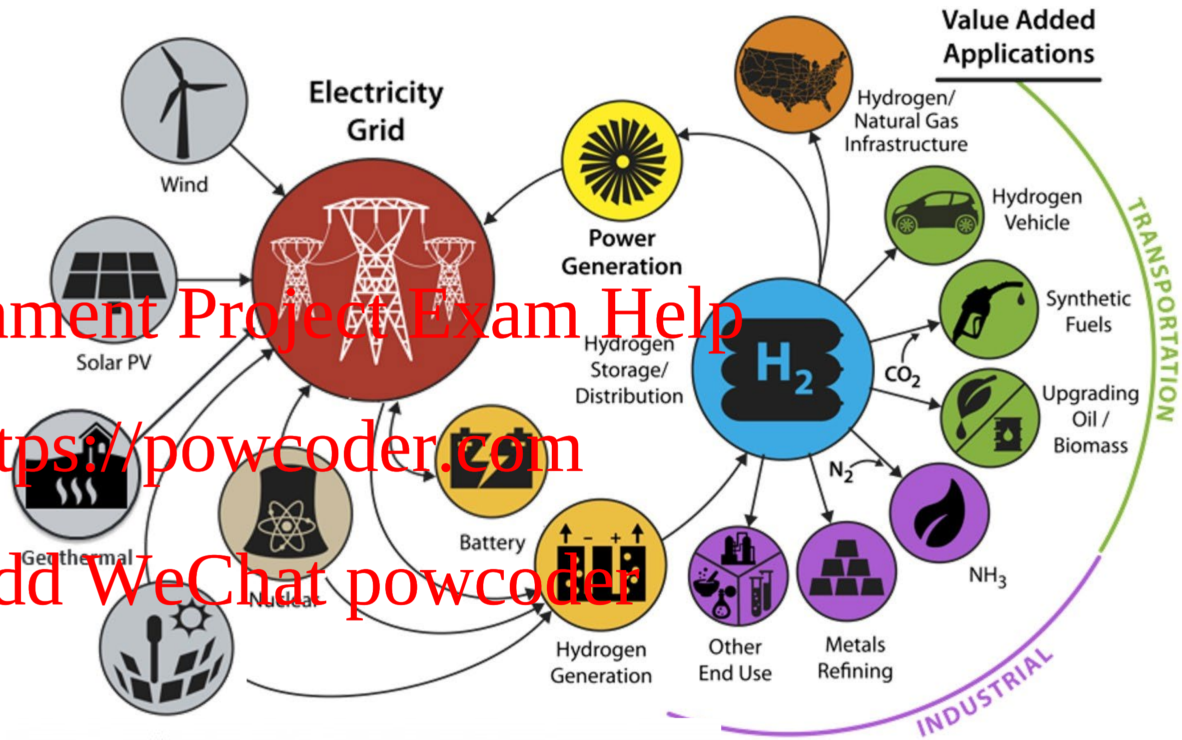
- Hydrogen can be produced from many primary sources.
- No greenhouse gases are produced when hydrogen is used as a fuel
- Hydrogen has the highest energy to weight ratio (120 MJ/kg) of any fuel
- Hydrogen is the ideal fuel for fuel cells and can also be used in an internal combustion engine.
- Hydrogen has the potential to be a new export industry for Australia

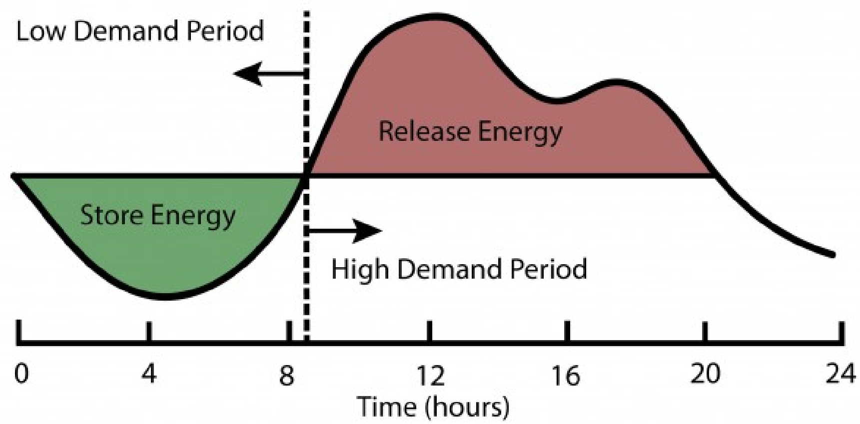
Learning Outcome Check

- Describe briefly what is meant by a solar-hydrogen economy.
- List 3 advantages of using hydrogen as a fuel source, compared to the current energy mix.

Hydrogen Applications and Prospects

1. Hydrogen production
2. Utilisation
3. Distribution
4. Storage





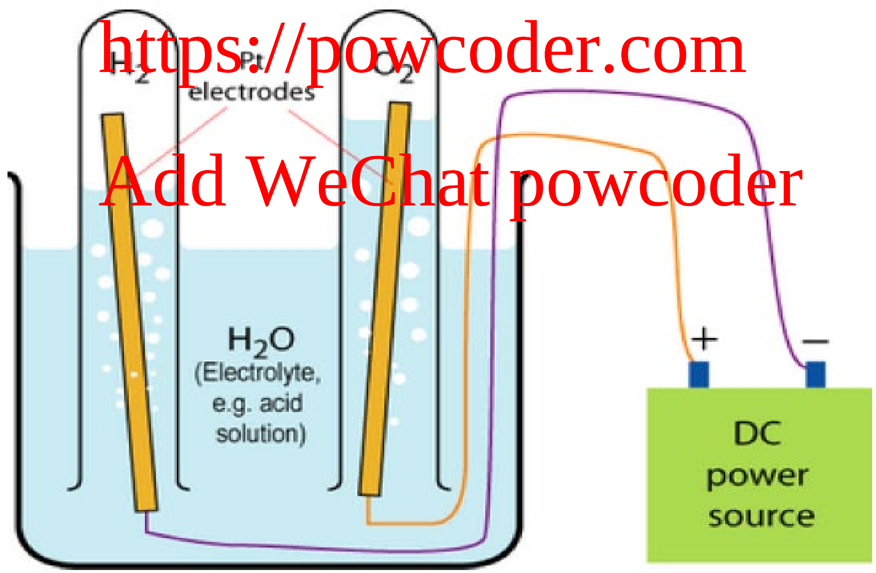
http://css.umich.edu

https://www.lbl.gov/

Electrolysis

Electrolysis

$H_2O + \text{electrical energy} \rightarrow H_2 + \frac{1}{2}O_2$



J.O. Jensen DTU Energy Technical University of Denmark (2016)

Types of electrolyzers

	Fuel cells	Electrolyzer cells	Temperature
Alkaline	*AFC*	***AEC***	**25 – 150 ºC**
Polymer	***PEMFC***	***PEMEC***	**80 ºC (150 – 200 ºC)**
Phosphoric acid	*PAFC*	*(PAEC)*	**-**
Molten Carbonate	*MCFC*	*(MCEC)*	**-**
Solid Oxide	***SOFC***	***SOEC***	**700 – 1000 ºC**

The largest electrolyzers

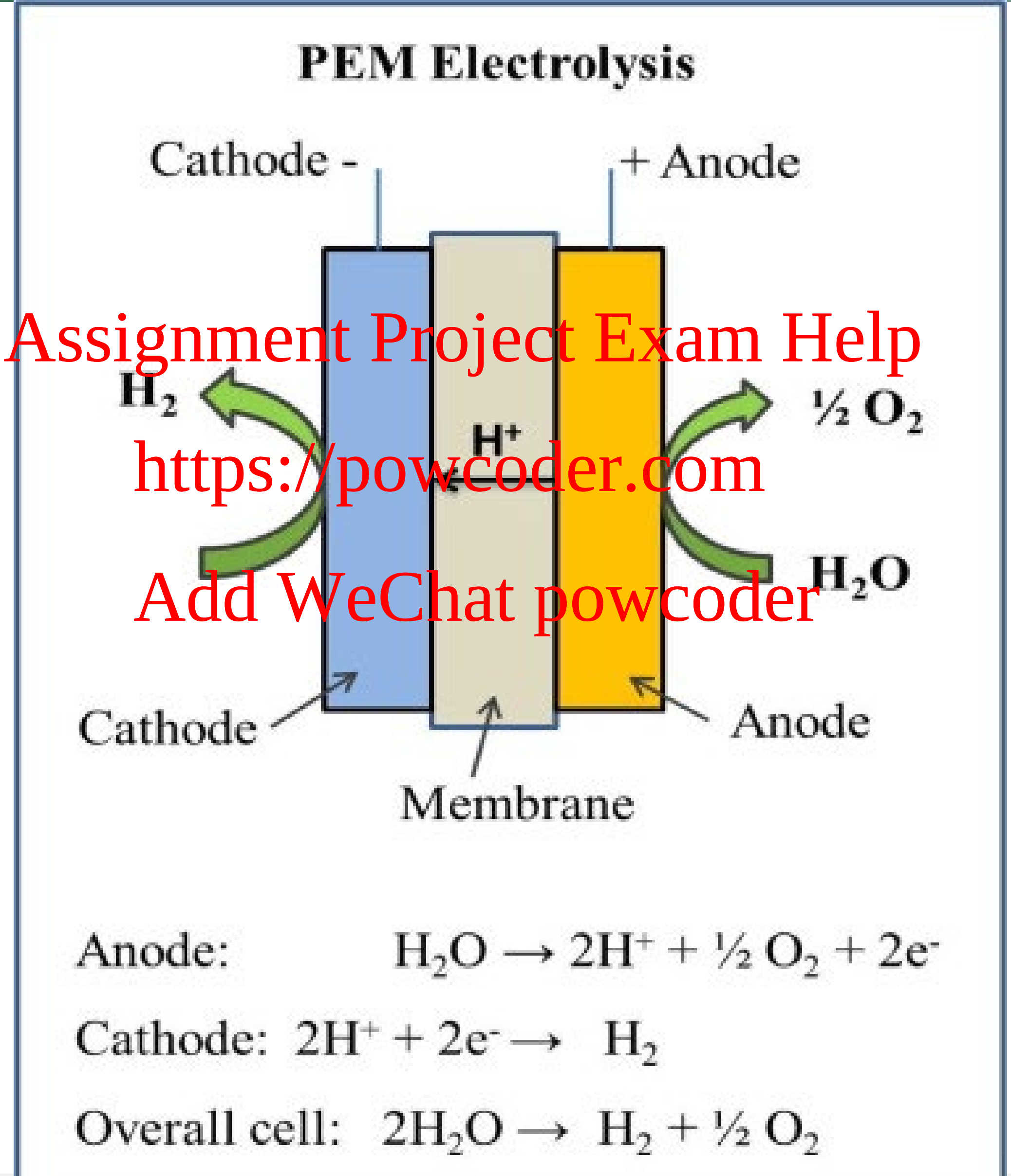
The largest electrolyzers

S-556 unit. 760 Nm^3/h H_2

iht
INDUSTRIE
HAUTE
TECHNOLOGIE
CLEAN HYDROGEN SOLUTIONS

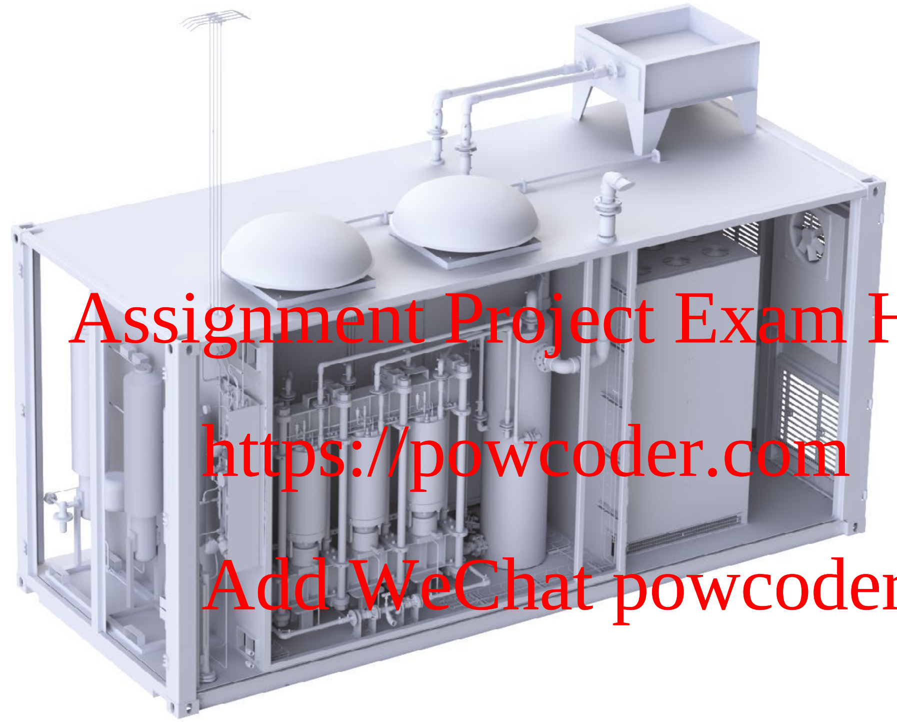
Probably the world's largest electrolysis plant
28 electrolysers Type S-556
21'000 Nm^3/h H_2 and
10'500 Nm^3/h O_2
In service since 1973 for Sable Chemical Industires in Zimbabwe

