The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

Workshop on "Physics for Renewable Energy"
October 17 - 29, 2005

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"Hydrogen: State-of-the-Art & Perspectives"

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Hydrogen: state of art and perspectives

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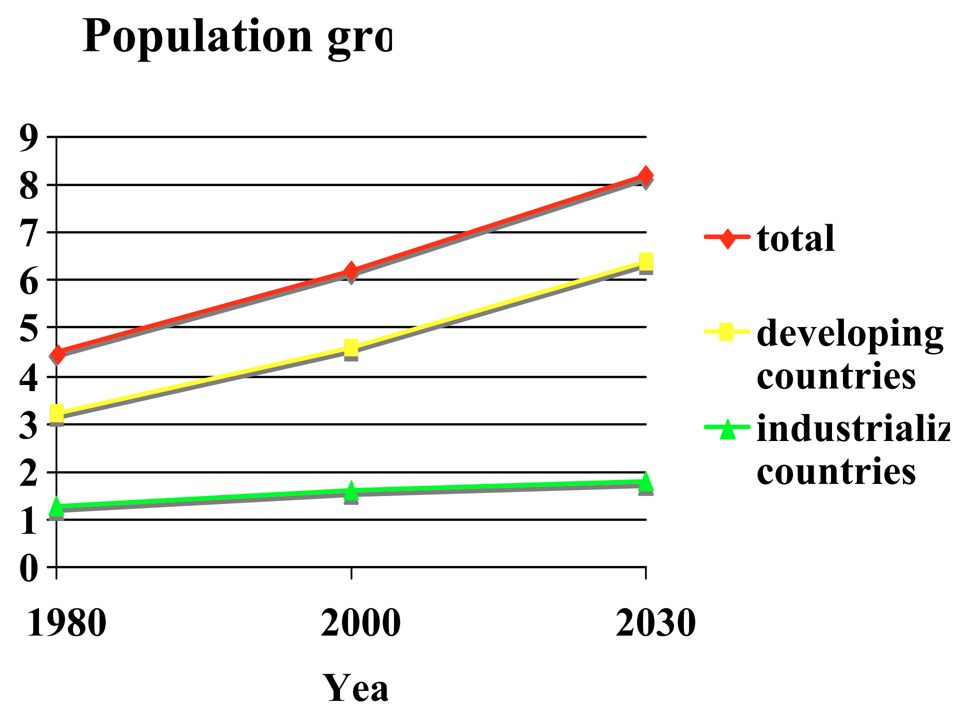
Workshop on ’PHYSICS FOR RENEWABLE ENERGY'

Trieste, Oct. 17-29, 200

Crucial points in energy supply

Growing Energy Demands

- growing population and domestic energy demand

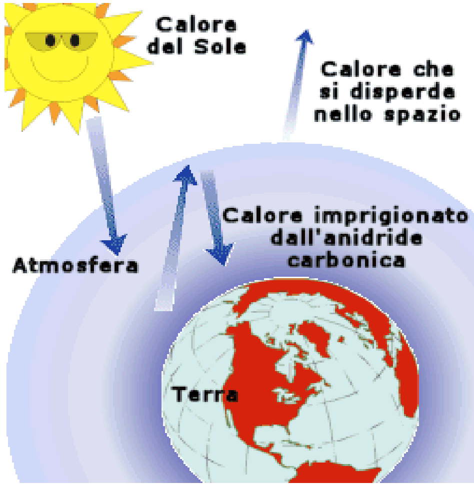


- Developing industry

- Increasing of transportation sector

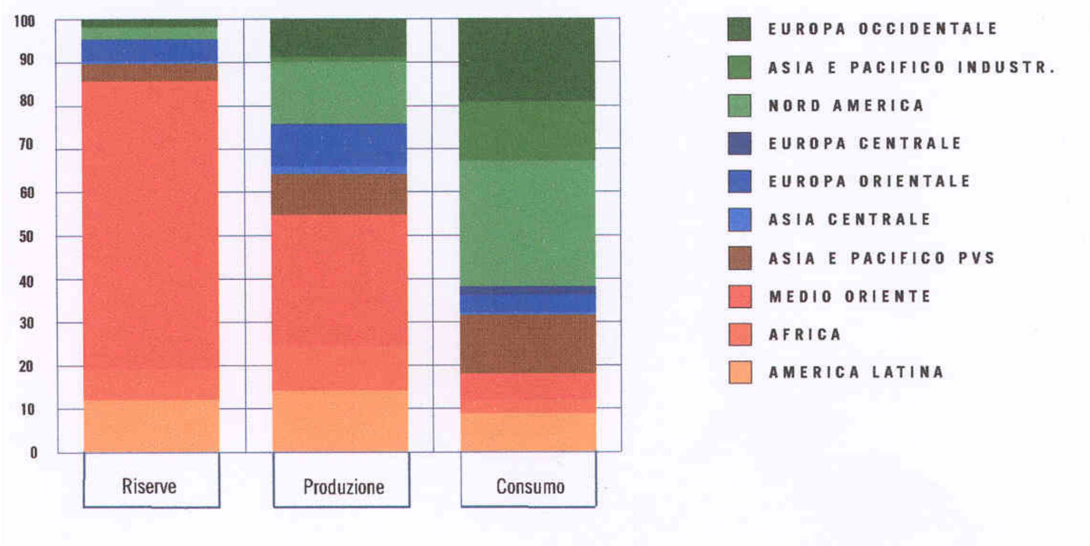
Crucial points in Energy field

- Increasing Environmental problems
  - Global climate change
  - Atmospheric pollution



- Depletion of valuable resources

- Security of supply.



Trends of energy policy

Actual trend:

Reduction of local pollutions emissions (industries, traffic)

Reduction of global emissions (CO2, acidic gases)

Diversification of energy sources

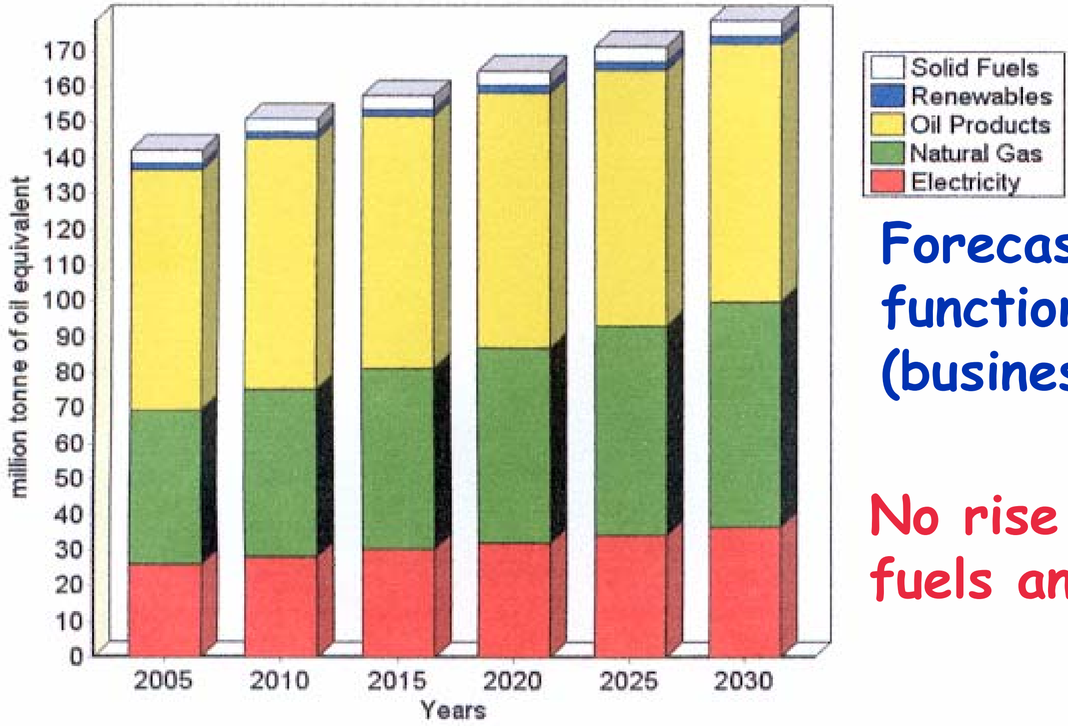
Main actions:

Decrease of oil derivates consumption to favour the use of natural gas

Increase of the energy generation plants overall efficiency.

Development of high efficiency energy utilizers

Trends of energy policy



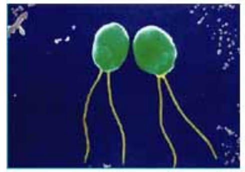
Forecast for energy consumption as a function of used energy source (business-as-usual scenario).

No rise of contribution from solid fuels and renewables can be expected.

