a) oil
b) natural gas
c) wind
d) solar
e) biofuels

f) all of the above

The answer to the big question of how to secure future energy supplies isn’t one of the above. It’s all of the above. That’s why, as the largest single producer of oil and gas in the UK North Sea, BP is using the latest technology to find new reserves and to increase recovery from existing fields. We are also investing in a major biofuels facility in Hull and expanding our global wind power generation and production of solar panels. It all adds up to a more dependable energy future. Learn more at bp.com

The Times, September 24th 2008
UK primary energy supply structure and the present and future position of UK energy mix.
"Global values of the low carbon economy could be as high as £3 trillion pa worldwide by 2050. It could employ more than 25m people with over 1m in the UK over the next 20 years."

Gordon Brown Nov 2007
The Challenges and Opportunities of Hydrogen

Hydrogen Production

- Biomass
  - Gasification
  - Bio-hydrogen
- Wind
  - Electrolysis
- Solar
  - Electrolysis
- Other?
- Natural gas
  - Reforming
  - Partial oxidation
- Coal
  - Gasification
  - In-situ gasification incl. CO₂ sequestration
- Fission / fusion
  - Electrolysis
  - Thermo-catalytic
- Petroleum Coke/Residue
  - Gasification incl. CO₂ sequestration

Sustainable Hydrogen, a European Perspective, Prof. Dr. J. Schoonman
GCEP Hydrogen Conference, Stanford University, April 14-15, 2003
Hydrogen Production Challenges: Hydrogen from Fossil Fuels

- **Steam Reforming:**
  - Reaction: $\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2$
  - $\Delta G = +150 \text{ kJ}$

- **Water-Shift Reaction:**
  - Reaction: $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$
  - $\Delta G = -19 \text{ kJ}$

**CO$_2$ technology in place**
**marginal effect on energy challenges**
CO₂ Capture and Storage

- Terrestrial
  - Stable Solids
  - Fuels
  - Useful Products
  - Enhanced Oil Recovery
  - Unmineable Coal Beds
  - Depleted Oil or Gas Reserves
- Geologic Disposal
- Ocean Disposal
- Power Station with CO₂ Capture
  - 1. Dense plume
  - 2. Droplet plume
  - 3. Towed pipe
  - 4. Dry ice
  - 5. CO₂ lake
- Deep Saline Formation
Ocean acidification due to increasing atmospheric carbon dioxide

Action needs to be taken now to reduce global emissions of CO₂ to the atmosphere to avoid the risk of large and irreversible damage to the oceans. We recommend that all possible approaches be considered to prevent CO₂ reaching the atmosphere. No option that can make a significant contribution should be dismissed.
Carbon Dioxide Elaboration: The Oxford Energy Cycle

**Renewable Energy** (all Known Sources)

**Electricity** - then electrolysis of water

**Hydrogen**

\[ 2H_2 + CO \rightarrow (CH_2)_n + H_2O \]

**Hydrocarbons**

*Sequestered*

\[ CO_2 + H_2 \rightarrow CO + H_2O \]

*Store energy as hydrocarbons*

*Transport energy as hydrocarbons*

*Use hydrocarbons as liquid fuels*

Hydrocarbons + air \[ \rightarrow CO_2 + \text{water} \]

**NET production of carbon dioxide is ZERO**
Hydrogen Production Challenges: Hydrogen from H₂O Splitting

the H₂/water cycle

ΔG = 474 kJ →

H₂

H₂

ΔG = - 474 kJ

H₂O

H₂O

energy sources
non-fossil electricity
solar, hydro, wind, nuclear
solar/nuclear heat
fossil electricity/heat

H₂ liberation
electrolysis
photo-electrolysis
dissociation
thermochemical cycle

H₂ conversion
fuel cell: electricity/heat
heat engine
combustion
Water Splitting
The Challenges and Opportunities of Hydrogen

Hydrogen Storage

Hydrogen Storage Materials
The Key Technology Barrier

Energy Production  Energy Storage  Energy Use

Gas  Oil  Hydro  Geothermal  Transport
Reform  Wind  Wave  Consumer
Nuclear  Solar

The Perfect Store?
Hydrogen Storage: Gas and Liquid

Gaseous storage
- 5000 psi = 350 bar
- 10000 psi = 700 bar
- Fiber reinforced composite containers

Liquid storage
- Standard in stationary applications
- Portable cryogenics for auto
- 30-40% energy lost to liquefaction

Within technological reach
Hydrogen Storage

Toyota Fuel Cell Hybrid Vehicle

70 Mpa (700 atmosphere) hydrogen tank

Range 760 kilometers (472 miles), Cold Start -30° Celsius
Hydrogen to fuel this car for 400km; stored as compressed gas, cryogenic liquid and solid state stores.