PEM Electrolysis



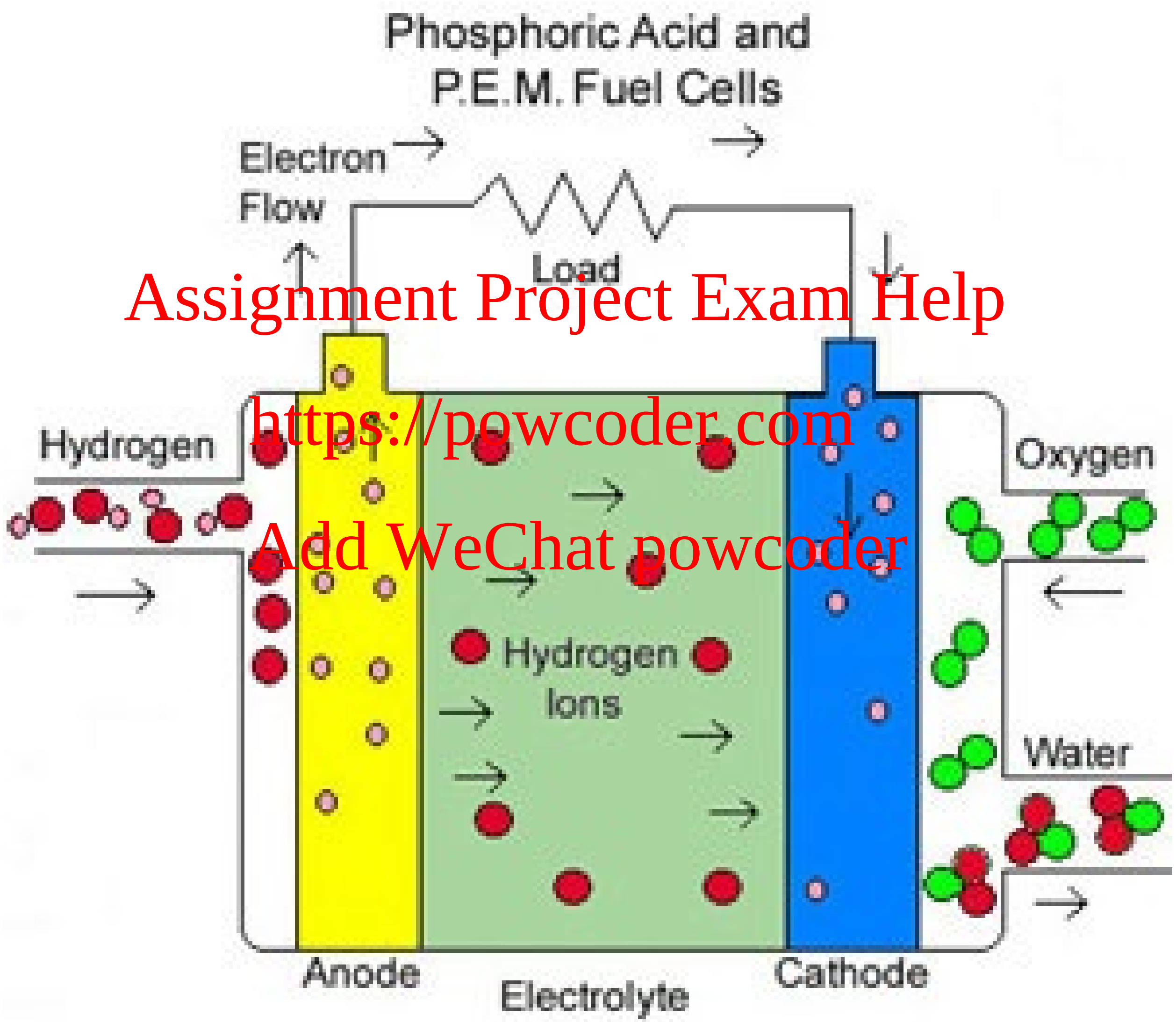
Shiva et al Materials Science for Energy Technologies **2** (2019) 442.

ITM Power HGas PEM Electrolyser



System power	0.1 – 100 MW
H_2 production rate	40 – 40,000 kg/24 h
H_2 pressure	20 bar (50 bar optional)
H_2 purity	99.5 – 99.999 %

Fuel Cells



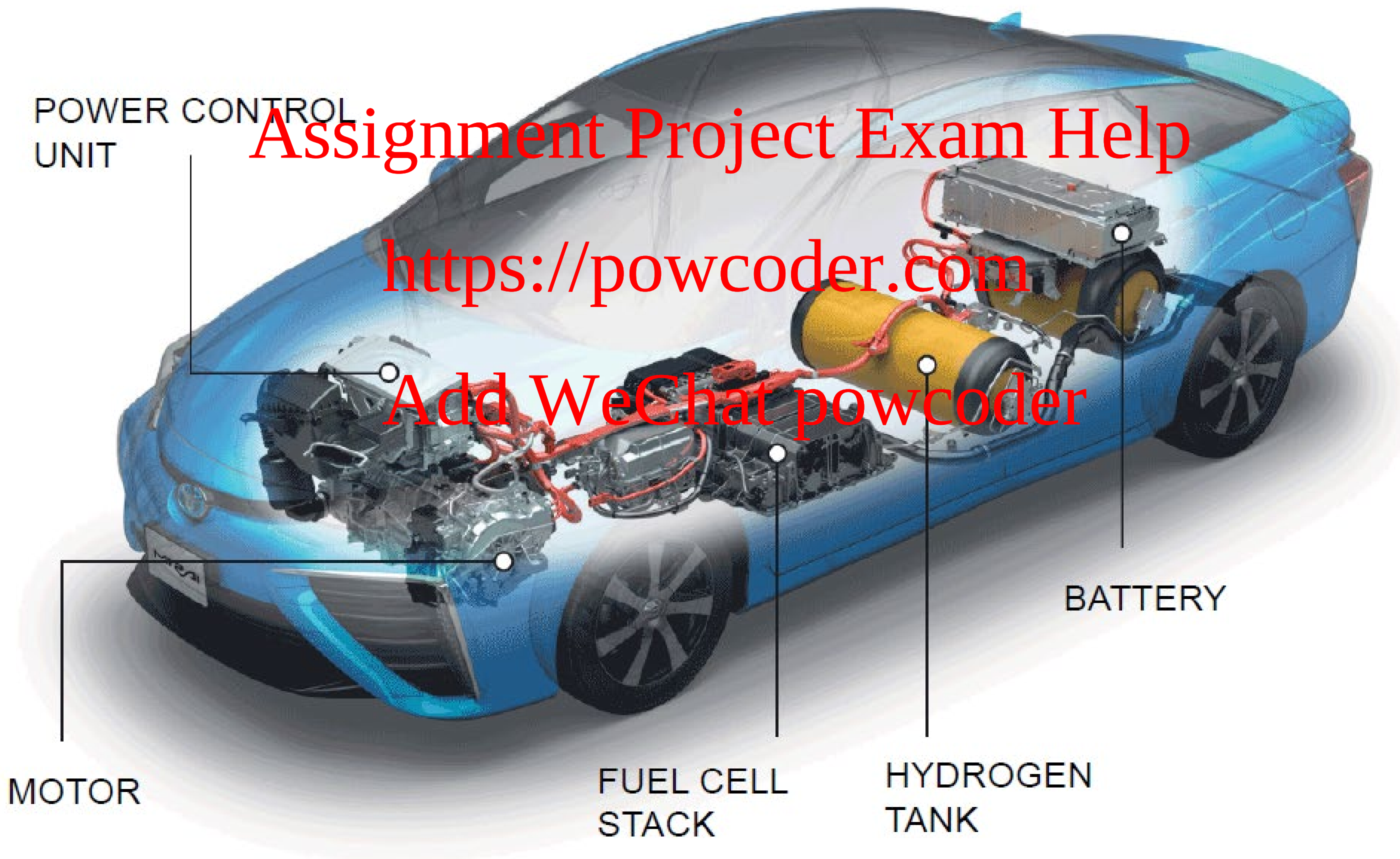
Fuel Cell Basics *Smithsonian Institute* (2017) https://americanhistory.si.edu/fuelcells/basics.htm

Types of Fuel Cells

Type	Abrev.	Temp.	Electrolyte
Low temperature systems			
Alkaline FC	AFC	60 – 80 °C	aq. KOH
Polymer FC	PEMFC	60 – 80 °C	Polymer
Direct methanol FC	DMFC	60 – 80 °C	Polymer
Phosphoric acid FC	PAFC	200 °C	H_3PO_4
High temperature systems			
Molten carbonate FC	MCFC	650 °C	Molten salt
Solid oxide FC	SOFC	700 - 1000 °C	Ceramic

Fuel Cells

Toyota FCV from 2015



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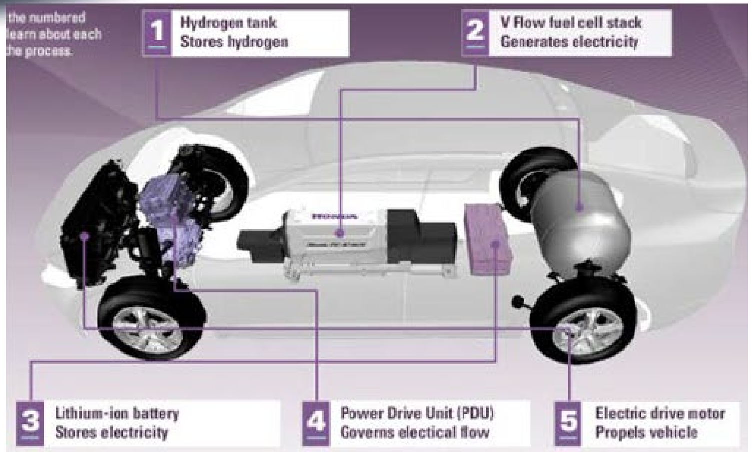
Honda Clarity



J.O. Jensen DTU Energy Technical University of Denmark (2016)

Fuel Cells

https://commons.wikimedia.org/wiki/File:Hyundai_Nexo_Genf_2018.jpg

Progress Around the Globe

Toyota Mirai

$57,500 USD

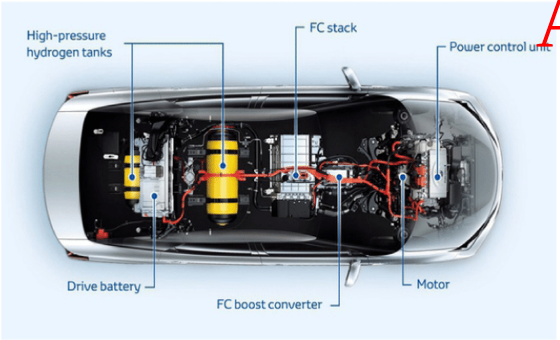
Honda Clarity

$60,000 USD

Hyundai Tucson

Hyundai Genesis

Nikola



DOI: 10.1016/j.pnsc.2018.03.001

500 – 700 km per tank

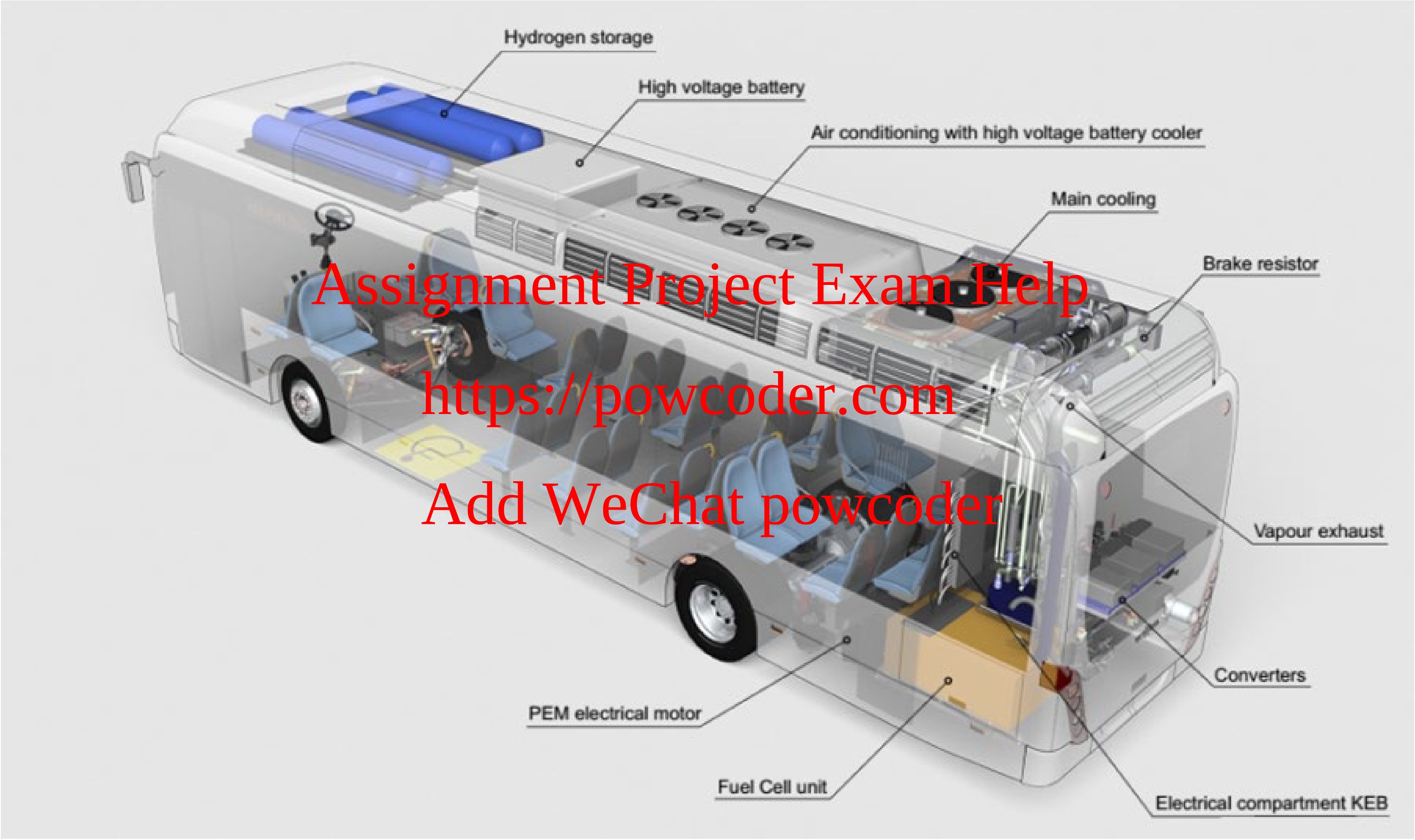
FCEVs fuel quickly (3 - 5 minutes)