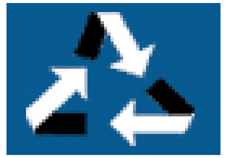
Electricity, oil products and natural gas will cover the increase of energy demand.

*) ENEA- Rapporto Energia ed Ambiente

Hydrogen: the energy vector of the future

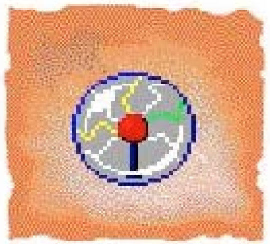


Easy to obtain from different energy source



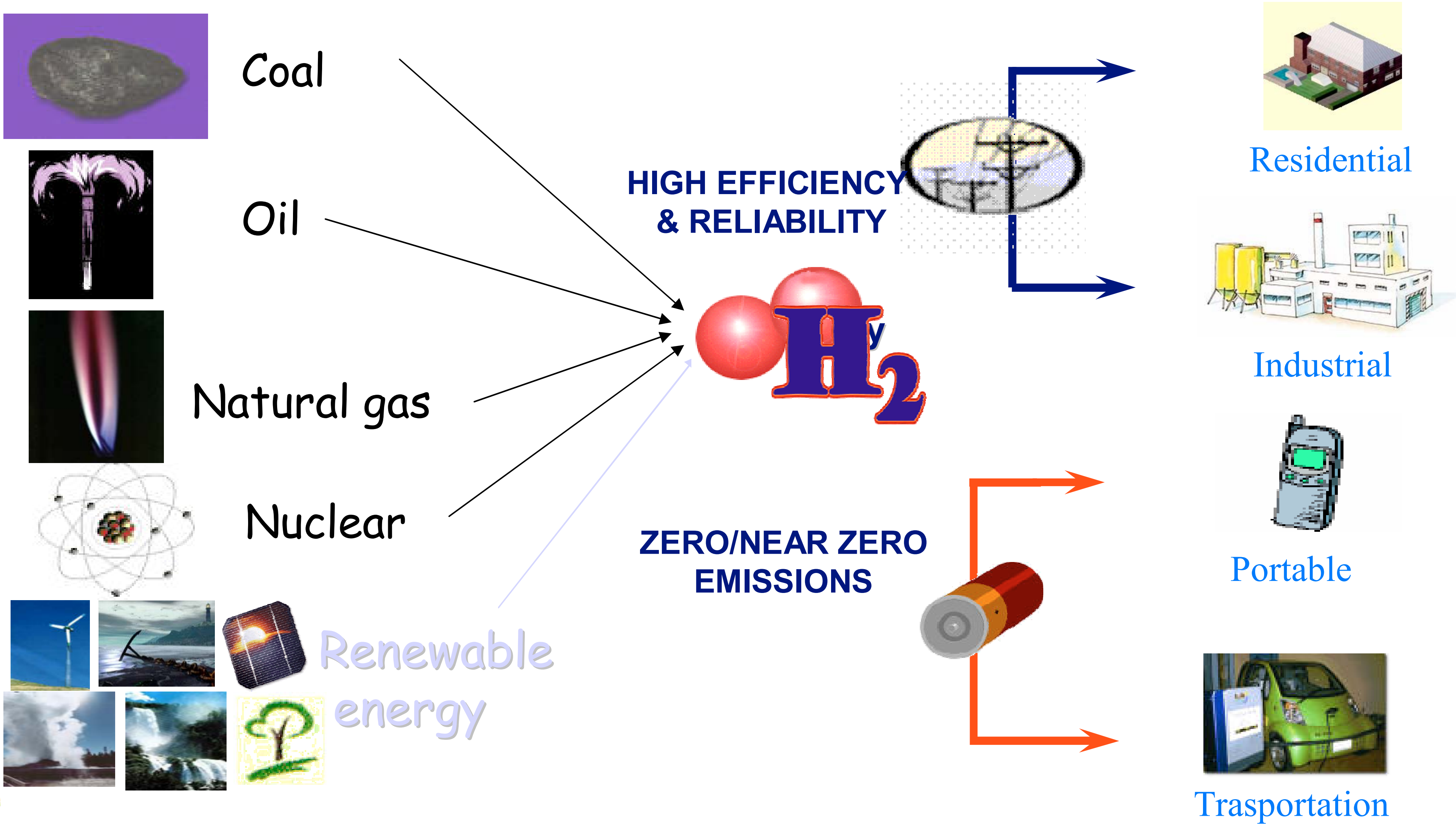
Efficient transformation into other energy forms