“There exists the necessity for an epoch-making advance in new materials for hydrogen storage.... This is the hardest challenge”

Masatami Takimoto
Executive Vice President, Toyota Motor Corporation
## Hydrogen Storage

<table>
<thead>
<tr>
<th>Method</th>
<th>Operating Temperature</th>
<th>Corresponding Energy to Release Hydrogen (MJ per kg H₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid hydrogen</td>
<td>-253°C</td>
<td>0.45</td>
</tr>
<tr>
<td>Cryo-adsorption</td>
<td>&gt; -200°C</td>
<td>3.5</td>
</tr>
<tr>
<td>Interstitial metal hydride</td>
<td>0 - 30°C</td>
<td>15</td>
</tr>
<tr>
<td>Compressed hydrogen</td>
<td>25°C</td>
<td>n/a</td>
</tr>
<tr>
<td>Alanate</td>
<td>70 - 170°C</td>
<td>23</td>
</tr>
<tr>
<td>Salt-like metal hydride</td>
<td>330°C</td>
<td>37</td>
</tr>
<tr>
<td>Water</td>
<td>&gt;&gt; 1000°C</td>
<td>142</td>
</tr>
</tbody>
</table>

*R.Helmolt, U.Eberle (General Motors), J. Power Sources, 2007, 165, p.833*
Performance Criteria

Weight %

- 8 wt%
- 10 wt%

Cycles

- $10^2$ cycles
- $10^3$ cycles
- $10^4$ cycles

$T_{dec}$

- 100°C
- 80°C
Hydrogen Storage

- High gravimetric density
  - The challenge of the light periodic table

- Low decomposition temperature
  - Thermodynamic control

- Reversibility
  - Electronic and ionic mobility

LaNi$_5$ $\leftrightarrow$ LaNi$_5$H$_7$
Controlling Gravimetric and Volumetric Densities

Specific Energy (kWh/kg)

Volumetric density (kg H₂ m⁻³)

Gravimetric H₂ density (weight % of H₂)

Energy density (kWh/L)

Legend:
- Liquid H₂ tank
- Compressed H₂ tank (700 bar)
- Li-ion batteries

Material Points:
- LiNH₄
- MgH₂
- NaBH₄
- NH₃ (liq.)
- H₂ (liq.)
- NH₄⁺[BH₄⁻]

DoE System Targets:
- 2010 DoE system target
- 2015 DoE system target
Li$_4$BH$_4$(NH$_2$)$_3$, LiNH$_2$
High-capacity hydrogen storage in lithium and sodium amidoboranes

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⁵ISIS Facility, Rutherford Appleton Laboratory, Chilton OX11 0QX, UK
*e-mail: phychenp@nus.edu.sg
The Perfect Store for Hydrogen
Not Yet Discovered

Only a few elements can make suitable lightweight storage materials

Li  B  C  N  Na  Mg  Al  P  Si

Make tens of thousands of new materials from combinations of these elements

Rapidly identify and test these new materials

Together will aim to discover new materials with > 6wt% hydrogen storage

Robotic Synthesis Industrial Partners

Oxford University

Rutherford Appleton Laboratory

Diamond Beam
Rapid throughput materials discovery and characterisation

robotic synthesis ~30mg quantities
Hydrogen Economy

Outlook: The Step-Change Hydrogen Economy

Production by splitting water renewably

Storage in solid materials

Use in fuel cells

addresses the energy challenges supply, security, pollution, climate

science within reach breakthrough research discoveries catalysis, materials, nanoscale science and engineering, bio-mimetics

George Crabtree, UK-US Vision for Hydrogen Technology, October 11-12, 2004
Transition from today’s technologies to future hydrogen-powered fuel cell vehicles

Energy Materials: Meeting the Challenge

Synthesis

Structure

Properties

Performance
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