High pressure (700 bar H_2 tanks)

Japan's FCEV
2017 – 3,000 units
2020 – 40,000 units
2025 – 200,000 units
2040 – 800,000 units

http://ieahydrogen.org/pdfs/Global-Outlook-and-Trends-for-Hydrogen_Dec2017_WEB.aspx

Fuel Cells



A fuel cell electric bus is the same as a battery electric bus only with a smaller battery, hydrogen tanks and FC

Fuel Cells

Completed: Validation of fuel cell forklifts

Collaboration: Dept. of Defense- The Defense Logistics Agency (DLA)

Ongoing: Analysis and Testing of Emergency urban power and fuel cell buses

Collaboration: NREL and Dept. of Transportation- Federal Transit Administration (FTA)

Potential: Light duty vehicles for military applications

Potential collaboration: Army

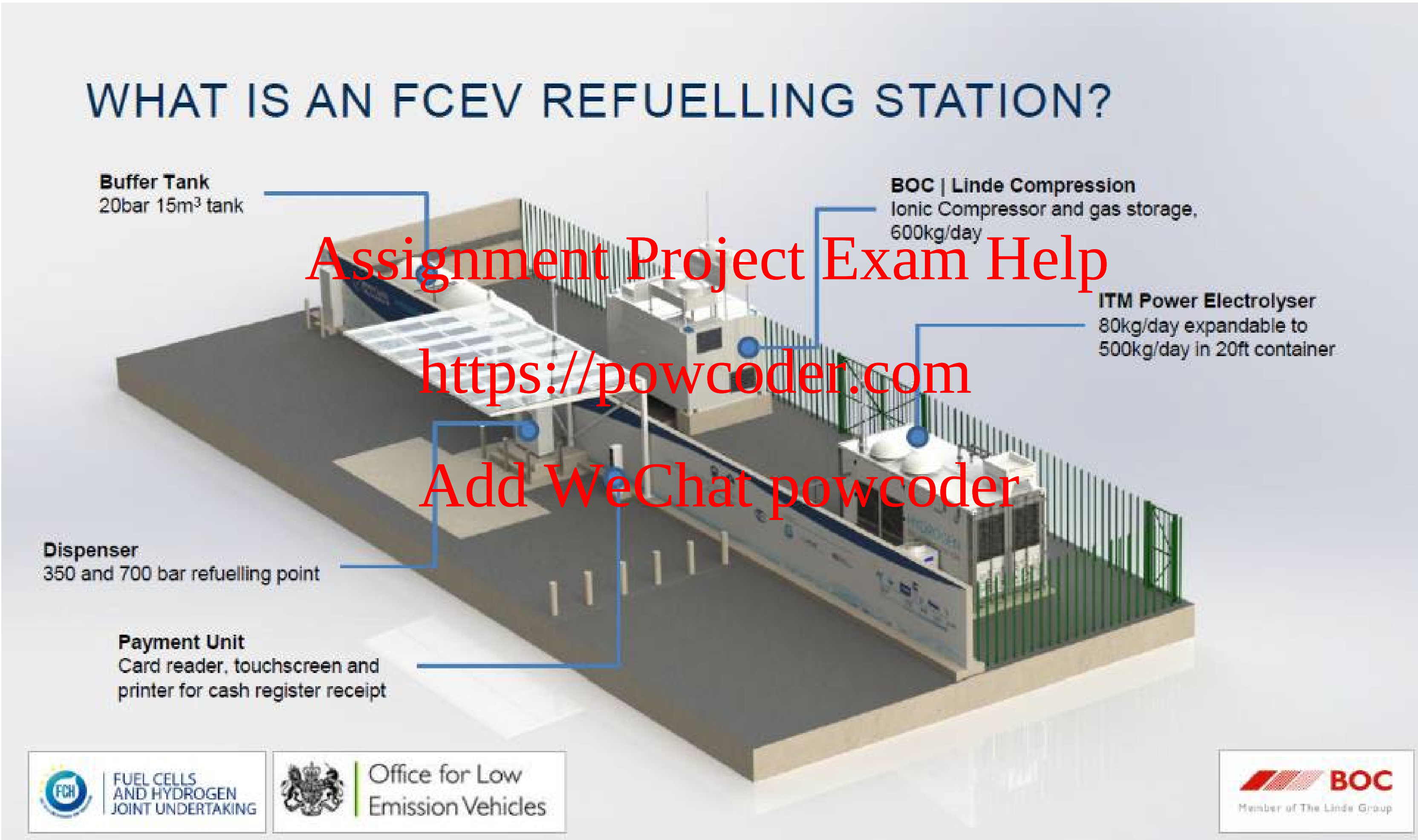
Potential: Unmanned Underwater Vehicles (UUV)

Potential collaboration: Navy

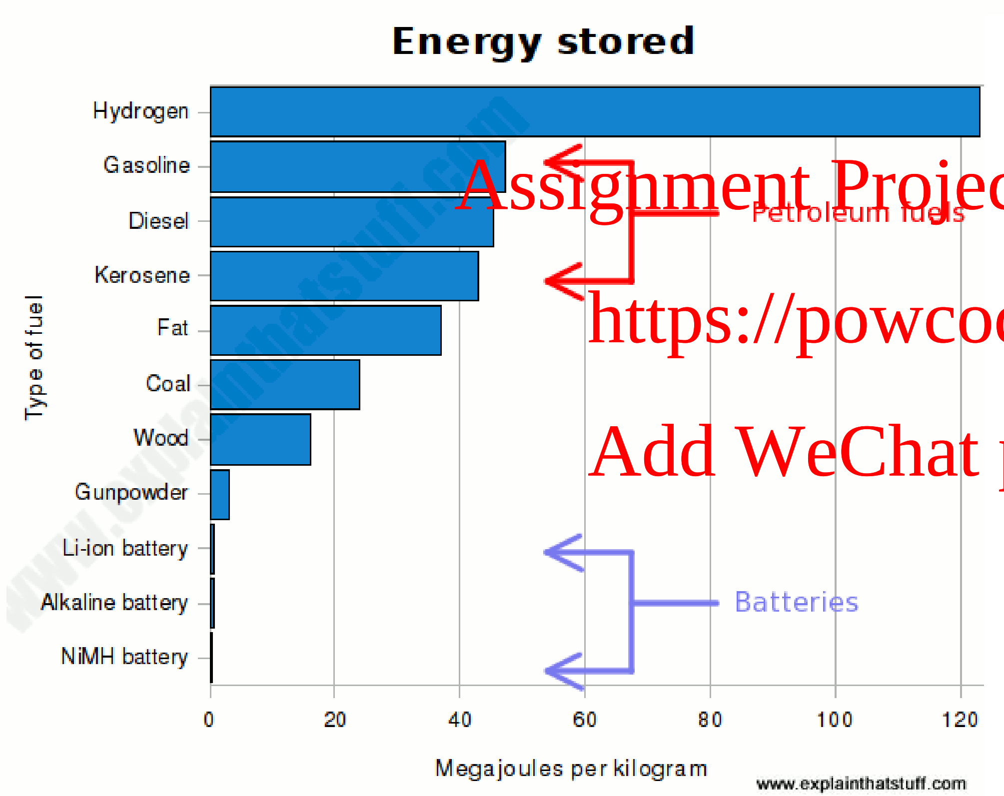
Potential: Unmanned Aviation Vehicles (UAV)

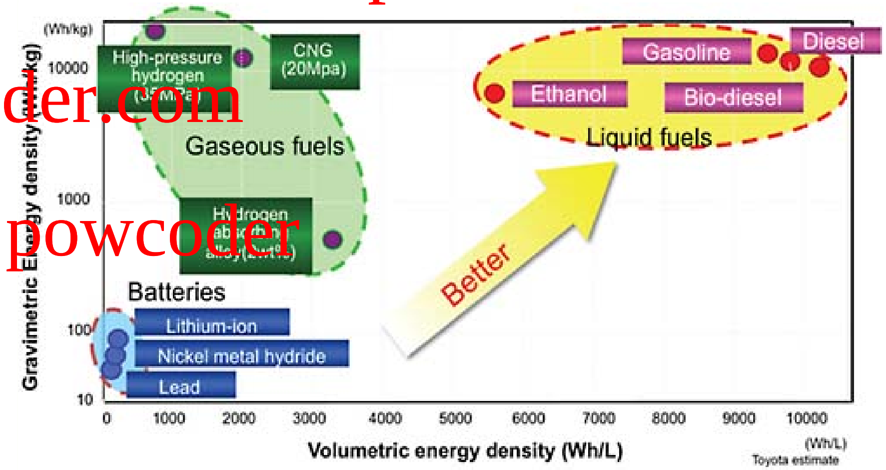
Potential Collaboration: DOT - Pipeline Management