Easy transmissibility for short and long distances

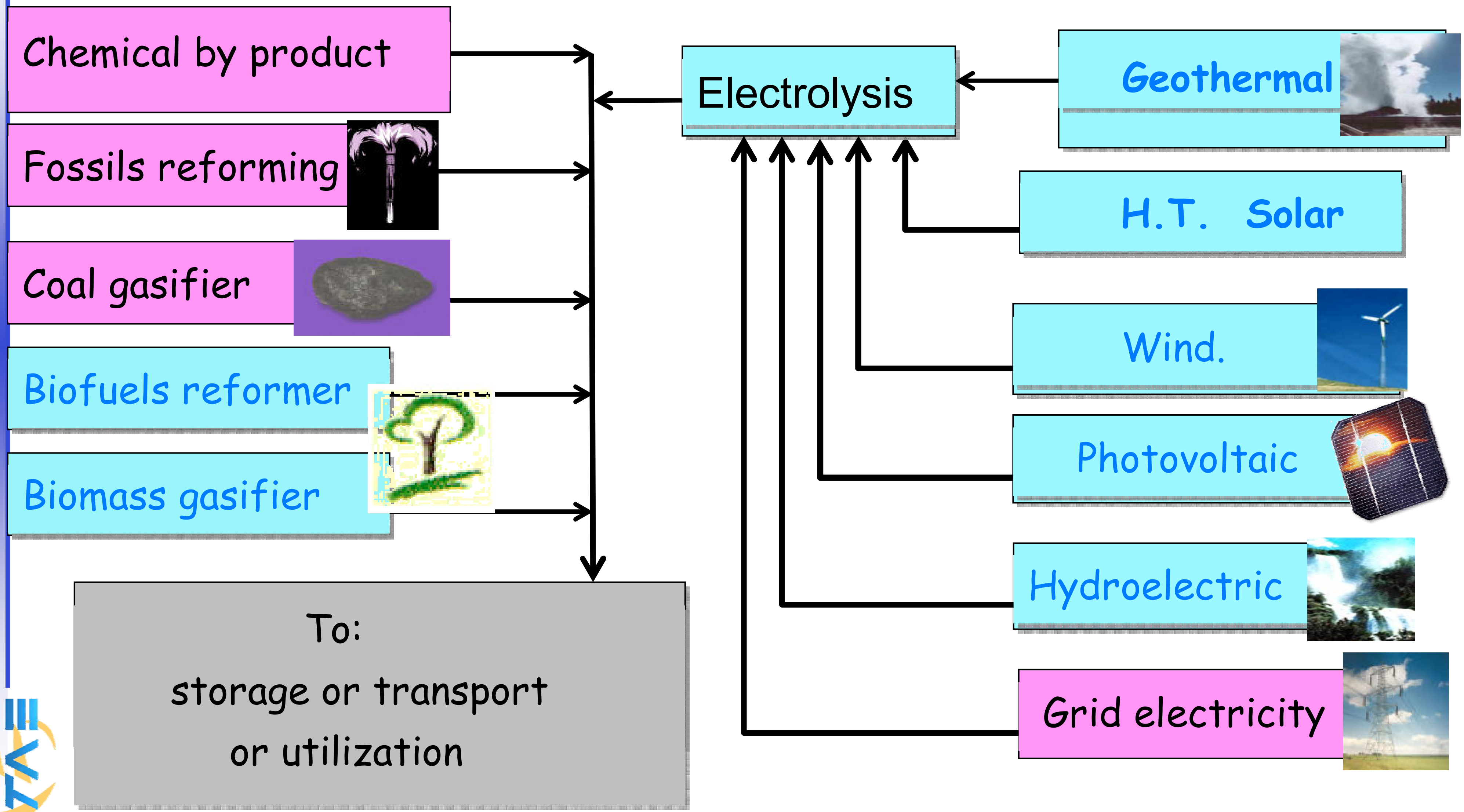


Good storage capacity

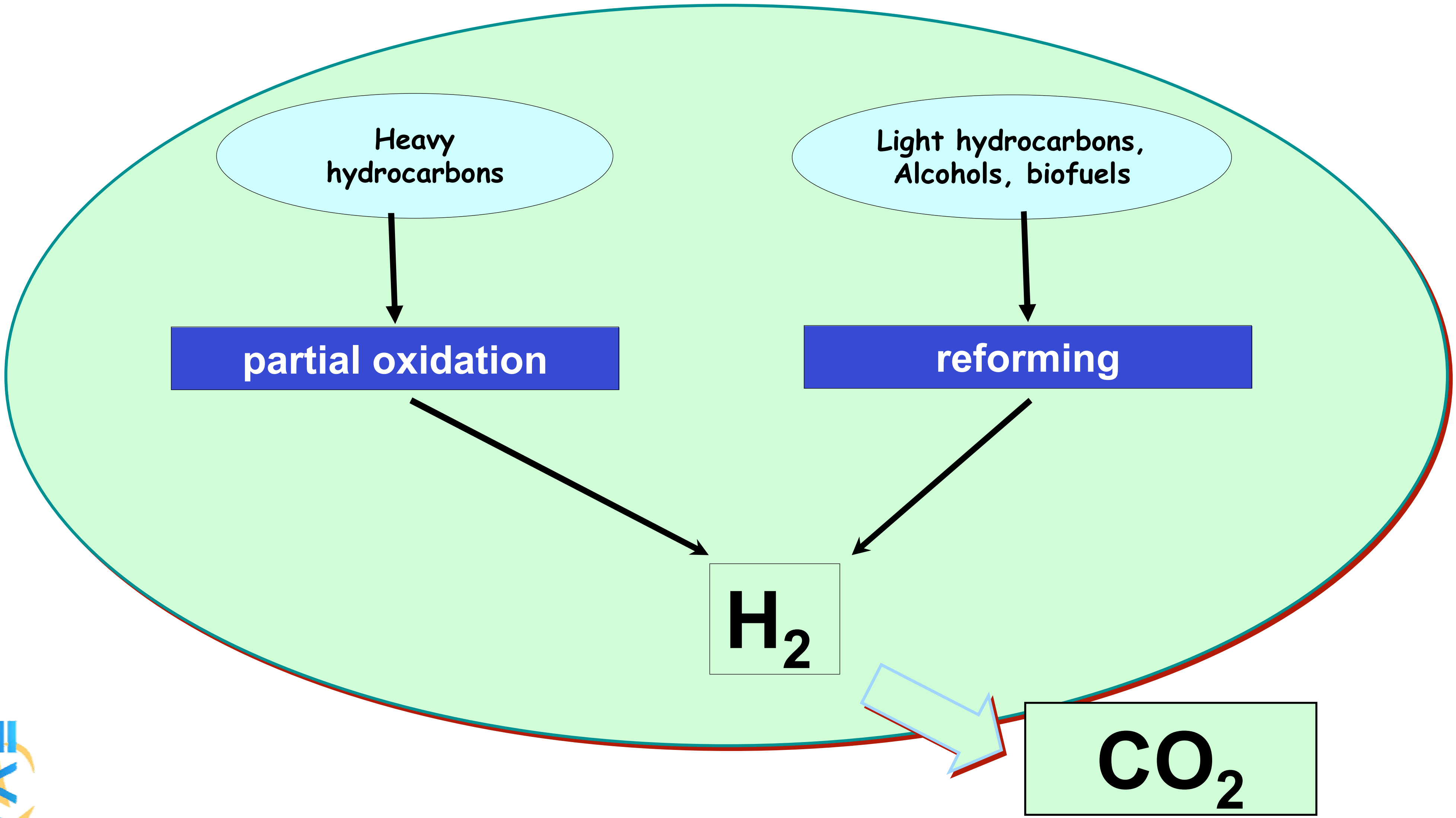
Electric energy



Hydrogen production



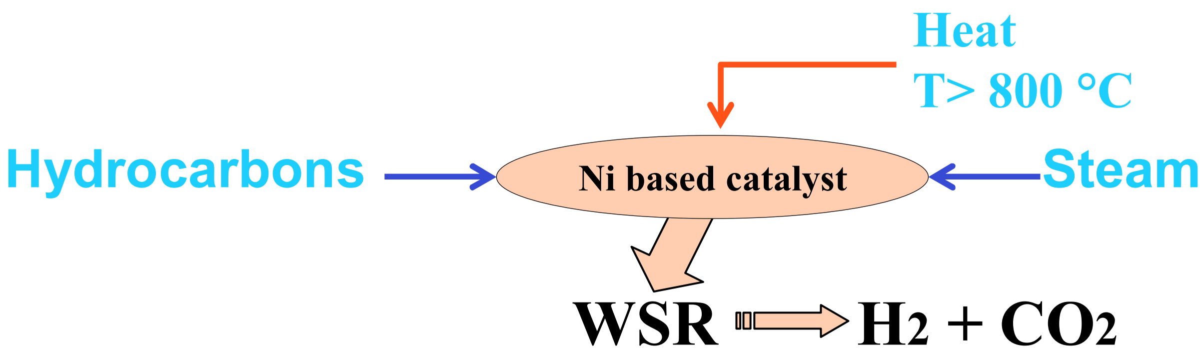
Reforming of hydrocarbons

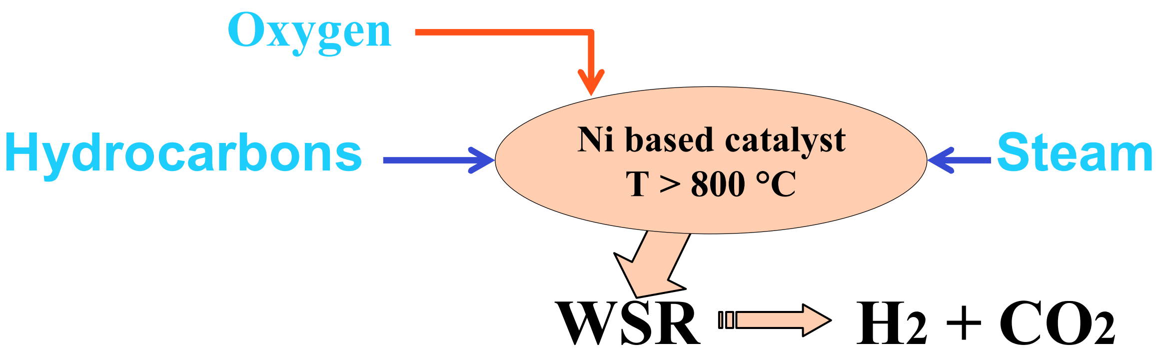


- **Steam reforming**

70-80% of efficiency.

S is not tollerated.





- **Autothermal Reforming**

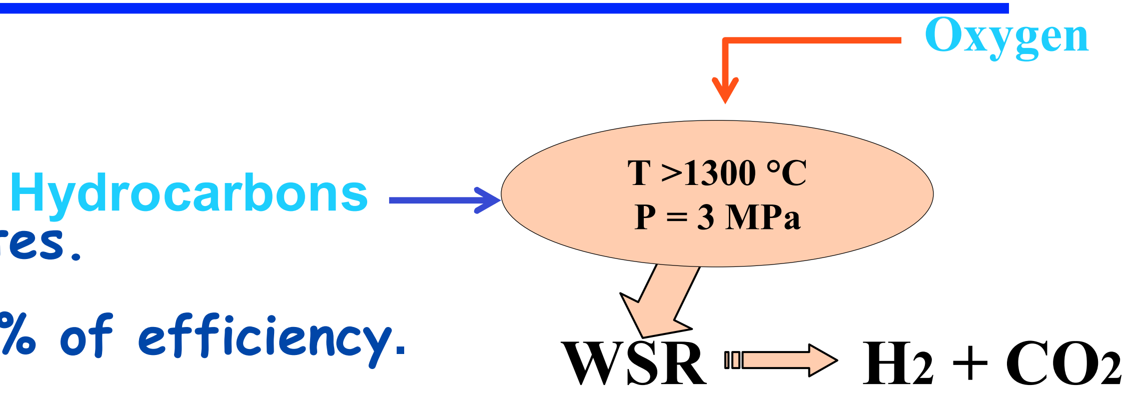
70-80% of efficiency.

S is not tollerated.

- **Partial Oxidation**

S-containing oils well tollerates.

No catalyst required. 70-85% of efficiency.