Hydrogen Refuelling Station

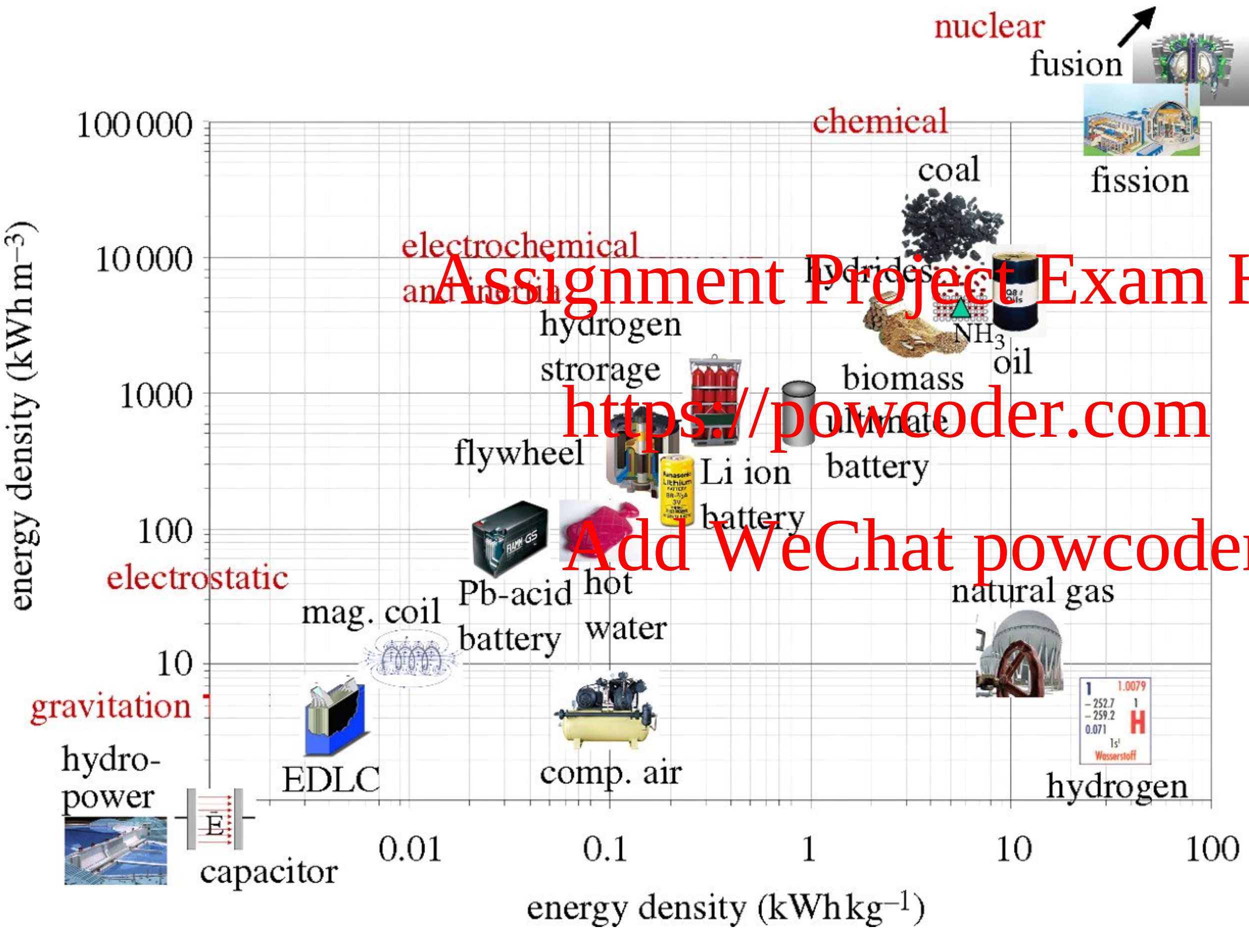


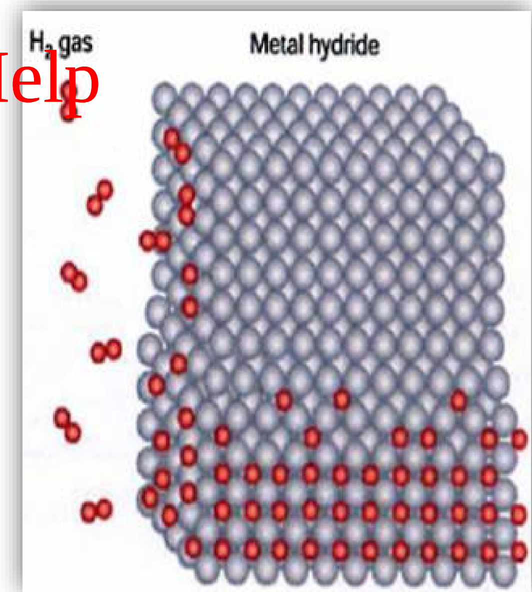
Hydrogen Energy Density





Hydrogen Storage



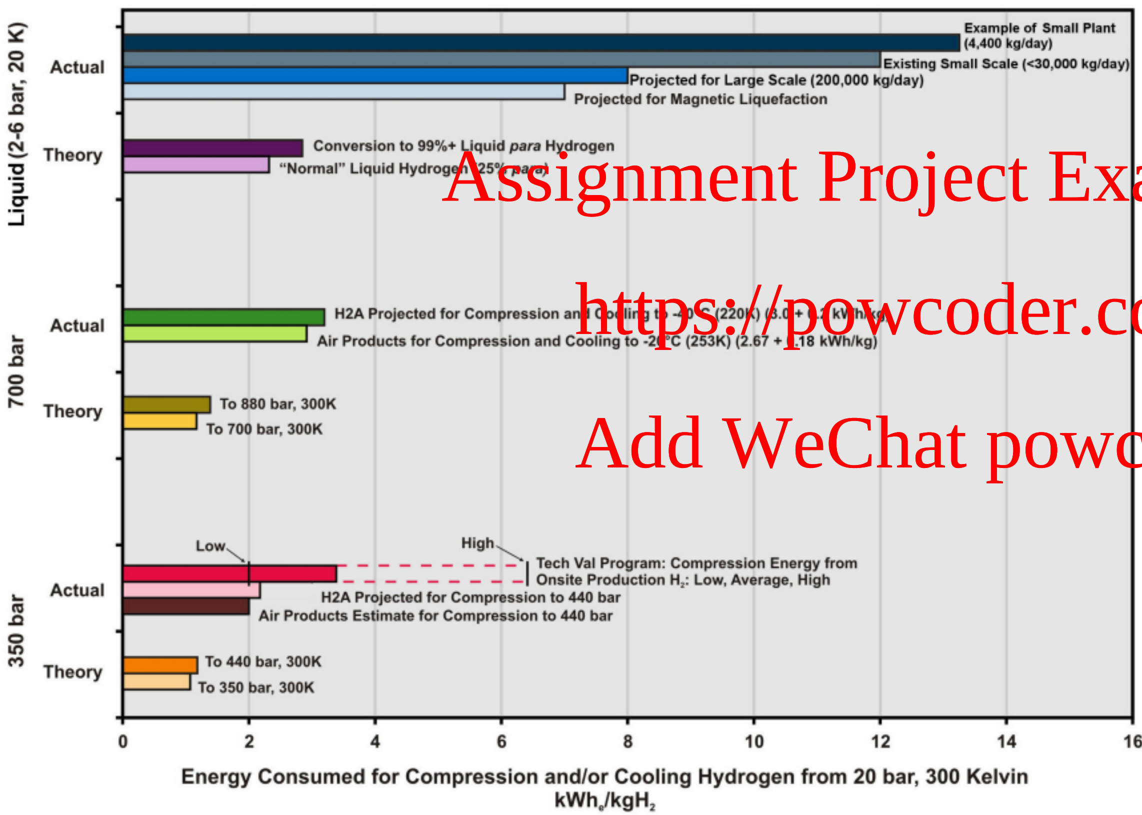


Hydrogen Storage: The best way?

Technique	Volume kg H_2/m^3	Mass %	Pressure atm	Temperature °C	Cost
Compressed Gas	39.2	5.4	700	25	Low
Liquid Hydrogen	71	100	1	-253	Modest
Porous Materials	20	4	70	-200	Modest
Metal Hydrides	150	3	30	25	High
Complex Hydrides	150	10	30	300	Modest
Hydrolysis	100	10	1	25	High

Hydrogen Storage – High Pressure

Figure 1: Energy Required for Vehicle Storage of Hydrogen in Different Thermodynamic States



Hydrogen has an energy density of 33.33 kWh/kg.

<u>Energy loss on compression/cooling</u>

Liquefaction – 36%

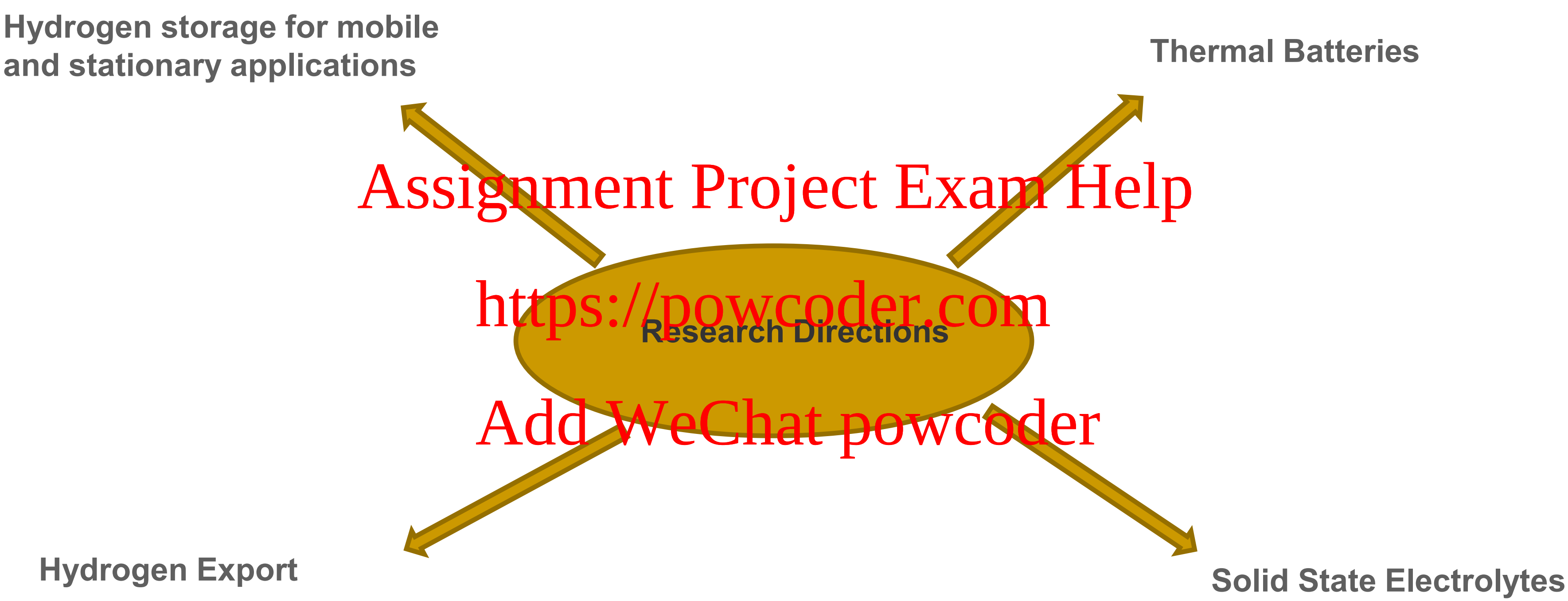
700 bar compression – 9%

Must consider energy required to store hydrogen and release it.

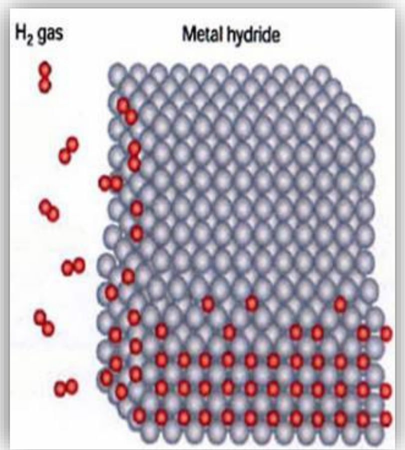
Learning Outcome Check

- Calculate and compare the mass of different fuels required to achieve the same heating duty.
- List 5 techniques used to store hydrogen. Comment on their relative temperatures and pressures, and cost.

Hydrogen Storage Research Group



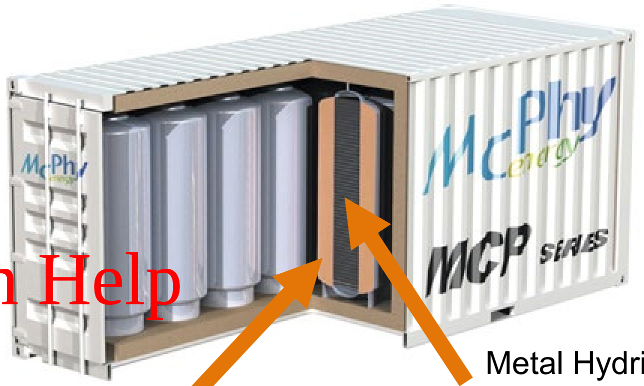
Mobile and Stationary Applications

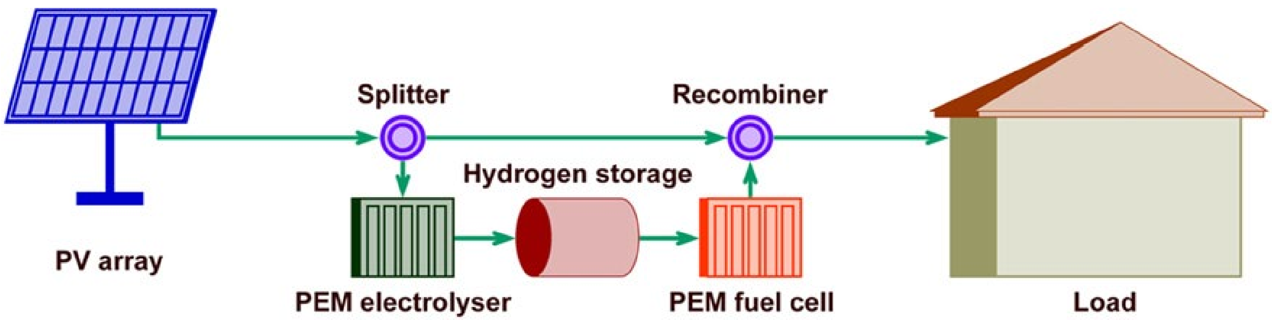


Vehicular Applications

Toyota Mirai

Remote Energy Applications





Gray et al *IJHE* 36 (2011) 654

Green Hydrogen for Road Transport in Western Australia - Future Energy Exports Cooperative Research Centre (CRC)

- Partners: Sustainable Built Environment National Research Centre (through its partners MRWA, BGC Australia and ATCO), Curtin University and UWA.