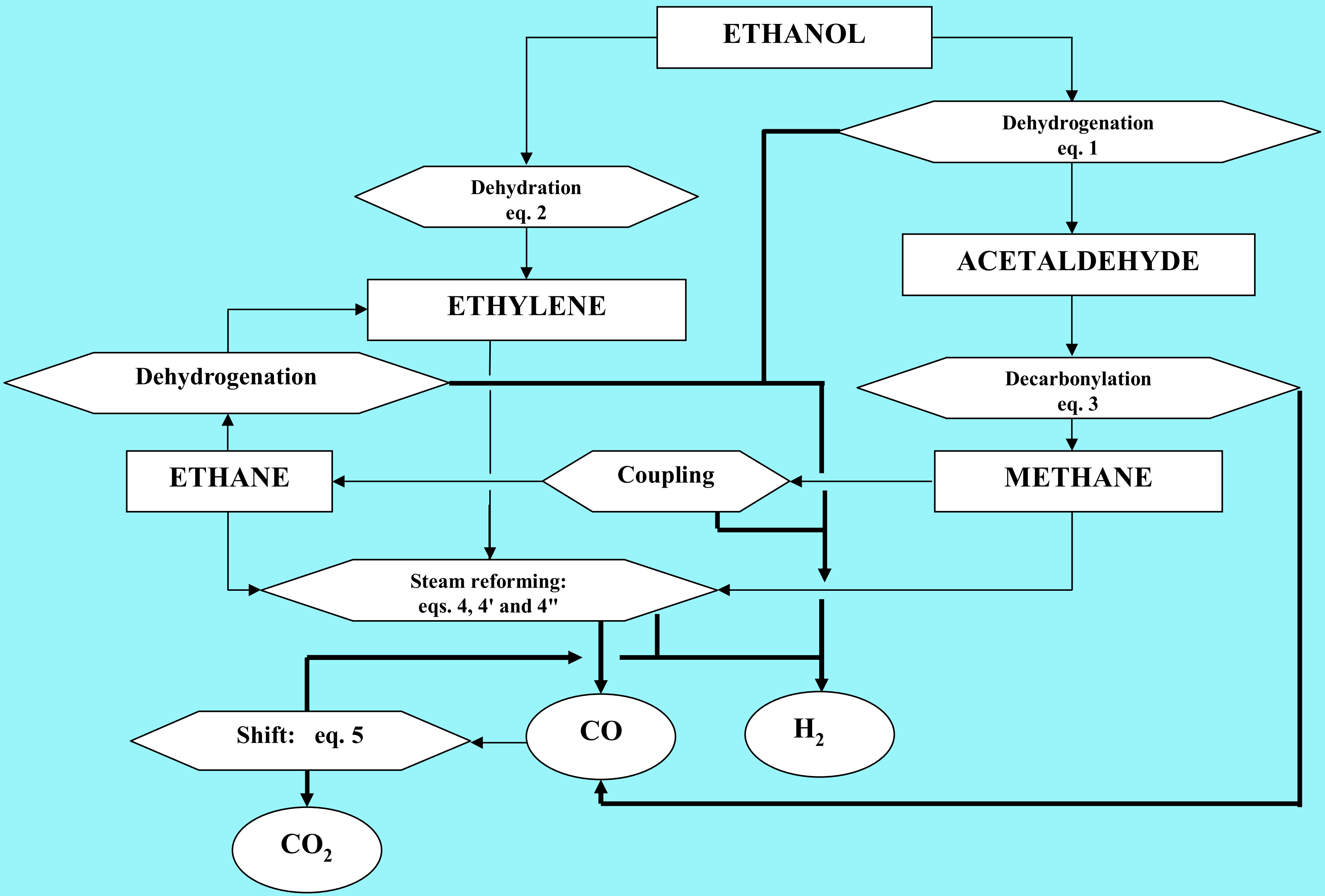
Process of Reforming

Research needs: Study on decomposition mechanisms

Ethanol steam reforming reactions

- C_2H_5OH $CH_3CHO + H_2$ /Eq.1/
- C_2H_5OH $C_2H_4 + H_2O$ /Eq.2/
- CH_3CHO $CO + CH_4$ /Eq.3/
- $CH_4 + H_2O$ $CO + 3 H_2$ /Eq.4/
- $CO + H_2O$ $CO_2 + H_2$ /Eq.5/

Ethanol steam reforming mechanism



Research needs: Development of materials and catalysts

Catalysts problems

- poisoning due to impurities
- sintering due to temperature
- deactivation due to carbon formation
- ageing effects
- commercial availability

Plant problems

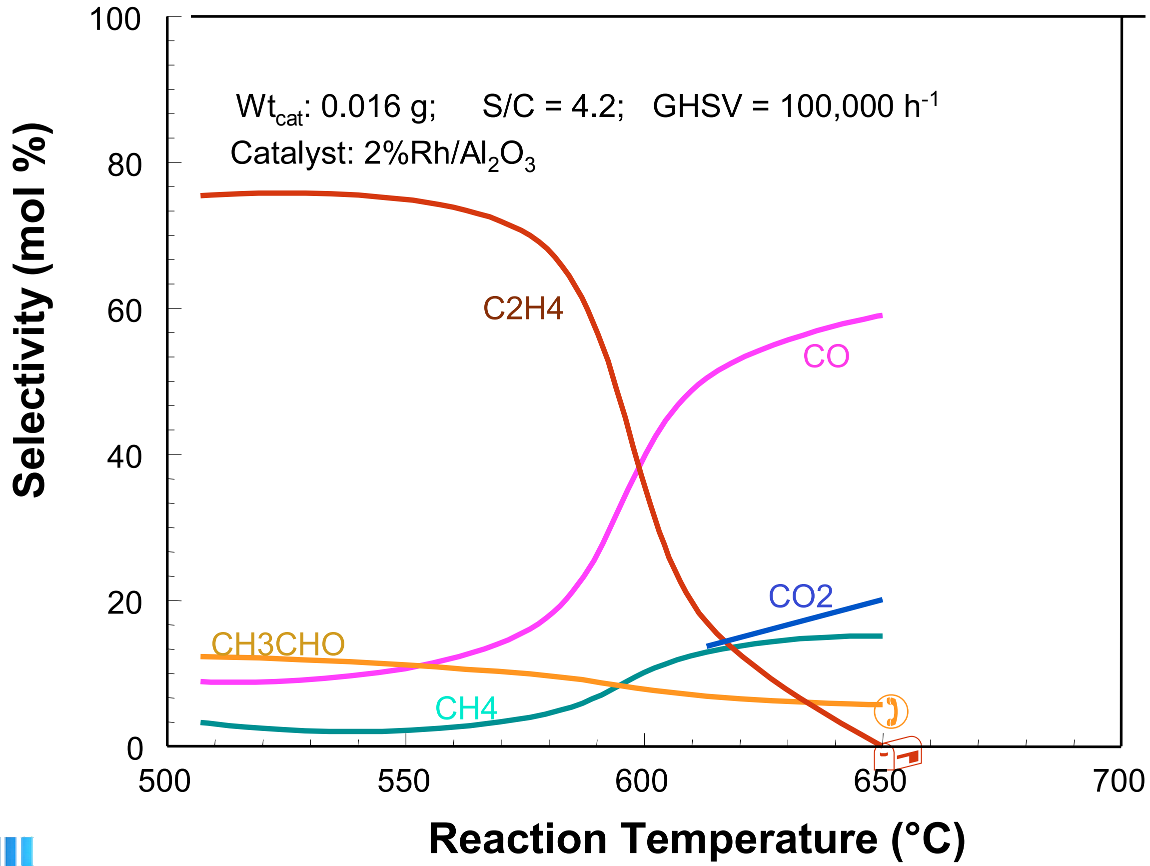
- development of small scale reformers
- integration with hydrogen purification sub-modules

Out-of-cell tests: a powerful tool

Aims of out-of-cell tests:

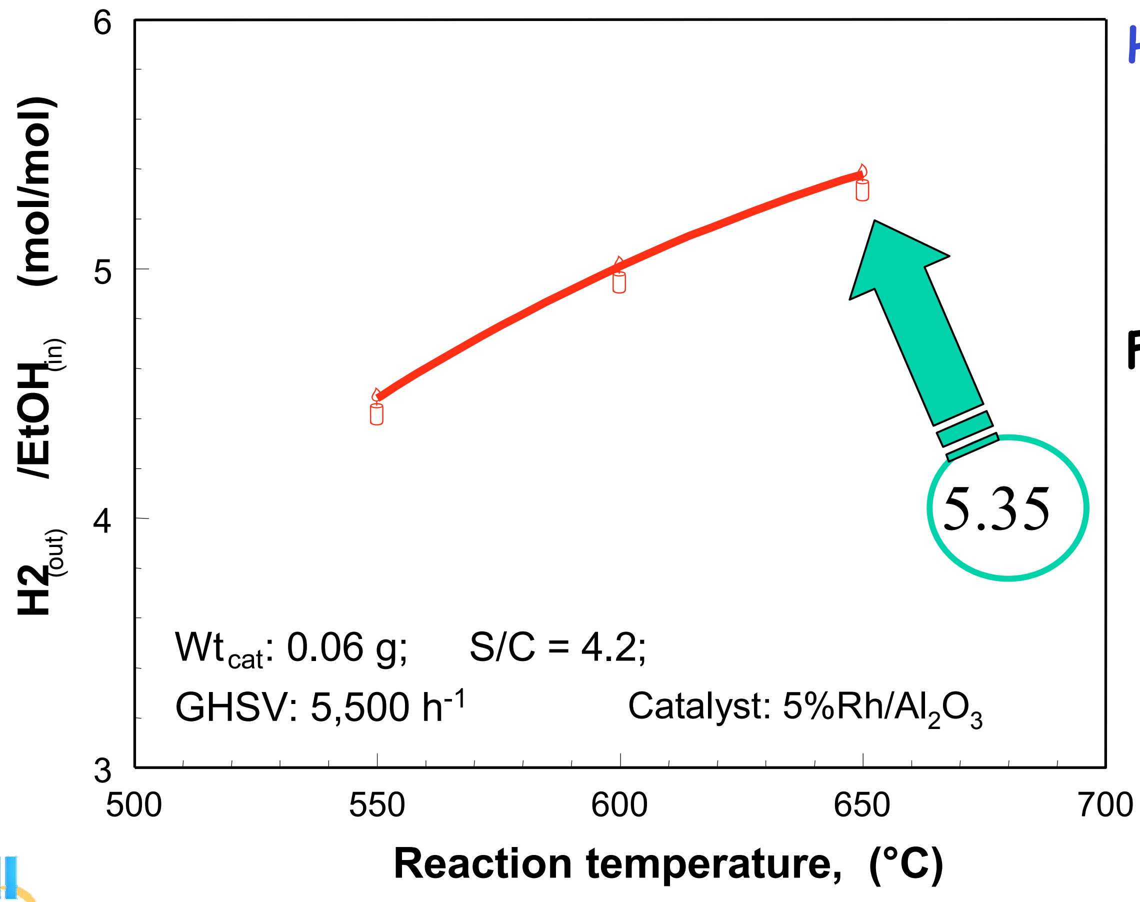
- Determination of catalytic activity
- Detection of catalysts deactivation causes
- Checking of catalysts stability

Out-of-cell tests: catalytic activity



- C2H4 detected for T > 923 K;
- C2H4 produces carbon formation;
- CO2 appears at T= 883 K;
- SR isn't prevailing reaction;
- the catalytic activity of the support seems to be stronger than active metal phase.

Out-of-cell tests: catalytic activity



H2 yield: outlet moles of hydrogen or each mole of inlet ethanol

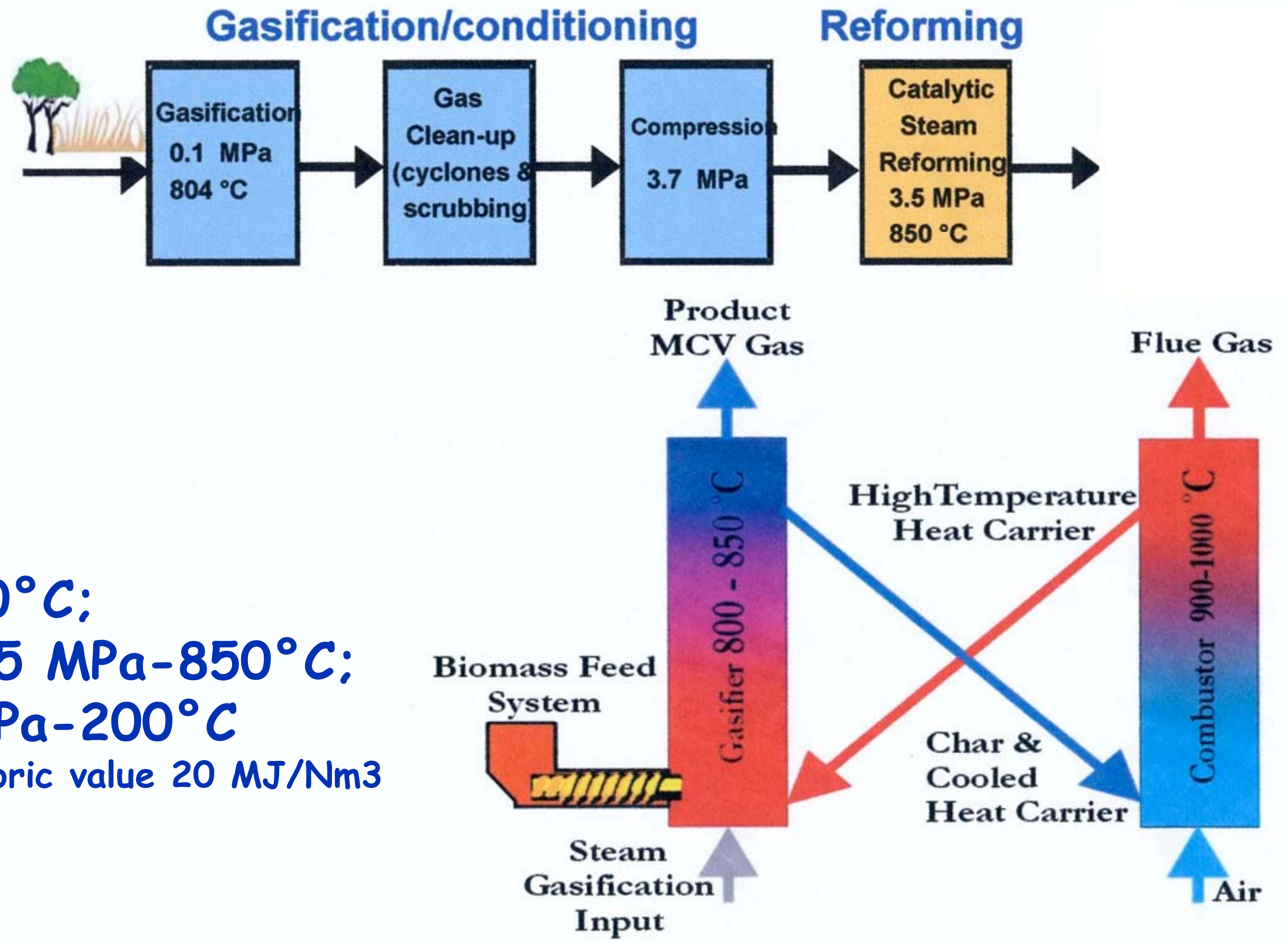
From stoichiometry of the reaction:

$$C_2H_5OH + 3H_2O \rightarrow 6H_2 + 2CO_2$$

The highest H2 yield is 6.0

Solid fuel gasification

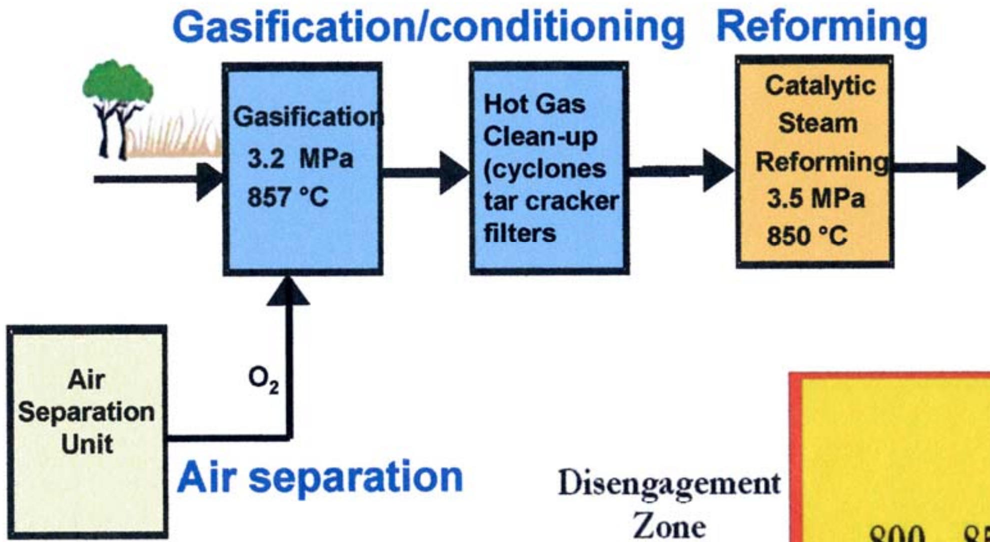
- Indirectly-heated gasification

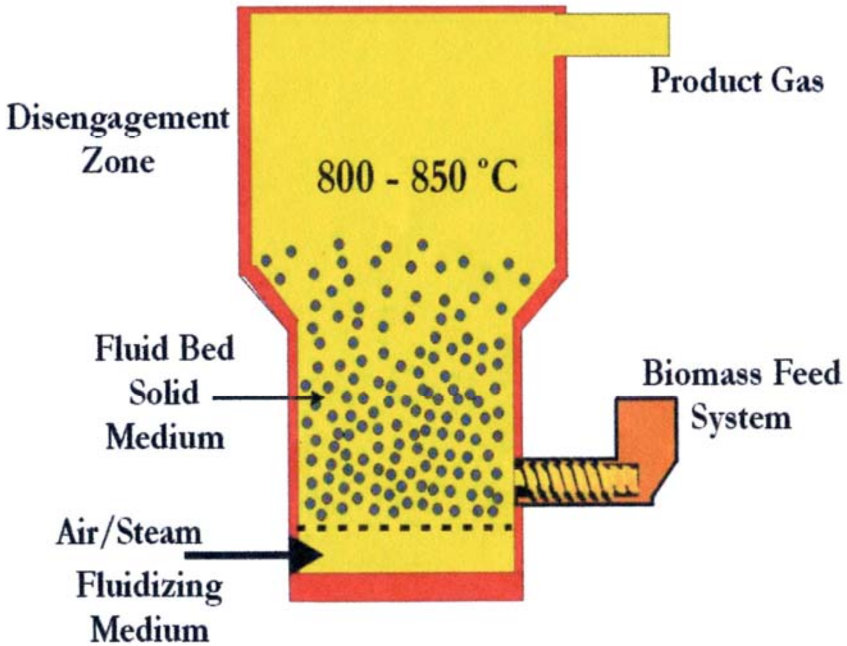


0.2MPa-830°C;
s.r. cat. 3.5 MPa-850°C;
shift 2.5 MPa-200°C
MCV=medium caloric value 20 MJ/Nm3