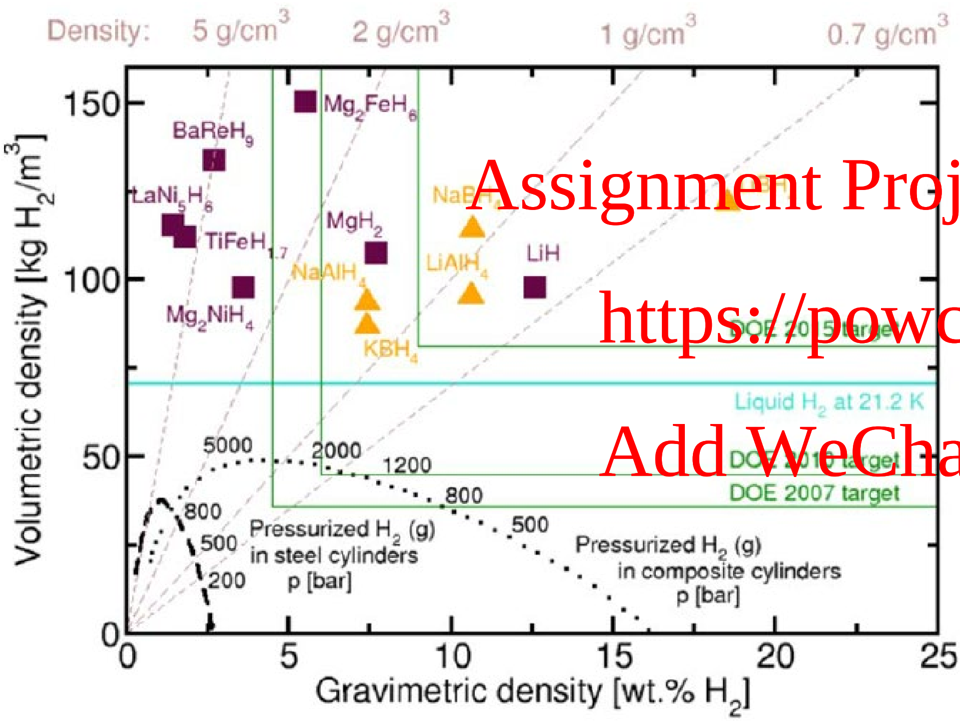
- 3 year project. Total Budget: $805 k.

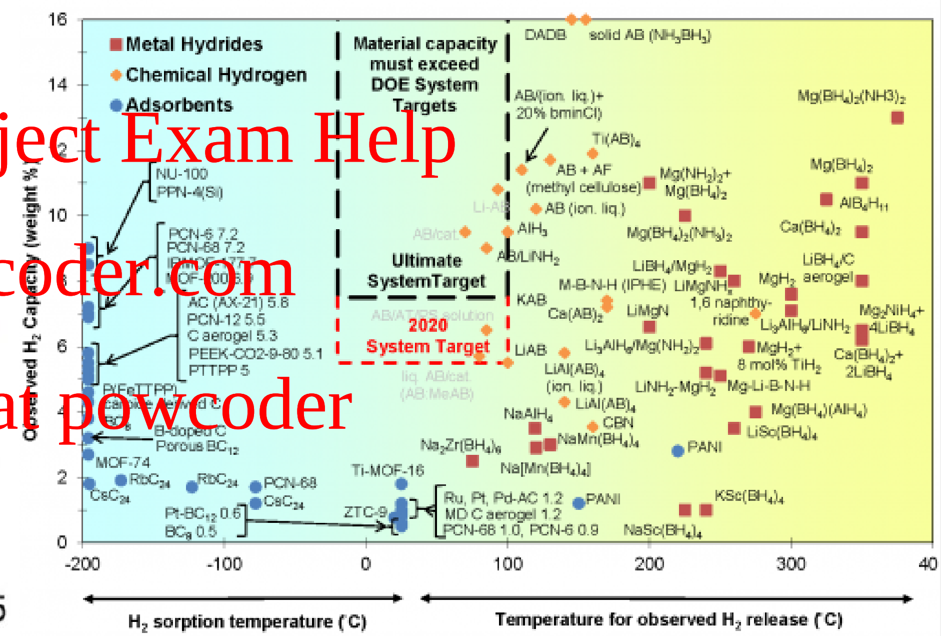
- Review on Green hydrogen for heavy transport applications and techno-economic analysis for the deployment of the required infrastructure in WA.

- Execution of the demonstration trial including deployment of a 5 ton maintenance truck and a 29 ton concrete agitator truck operating in the Midwest and Perth regions.

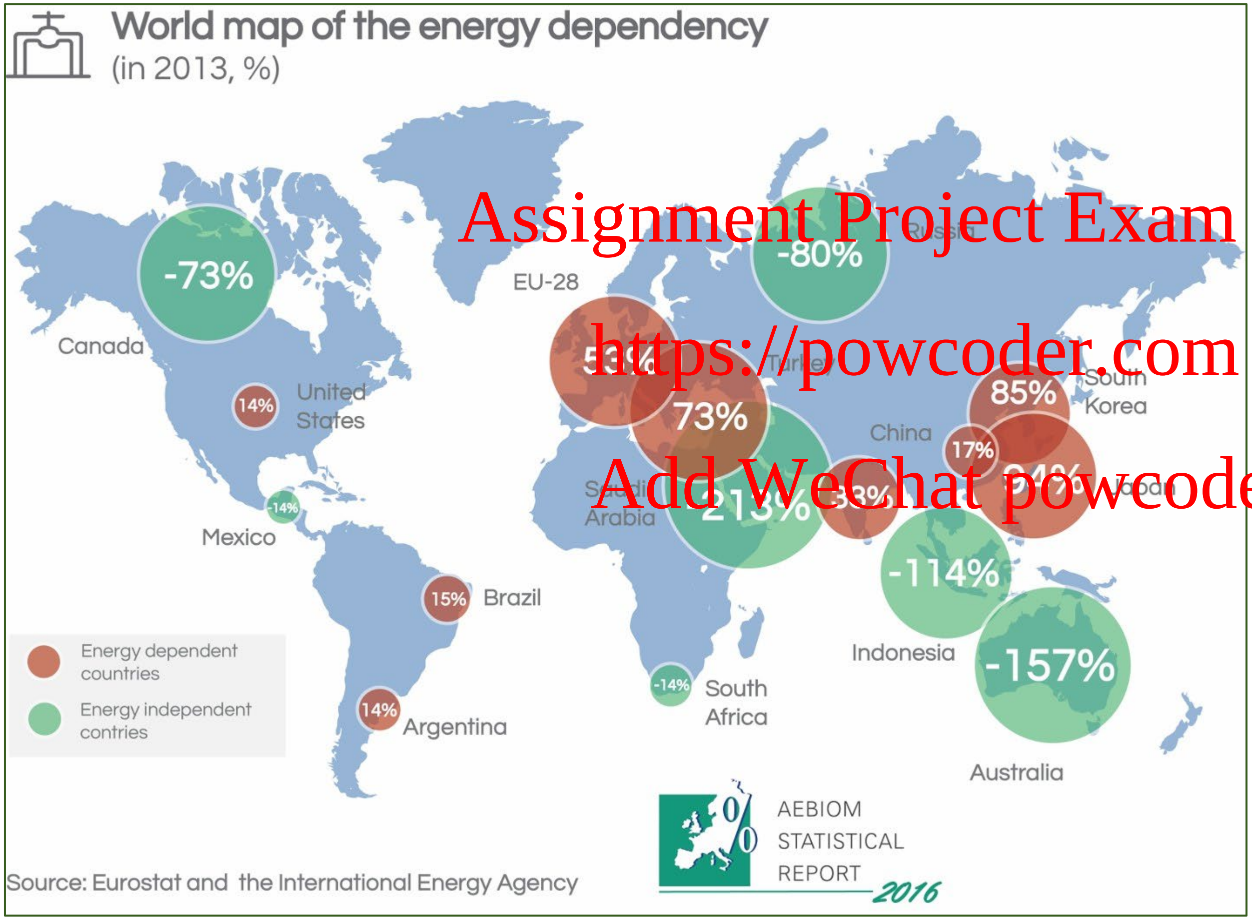
- Data collection and analysis according to the defined metrics to evaluate the performance of the vehicles and refuelling stations.

Hydrogen Storage in Powders





Hydrogen Export from Australia



Hydrogen gas takes up too much volume for export.

Options:

- Liquid ammonia
- Liquid organic hydrogen carriers
- Liquid hydrogen
- Solid-state metal hydride

International Export of Hydrogen

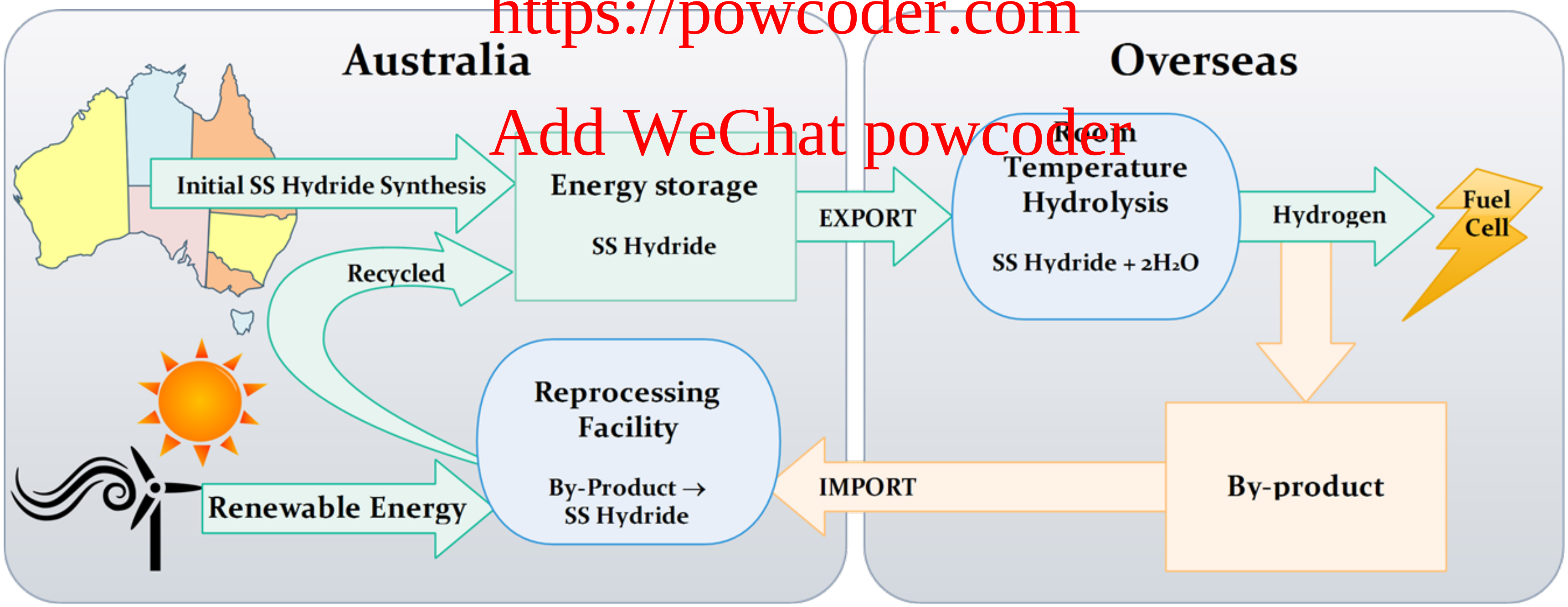
- Japan utilised renewable hydrogen for the 2021 Olympic Games
- Currently doesn't have infrastructure for mass production of H_2
- Australia uniquely positioned to become H_2 export leader
- Australian Government and Chief Scientist have also now suggested hydrogen as a future energy export vector to global markets

- Correct choice of export material must be made
- Dependent on conditions, volume density, H_2 release and cost

Hydrogen carrier	Transport conditions	Volumetric density of H_2 (kg/m^3)	Conditions for H_2 release
Gaseous H_2	25 °C (100 bar)	7.7	25 °C
Gaseous H_2	25 °C (700 bar)	39.2	25 °C
Liquid H_2	-253 °C	71.3	25 °C
Liquid NH_3	25 °C (10 bar)	107.1	400 – 500 °C
Dibenzyl toluene	25 °C	57.0	300 °C
Solid State Hydride	25 °C	< 115.0	25 °C in water

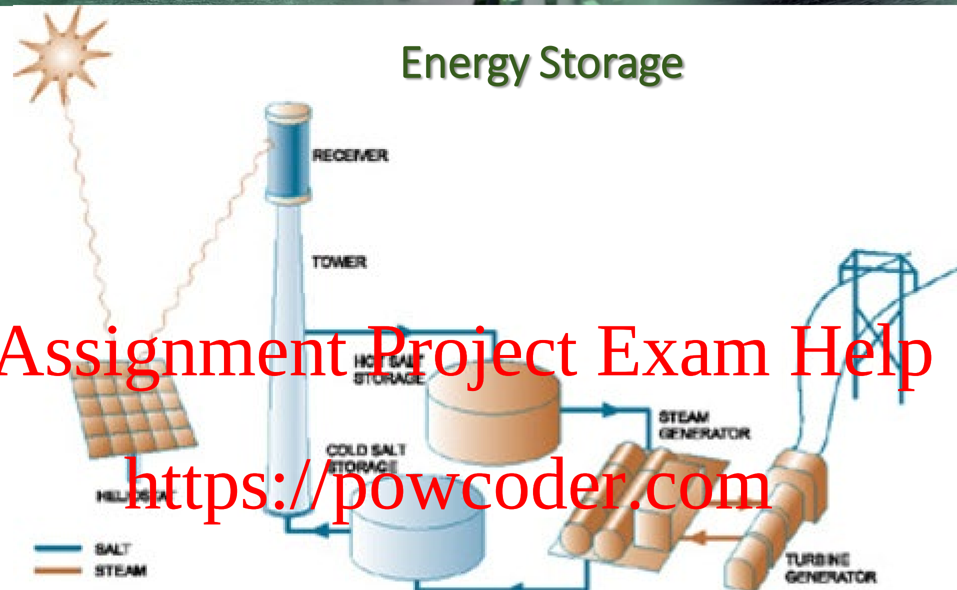
A Solid State Hydride as a H_2 export medium