Solid fuel gasification

Oxygen-blown gasification



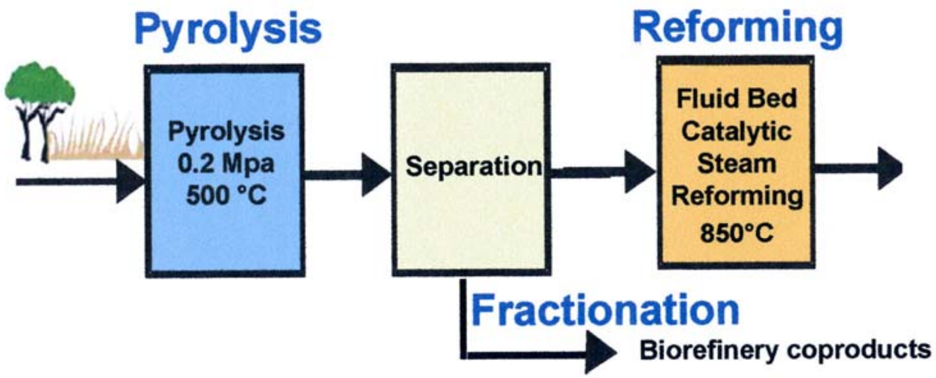


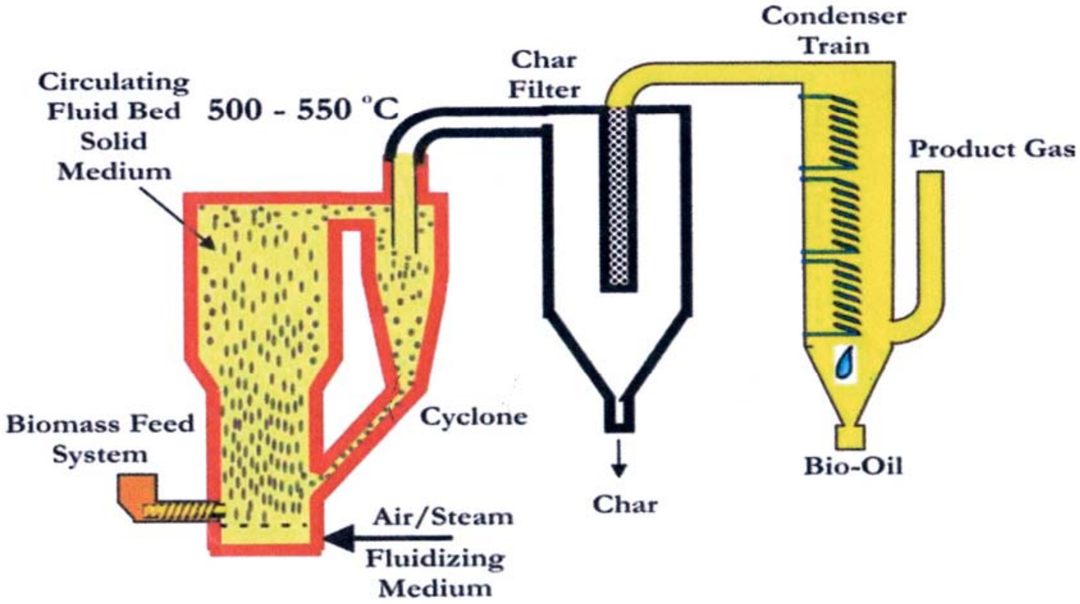
gasification:

3.2MPa-850°C; O_2 feed

Solid fuel gasification

Pyrolysis





0.2MPa-550°C
and fractionation of biorefinery coproducts

Solid fuel gasification

Research needs:

Higher process efficiencies => lower cost

System integration

- Modular system development
- Catalyst regeneration

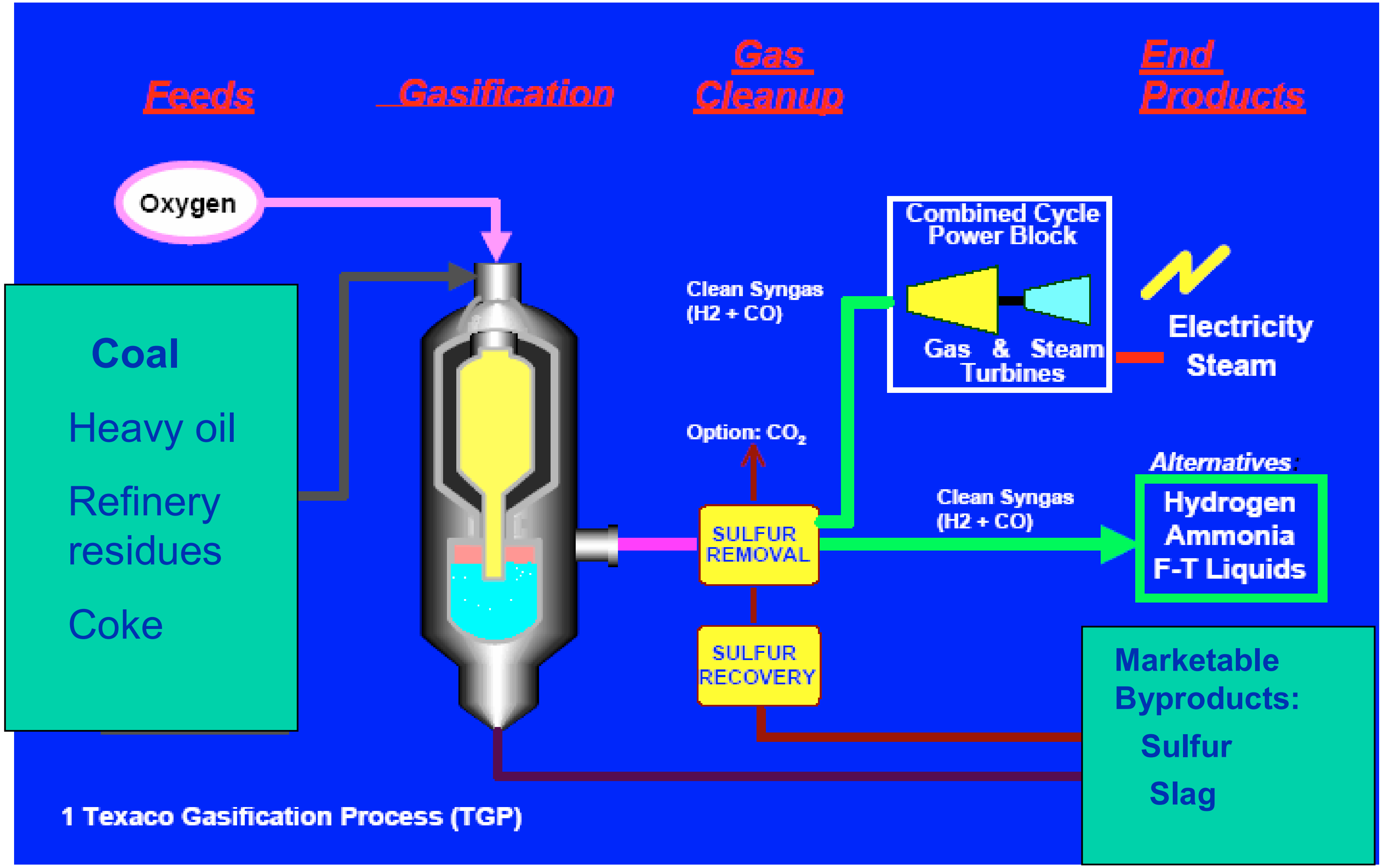
Feedstock development

- Energy crop yield optimization

Coal gasification

- CG is similar to Partial Oxidation
- Plant requires pure O2 and the coal must be pulverized prior to gasification
- Can achieve ~ 48% efficiency
- Operates at temperatures around 1100-1300°C
- CG is mature technology