- Key questions:
  - Can we manufacture large quantities of a solid state (SS) hydride in Australia?
  - How will it be transported?
  - How will H_2 be released?
  - Can we regenerate in high yields?
- A regenerative cycle has been identified



Thermal Battery Research based on Metal Hydrides and Metal Carbonates

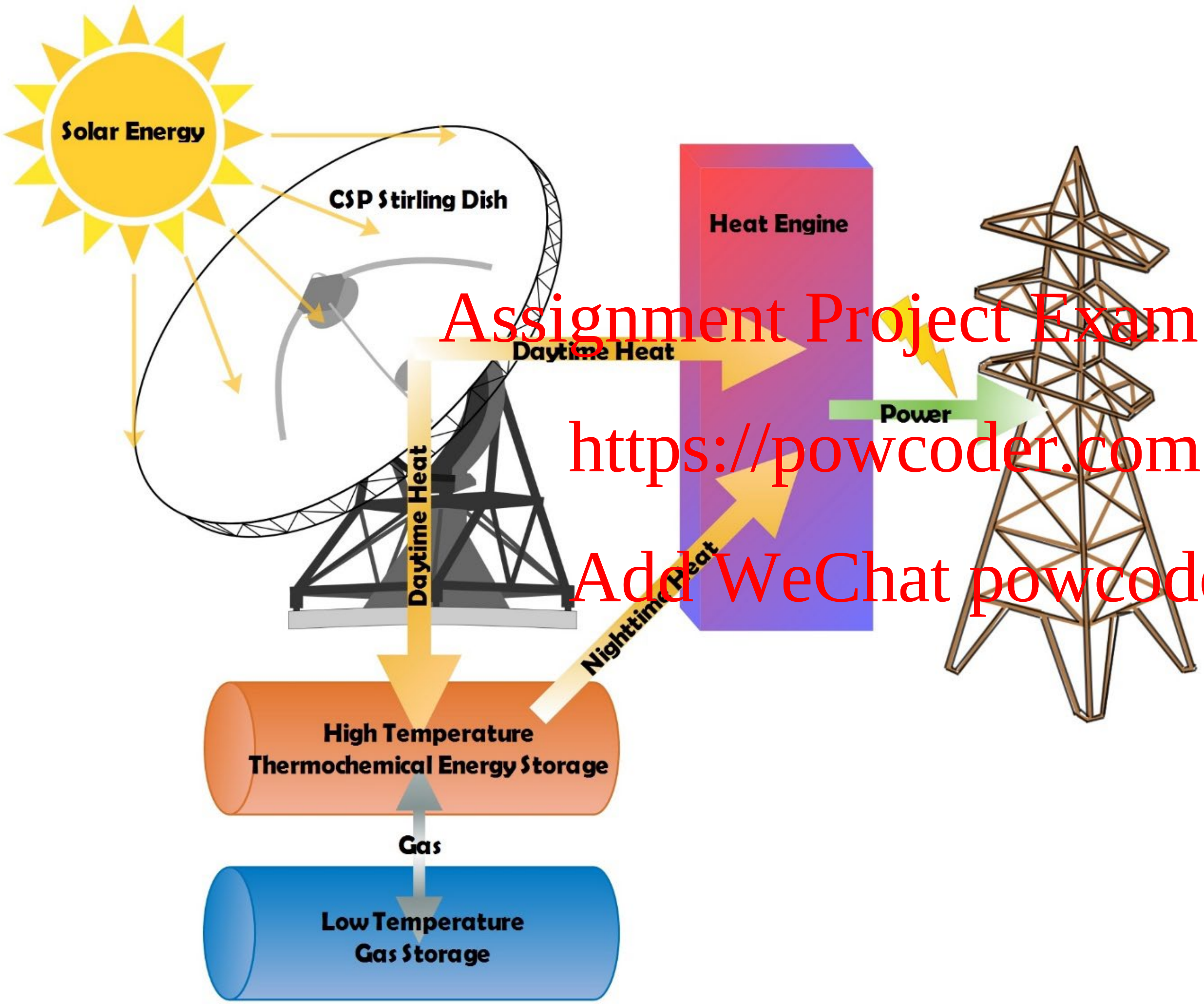
High Temperature Metal Hydrides for Concentrated Solar Thermal Energy Storage



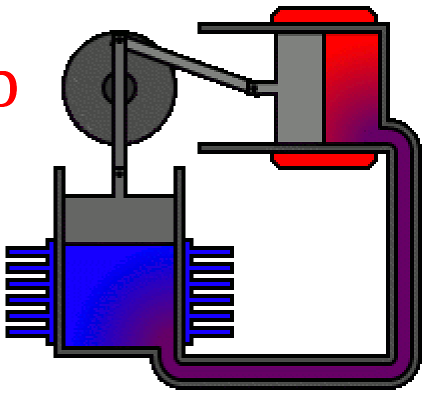
- Most current CST systems use the simplest method, sensible heat storage, and the predominant materials used are binary (60% $NaNO_3$; 40% KNO_3) molten salt mixtures.
- Solar Millenium's 50 MW Andasol I plant with 7.5 hours storage uses 28,500 tonnes of molten salt

Type of thermal energy storage (TES)	Example of TES material	Total heat storage capacity (kJ/kg)
Sensible heat	Molten salt mixtures	153 per 100°C
Latent heat / phase change materials	$NaNO_3$	282
Thermochemical	Oxidation of Co_3O_4	1055
Metal Hydride	$MgH_2 \rightarrow Mg + H_2$	2814