Coal gasification



Coal gasification

- **Carbon Steam Reaction:**

$$C + H_2O > CO + H_2$$

- **WGSR to 500° C and FeO_x catalysts**

$$CO + H_2O > CO_2 + H_2$$

- **Coal Gasification process**

$$C + 2H_2O > CO_2 + 2H_2$$

Water electrolysis

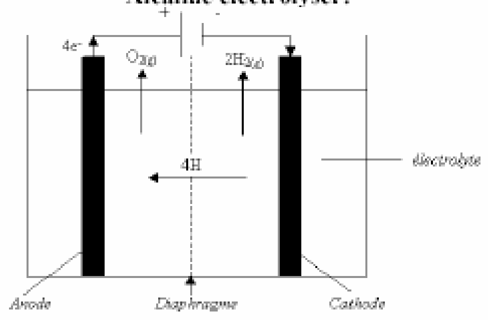
Electrolysis of water is the dissociation of water into hydrogen and oxygen gas

Different types

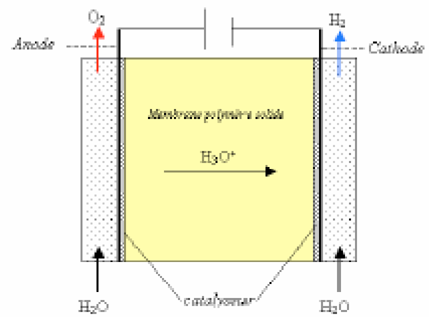
type	Electrolyte / Membrane	Electrodes / Catalysers	global reaction
Alcaline	KOH/NiO, IMET™ (Inorganic Membrane Electrolysis Tech.)	Anode : Ni, Fer / Ni alloys, metal oxides Cathode : steel + Ni / Ni-Co	Anode : $4HO^-_{(l)} \Rightarrow O_{2(g)} + 2H_2O_{(l)} + 4e^-$ Cathode: $4H_2O_{(l)} + 4e^- \Rightarrow 2H_{2(g)} + 4HO^-_{(l)}$
Acid PEM	Solid, proton exchange polymer membrane (Nafion®)	Anode : Graphite-PTFE + Ti / RuO_2, IrO_2 Cathode : Graphite + Pt / Pt	Anode : $6H_2O_{(l)} \Rightarrow O_{2(g)} + 4H_3O^+_{(l)} + 4e^-$ Cathode: $4H_3O^+_{(l)} + 4e^- \Rightarrow 4H_{2(g)} + 4H_2O_{(l)}$
High temp. steam	a) Zirconia ceramics ($0{,}91ZrO_2$-$0{,}09Y_2O_3$) b) Zirconia oxide ceramics	Anode : ceramics (Mn, La, Cr) / Ni Cathode : Zr & Ni cermets / CeOx	**a)** Cathode: $2H_2O_{(g)} + 4e^- \Rightarrow 2O_2^- + 2H_{2(g)}$ Anode : $2O_2^- \Rightarrow O_{2(g)} + 4e^-$ **b)** Anode : $2H_2O \Rightarrow 4H^+ + O_{2(g)} + 4e^-$ Cathode: $4H^+ + 4e^- \Rightarrow 2H_{2(g)}$

Principle of operation

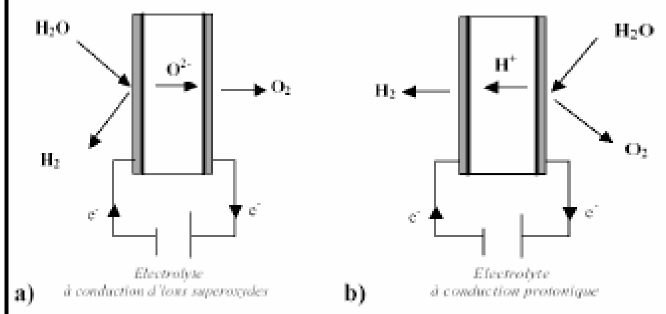
Alcaline electrolyser:



PEM electrolyser :



High temperature electrolyser :



Technical data

type	Temperature of operation	Pressure of operation	Electric consumption	Energy Efficiency	Life duration	State of development
Alcaline	50 - 100 °C	3 - 30 bars	4-5 kWh / Nm^3 of H_2	75 - 90 %	15 - 20 years	marketed
PEM	80 - 100 °C	1- 70 bars	6 kWh / Nm^3 of H_2	80 - 90 %	150 000 hours (≅17 years)	development
High temp. steam	800 - 1000 °C	??	3-3.5 kWh / Nm^3 of H_2	80 - 90 %	??	research

Water electrolysis

Research needs:

Alkaline water electrolysis:

- Design optimization to reach conversion efficiency of 85% (60-70%) from fluctuating primary energy.
- Cost reduction and series

Membrane electrolysis:

- Design optimization to avoid formation of ignitable mixture due membrane fracture or gas cross-over.
- Suitable systems integrated with storage systems (70 MPa)

High-T steam electrolysis:

- Typical problems of materials development correlated to SOFC technology

Other processes

Thermochemical production:

- Based on thermally activated water decomposition (>2200 °C).
  By coupling chemical reaction, T of split lowers to 900 °C.
  iodine+sulphur dioxide+water > hydrogen iodide + sulphuric acide (120 °C)
  Sulphuric acid > oxygen + sulphur dioxide (850 °C)
  Hydrogen iodide> hydrogen + iodine (300 °C)

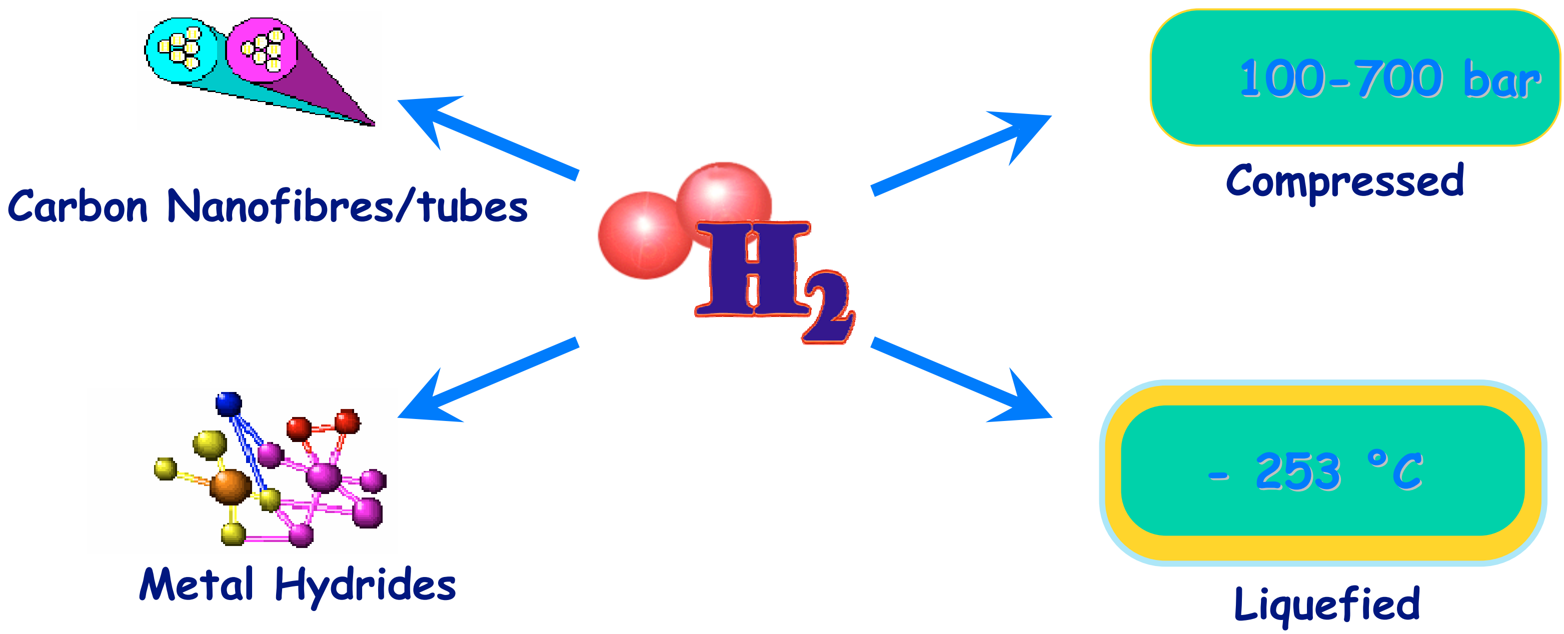
High conversion efficiency (up to 50%)