CSP Stirling Dish

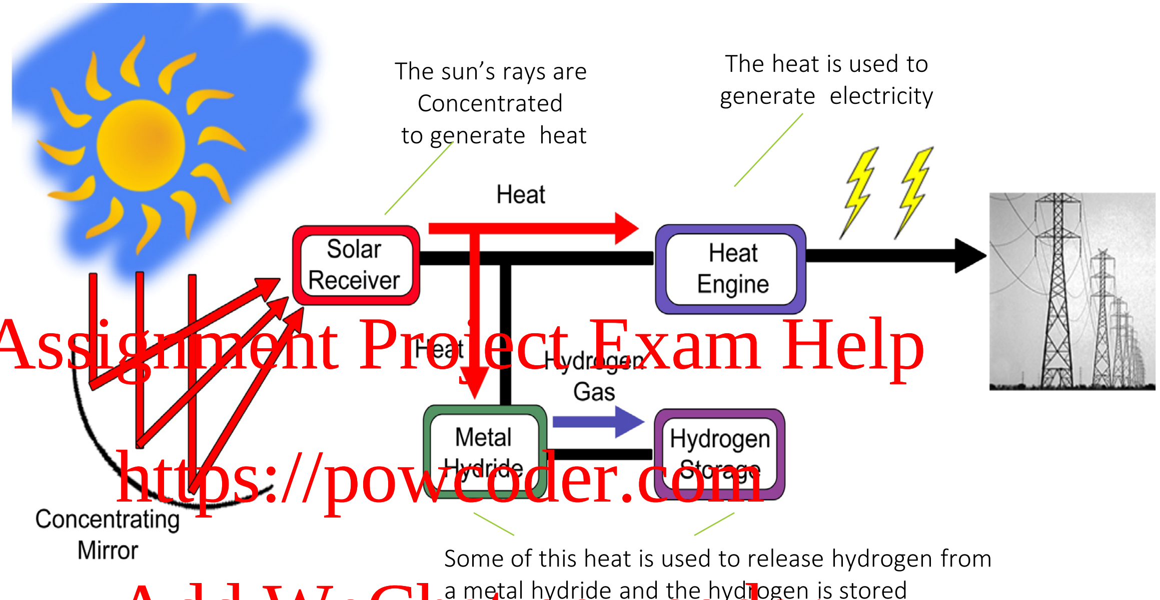


Stirling Engine

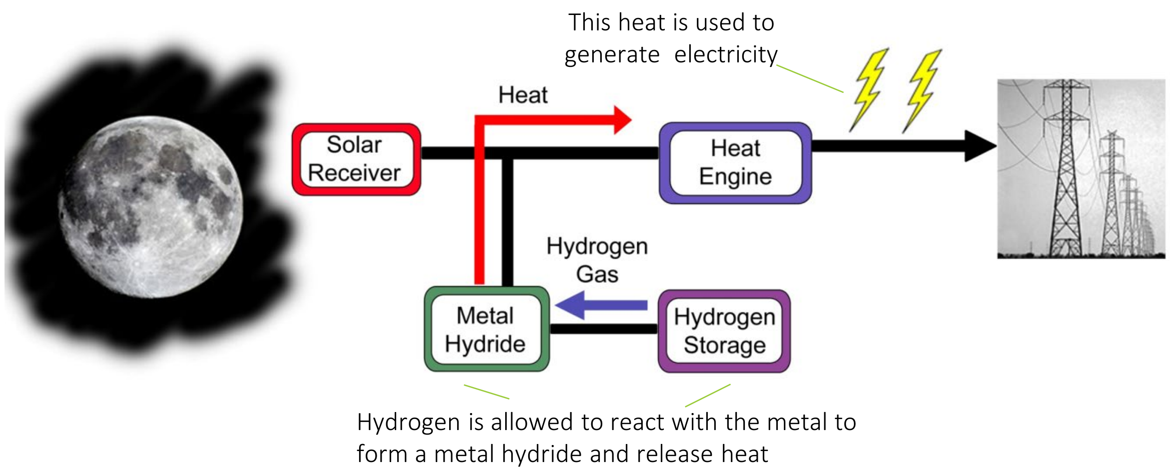


Solar Thermal Batteries - Hydrogen

During the Day

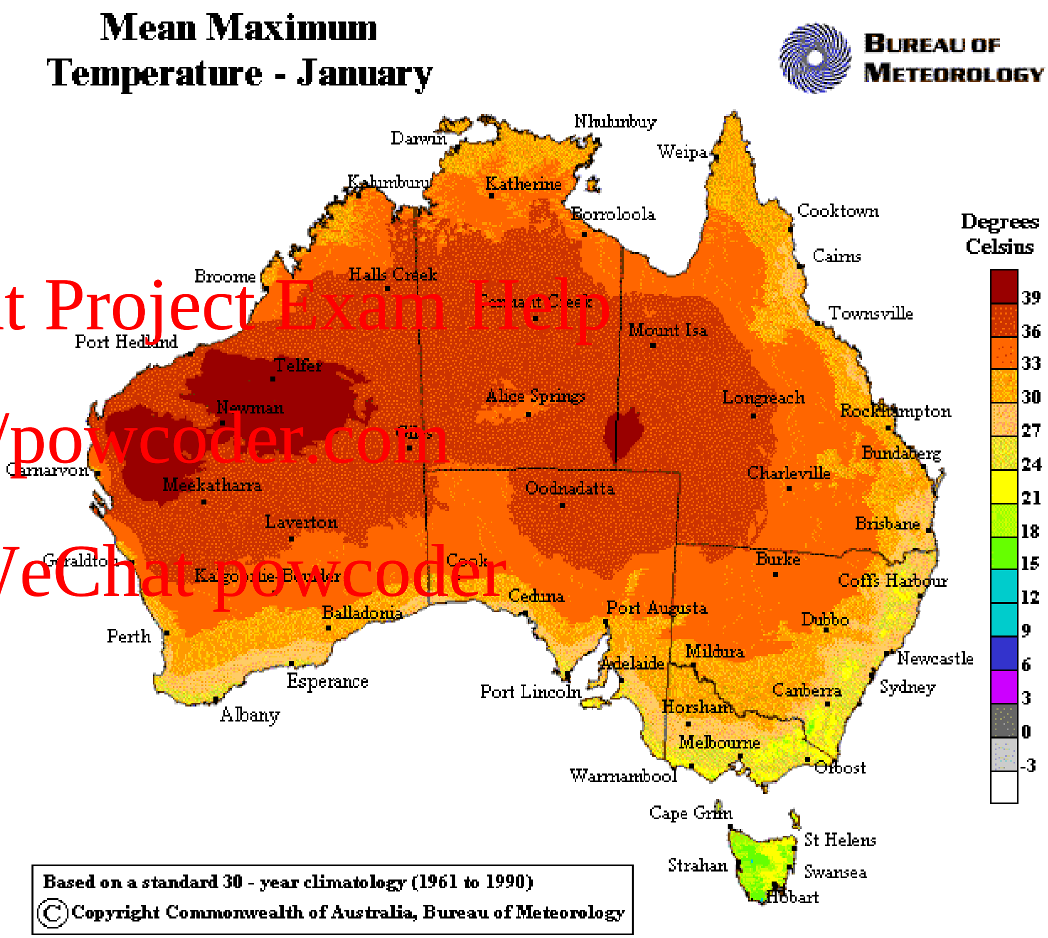


At Night

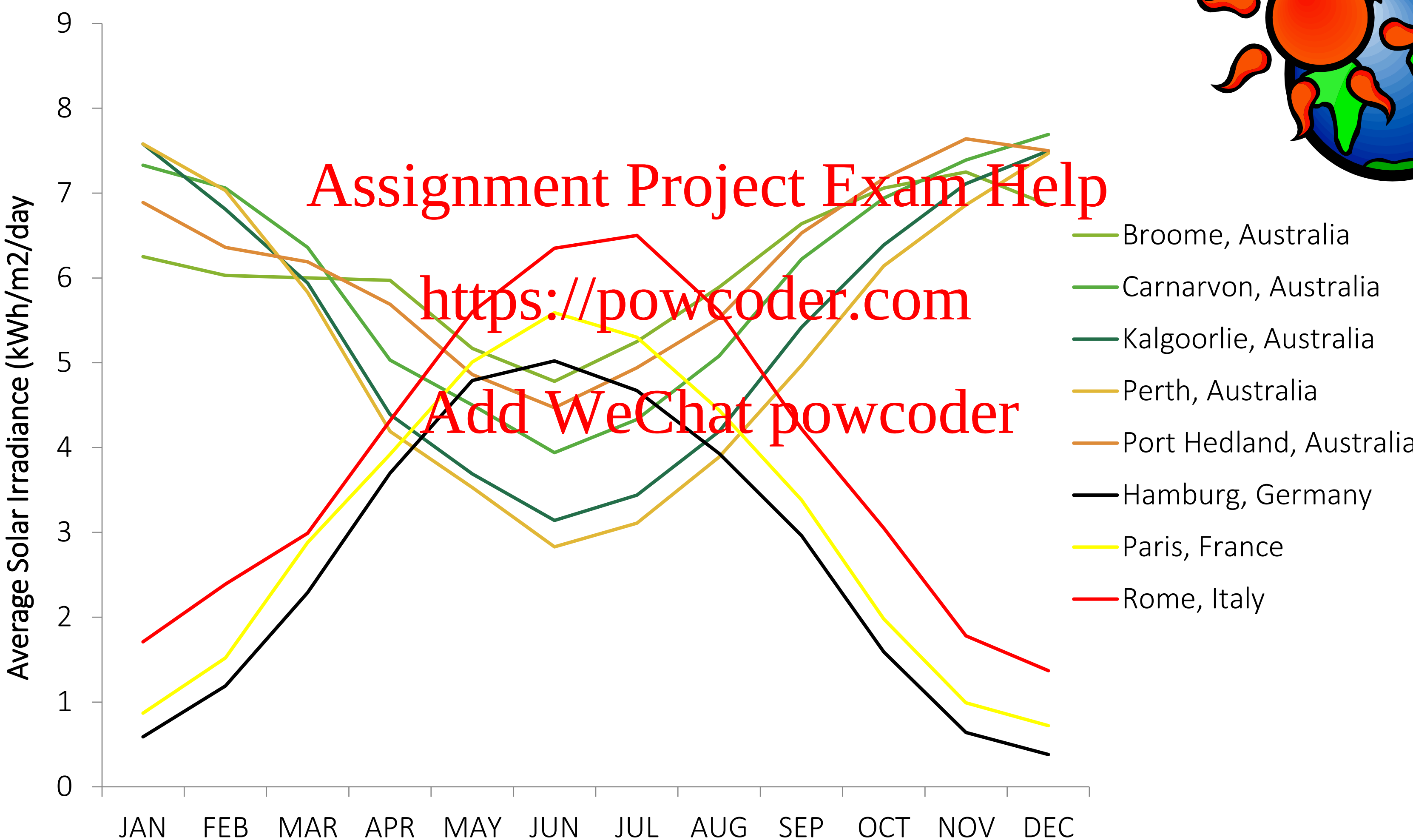


Australia

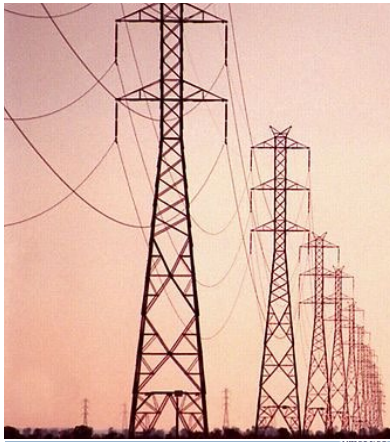

Finland
Norway
Sweden
Estonia
Scotland
Denmark
Lithuania
Russia
Ireland
Wales
England
Netherlands
Belgium
Germany
Poland
Belarus
France
Switzerland
Austria
Hungary
Romania
Italy
Croatia
Bosnia-Herzegovina
Yugoslavia
Bulgaria
Greece
Portugal
Spain
Sicily
Turkey
Algeria
Tunisia
Morocco
Libya
Egypt

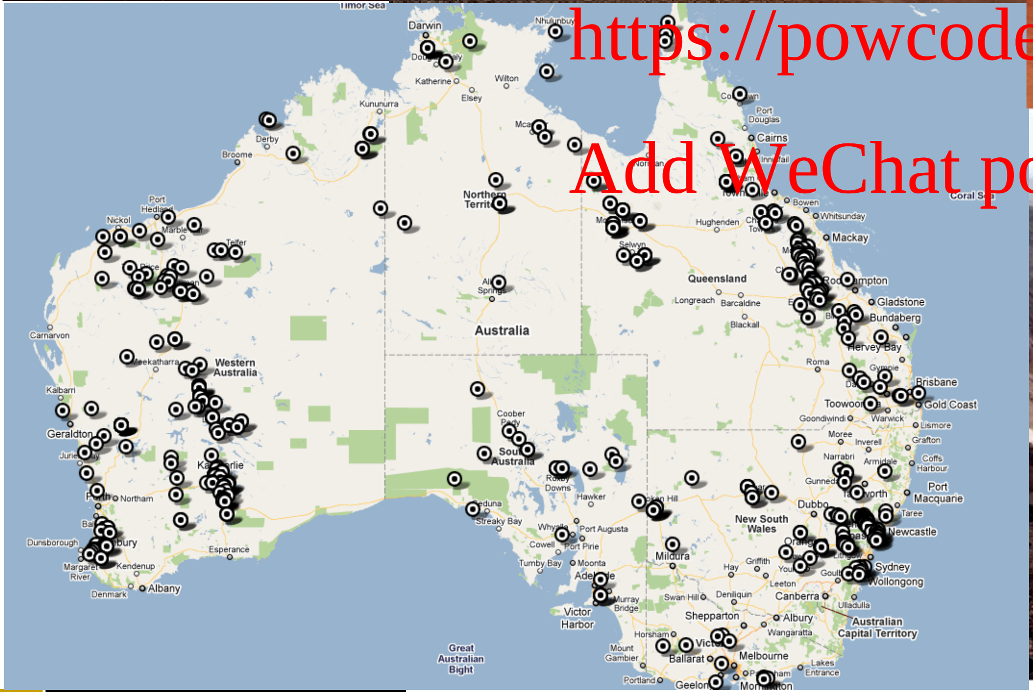

Mean Maximum
Temperature - January
Bureau of Meteorology
Degrees Celsius
39
36
33
30
27
24
21
18
15
12
9
6
3
0
-3
Darwin
Nhulunbuy
Weipa
Kalumburu
Katherine
Borroloola
Cooktown
Cairns
Broome
Halls Creek
Port Hedland
Mount Isa
Townsville
Telfer
Alice Springs
Longreach
Rockhampton
Newman
Bundaberg
Carnarvon
Meekatharra
Oodnadatta
Charleville
Laverton
Brisbane
Cook
Burke
Coffs Harbour
Ceduna
Port Augusta
Balladonia
Dubbo
Perth
Mildura
Adelaide
Newcastle
Esperance
Port Lincoln
Canberra
Sydney
Albany
Horsham
Melbourne
Orbost
Warrnambool
Cape Grim
St Helens
Strahan
Swansea
Hobart
Based on a standard 30 - year climatology (1961 to 1990)
© Copyright Commonwealth of Australia, Bureau of Meteorology

Average Solar Irradiance



Mining in Australia





Remote Area Power

Critical problem for remote area operations: Mining, Communities

The majority of remote mines cannot be connected to the power grid

All the electricity must be generated on-site

Diesel Generators – 2.2 MW each!

Remote Area Power

Electricity demand (typical mine site):

- Peak demand: 5 – 650 MW
- Fluctuating demand – peak during day
- High reliability required (auxiliary back-up is essential)

J. Paraszczak and K. Fytas, ICREPQ'12, Spain 2012

Diesel typically must be transported by trucks, adding to its consumption.

The iron ore industry

in Western Australia

consumes in excess of a 3 million litres of diesel

each DAY!!!

S. S. Shastri – Australia's Mining Thirst, GHD Perth, 2012

Diesel Usage

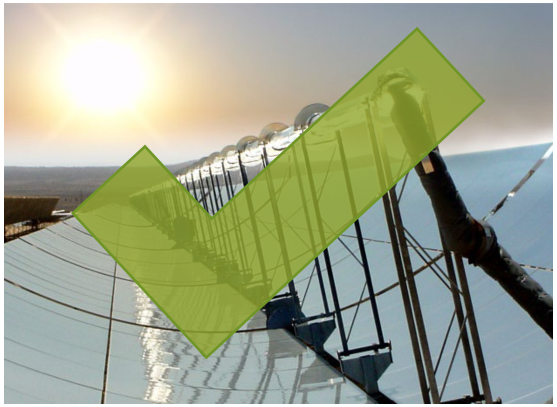
Diesel powered power plants
30 – 40 c/kWh

Solar thermal is more than competitive. CSP plant 13.5 c/kWh

High Temperature Metal Hydrides

Revisit high temperature materials that have been mostly overlooked

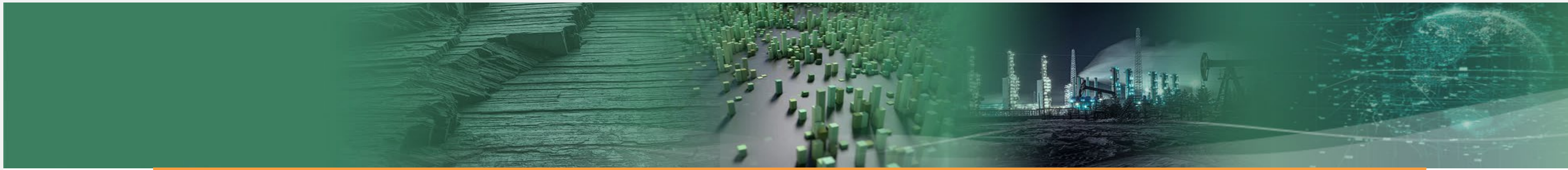
Material	Temperature	Enthalpy (kJ/mol H_2)
YH_3	> 1200 °C	220
CaH_2	> 950 °C	208
LiH	> 900 °C	134
ZrH_2	> 800 °C	212
TiH_2	> 700 °C	164
$NaMgH_3$	> 400 °C	87



Q. Lai, M. Paskevicius, D.A. Sheppard, C.E. Buckley, A.W. Thornton, M.R. Hill, Q. Gu, J. Mao, Z. Huang, H.K. Liu, Z. Guo, A. Banerjee, S. Chakraborty, R. Ahuja, K.F Aguey-Zinsou. "Hydrogen storage materials for mobile and stationary applications: Current state of the art." *ChemSusChem*, **8** (2015) 2789 – 2825.

D.A. Sheppard, M. Paskevicius, C.E. Buckley, M. Felderhoff, R. Zidan, D.M. Grant, M. Dornheim et al. "Metal hydrides for concentrating solar power energy storage" *Applied Physics A* **122:395** (2016) 1 – 15.

P.A. Ward, C. Corgnale, J.A. Teprovich Jr., T. Motyka, B. Hardy, D.A. Sheppard, C.E. Buckley, R. Zidan. "Technical challenges and future direction for high-efficiency metal hydride thermal energy storage systems" *Applied Physics A* **122:462** (2016) 1 – 10.



Materials	Theoretical Heat Storage Capacity (kJ/kg)	Operating Temperature (°C)
Sensible Heat		
$NaNO_3/KNO_3$	153 per 100 °C	290 - 565
Metal Hydrides		
$Mg_2NiH_4 \leftrightarrow Mg_2Ni + 2H_2$	1168	250 - 400
$MgH_2 \leftrightarrow Mg + H_2$	2811	300 - 400
$Mg_2FeH_6 \leftrightarrow 2Mg + Fe + 3H_2$	2096	350 - 550
$NaMgH_3 \leftrightarrow NaH + Mg + H_2$	1721	430 - 585
$NaMgH_3 \leftrightarrow Na + Mg + 1.5H_2$	2881	> 585
$TiH_{1.7} \leftrightarrow Ti + 0.85H_2$	2842	700 - 1000
$CaH_2 \leftrightarrow Ca + H_2$	4934	> 1000
$LiH \leftrightarrow Li + 0.5H_2$	8397	> 850

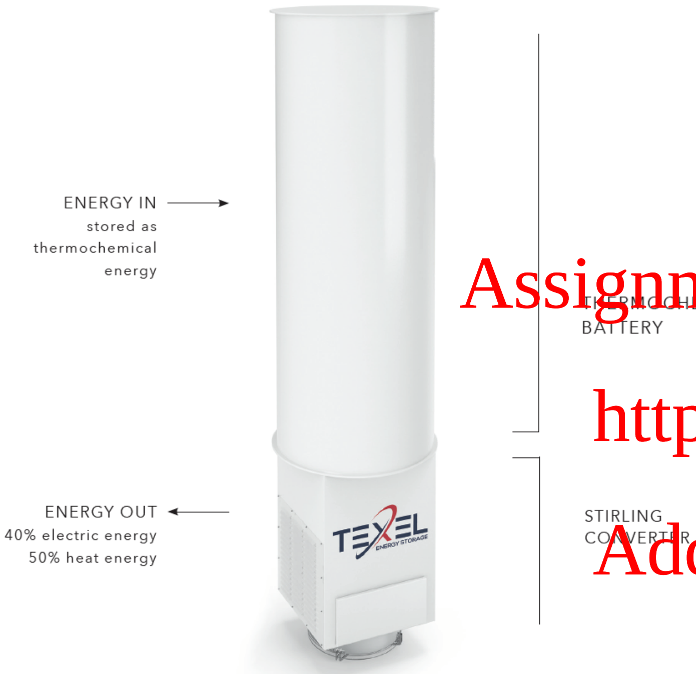
M. Fellet. Feature Editors C.E. Buckley, M. Paskevicius, D.A. Sheppard *MRS Bulletin* **38** (2013) 1012 – 1013.