Process engineering and material unsolved problems

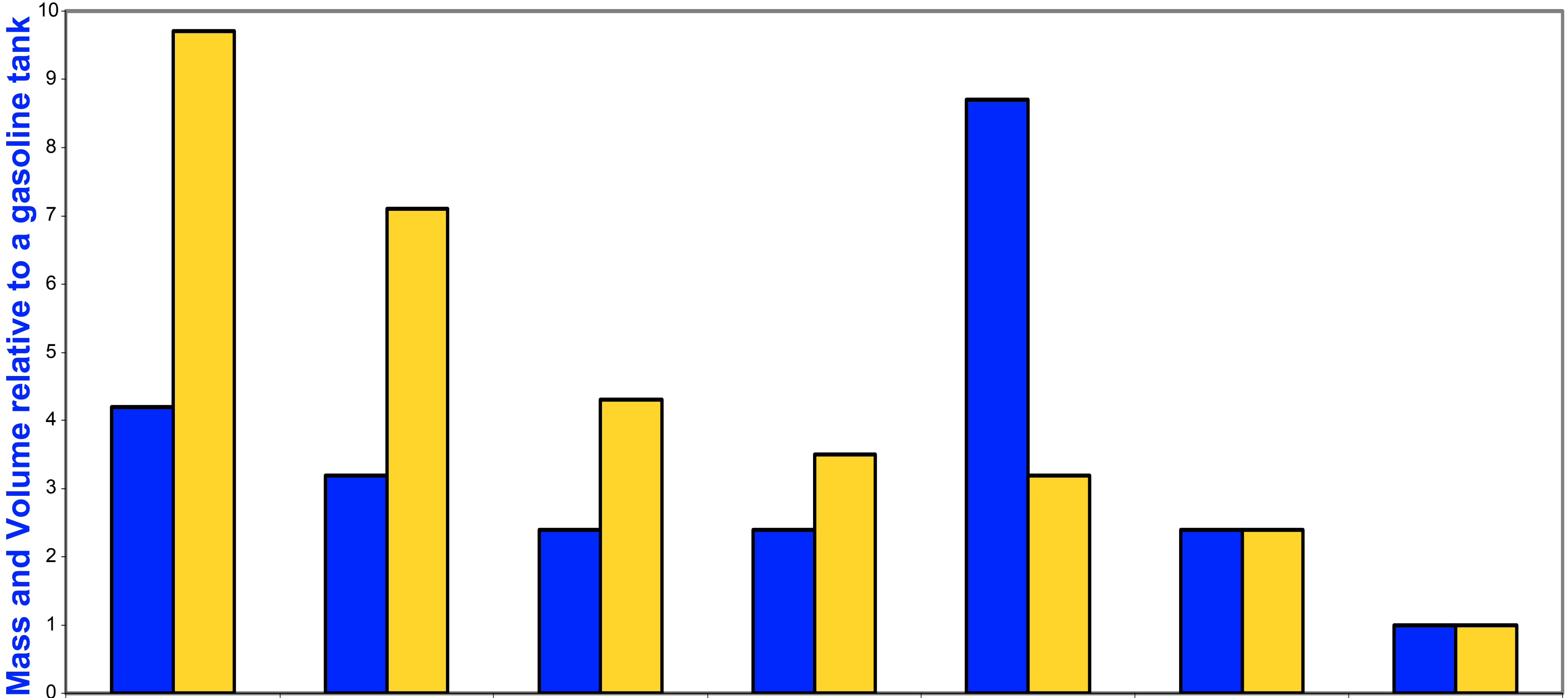
Photochemical production — Basic reseach stage

Biological production — Basic research stage

Hydrogen storage systems



Current status of Hydrogen Storage Systems

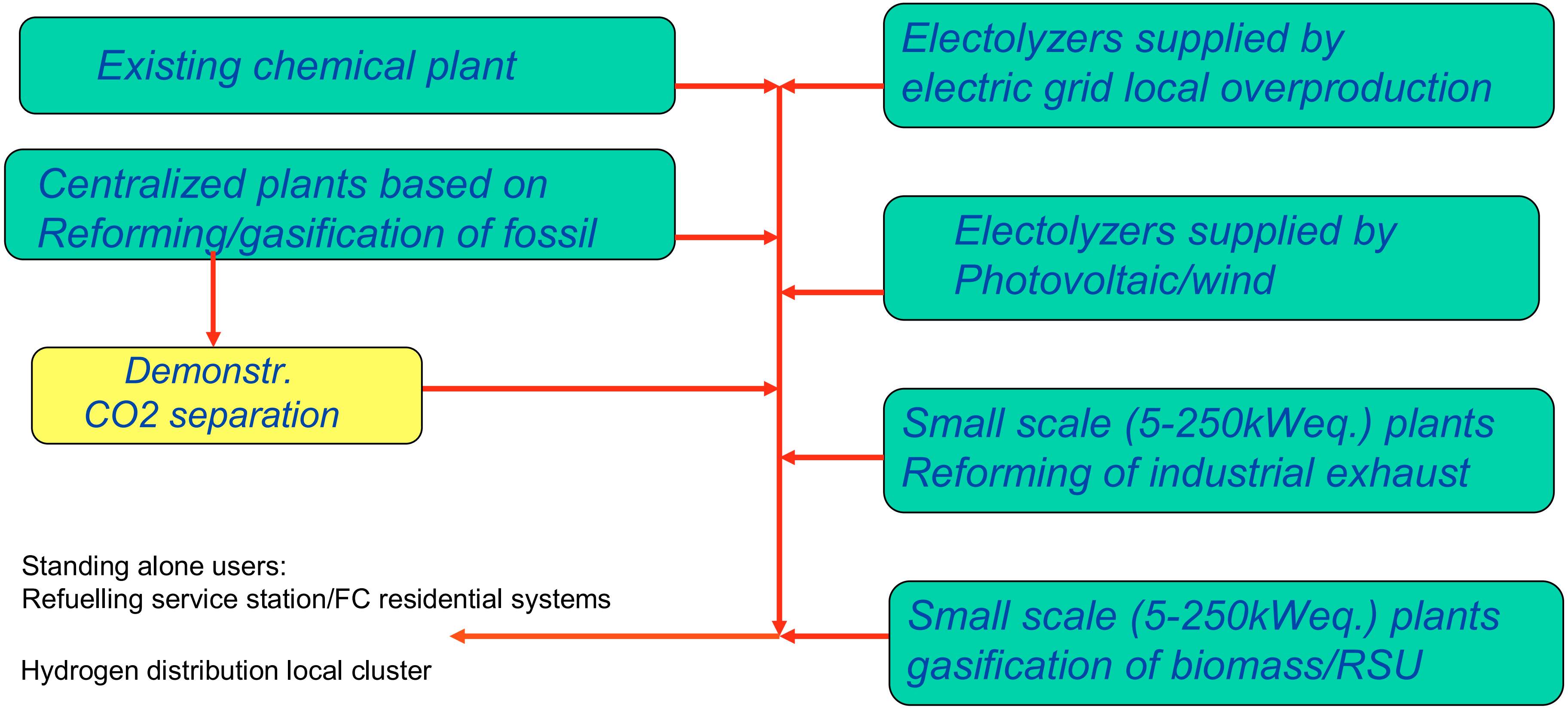


	Compressed H2 (250b	Compressed H2 (350b	Compressed H2 (700 b	Liquid Hydrogen	Metal Hydrides (low T	Metal Hydrides (high T	Gasoline
Weight	4,2	3,2	2,4	2,4	8,7	2,4	1
Volume	9,7	7,1	4,3	3,5	3,2	2,4	1

Future perspective

Short-term Period (10-15 years)

Main objectives: Demonstration of H_2 production feasibility
Improvement of social acceptance



Basic investigation on: thermochemical, Photochemical/biological H2 production

Future perspective

Short-term period (next 10-15 years)

Technological goals :

- *Improvements of life-time of generators*
- *High quality of produced hydrogen (reliable feedsotcks clean-up)*
- *High efficiencient electrolyzers based on PEFC and SOFC technologies*
- *Developments of CO2 separation and sequestration systems integrated with centralised power plants*

Future perspective

Medium-term period (2020-2030)

Main goals: **Improving durability and compatness of plants**
Lower main system components costs

Hydrogen market

Stationary power plant (< 5MW) with advanced electrochemical devices (PEM/MCFC) integrated with cogeneration systems.

F.C. plant of small power (< MW) to provide electricity/heat for residential/commercial buildings.

Refuelling station service for F.C. or ICE engines vehicles

Local extension pipe network (regional level)

Commercial plants

Co-generated power plant based on N.G. reforming

Co-generated power plant based on coal gasification with CO2 removal and local underground storage

Large power plants based on renewable sources

Earlier demonstrators based on thermochemical, Photochemical/biological H2 production

Hydrogen utilization in Fuel Cell

- Friendly environmental impact
- High electric efficiency independently to the size
- Production of heat usable for co-generation cycles
- Integration with gas turbine
- Fuel flexibility