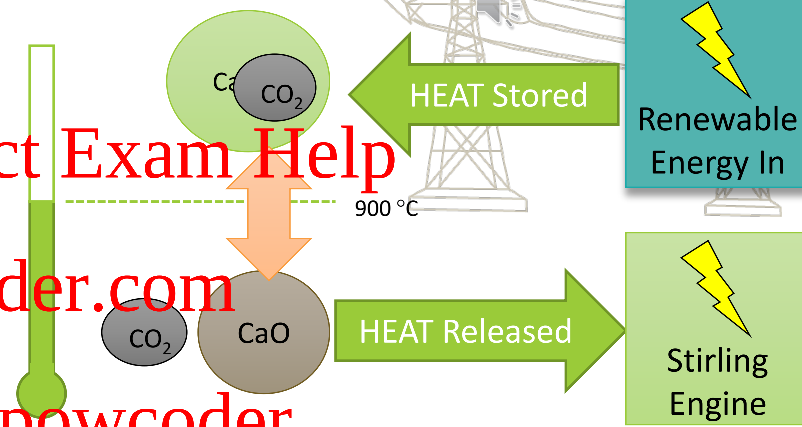
K. Manickam, C.E. Buckley et al. *International Journal of Hydrogen Energy*, **44** (2019) 7738 – 7745.

L. Poupin, C.E. Buckley et al. *Sustainable Energy & Fuels*, **3** (2019) 985 - 995.

T.D. Humphries, C.E. Buckley et al. *Journal of Physical Chemistry C*, **124** (2020) 5053 - 5060.

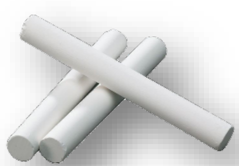
The CO_2 Thermal Battery





- Chemical reaction stores and releases heat energy
- Controlled using gas pressure
- Electricity in – Electricity out

Chalk



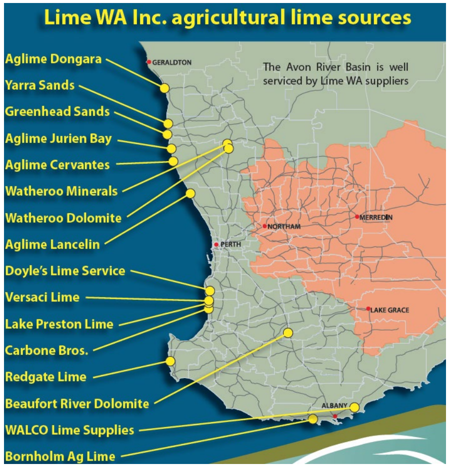
OR

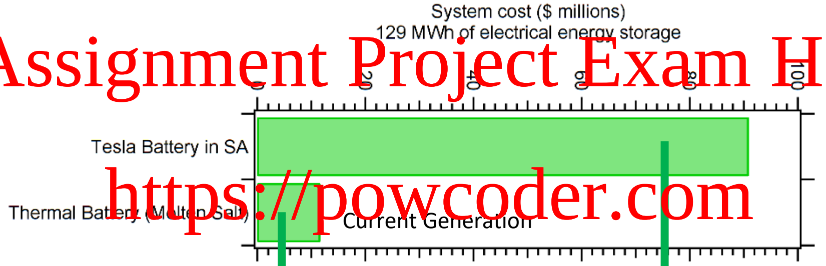
T.D. Humphries, C.E. Buckley et al. *J. Materials Chemistry A* **7** (2019) 1206 - 1215.

Thermal Battery Price

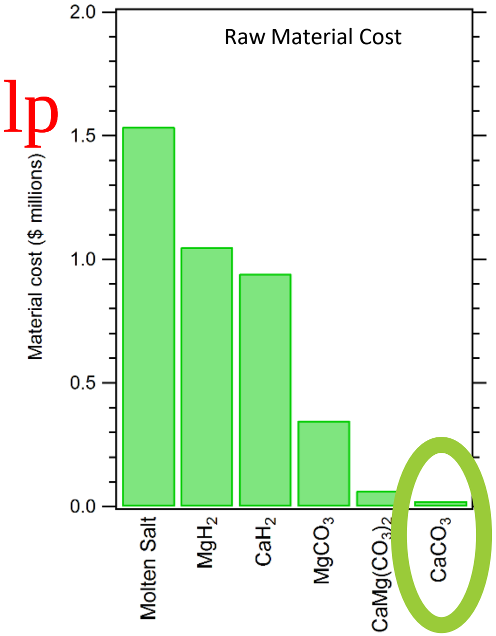
Limestone ($CaCO_3$) is the primary ingredient **$5 - 10 per tonne**

Literally DIRT cheap



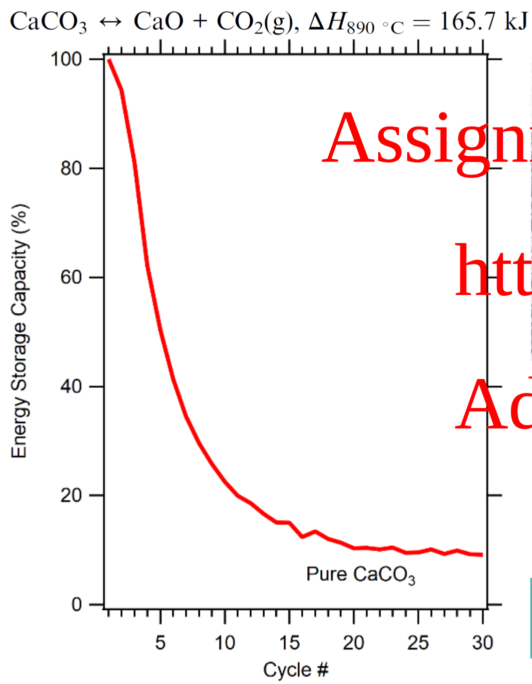


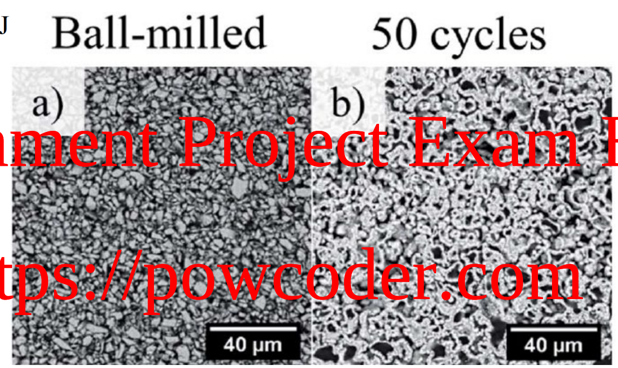
TESLA



K.T. Moller, C.E. Buckley et al. *J. Materials Chemistry A* **8**, (2020) 9646 - 9653

So why has this not already been done?





Catalyst Development

500 cycles → 90% capacity retention

Catalysts are expensive…

Al_2O_3 is cheap! $324/tonne

J. Mater. Chem. A, 2020, 8, 9646–9653

Our catalyst

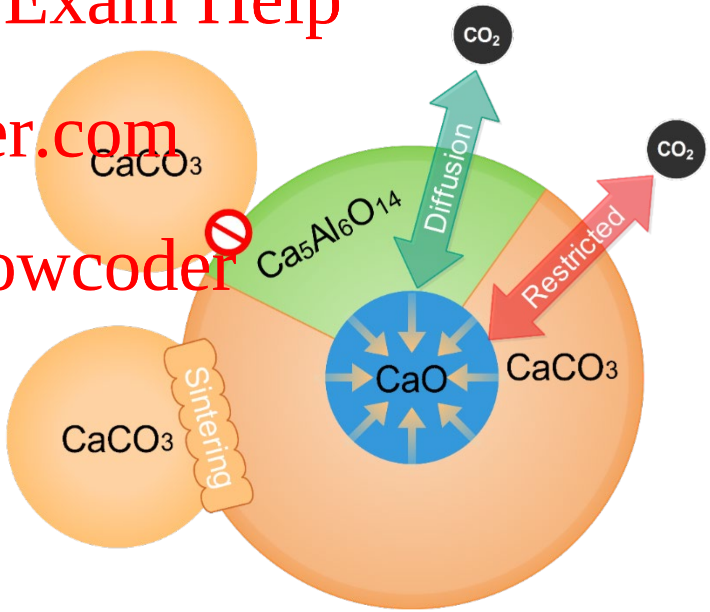
Breakthrough for
Thermal Battery
Lifetime

Thermochemical reaction (energy storage/release)

$$CaCO_3 \leftrightarrow CaO + CO_2(g),\ \Delta H_{890\ °C} = 165.7\ kJ$$

Catalyst formation (only occurs once)

$$5CaO(s) + 3Al_2O_3(s) \rightarrow Ca_5Al_6O_{14}(s)$$

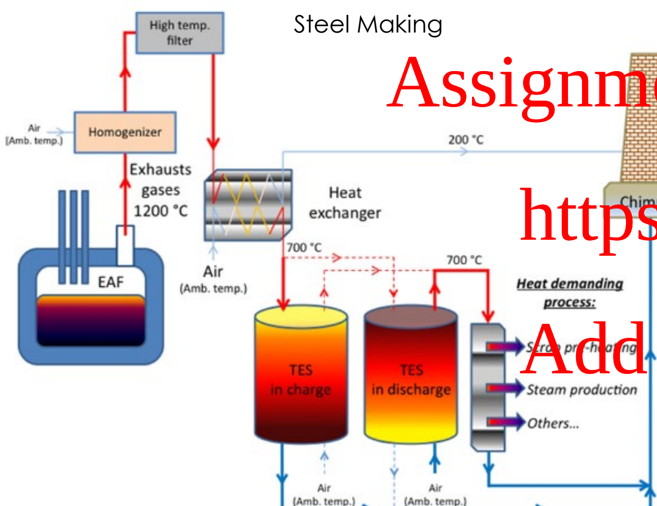


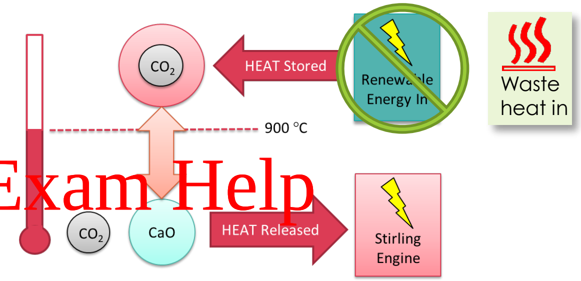
- Innovation and novelty is: working catalyst
- Patent has been submitted
- Optimisation and upscaling of technology in-progress

J. Mater. Chem. A, 2020, 8, 9646–9653

$CaCO_3$ for other Applications

Waste heat





High Temperature Heat Recovery

Table: Typical waste heat temperature at high temperature range from various sources

Types of Devices	Temperature (°C)
Nickel refining furnace	1370 – 1650
Aluminium refining furnace	650 –760
Zinc refining furnace	760 – 1100
Copper refining furnace	760 – 815
Steel heating furnace	925 – 1050
Copper reverberatory furnace	900 – 1100
Open hearth furnace	650 – 700
Cement kiln (Dry process)	620 – 730
Glass melting furnace	1000 – 1550
Hydrogen plants	650 – 1000
Solid waste incinerators	650 – 1000
Fume incinerators	650 – 1450

Applied Energy 237 (2019) 708–719

The Future for Hydrogen and Thermal Batteries

- Multiple applications for hydrogen = Variety of storage solutions.
- Small mobile storage (e.g. cars) → High pressure compressed gas tanks. 5 kg H_2 at 700 bar = 127.5 L.
- Medium mobile storage (e.g. trucks, buses) → Gas tanks, 50 kg H_2 at 350 bar = 2150 L.
- Large scale stationary storage (e.g. Hydrogen refuelling station, heat storage).
- Hydrogen will move forward in Australia as an energy carrier. It needs to be paired with renewables so that it carries 'clean' energy.
- Hydrogen can be used in Australia as a fuel or exported – new export industry.
- Hydrogen in metal hydrides can be used for heat storage to produce electricity 24/7.
- Thermal batteries can also be developed using CO_2 for heat storage.
- Some technical challenges to improve technology cost / efficiency / performance. However, hydrogen can be used **today**!

Learning Outcome Check

- Understand the term *thermal battery* and how it can provide a solution for energy stability.

Lecture Summary

✓Solar Power and Hydrogen

✓Why Hydrogen?

✓Hydrogen Storage Research Group (HSRG) Projects

✓Conclusion

Thanks for Listening

Any Questions?