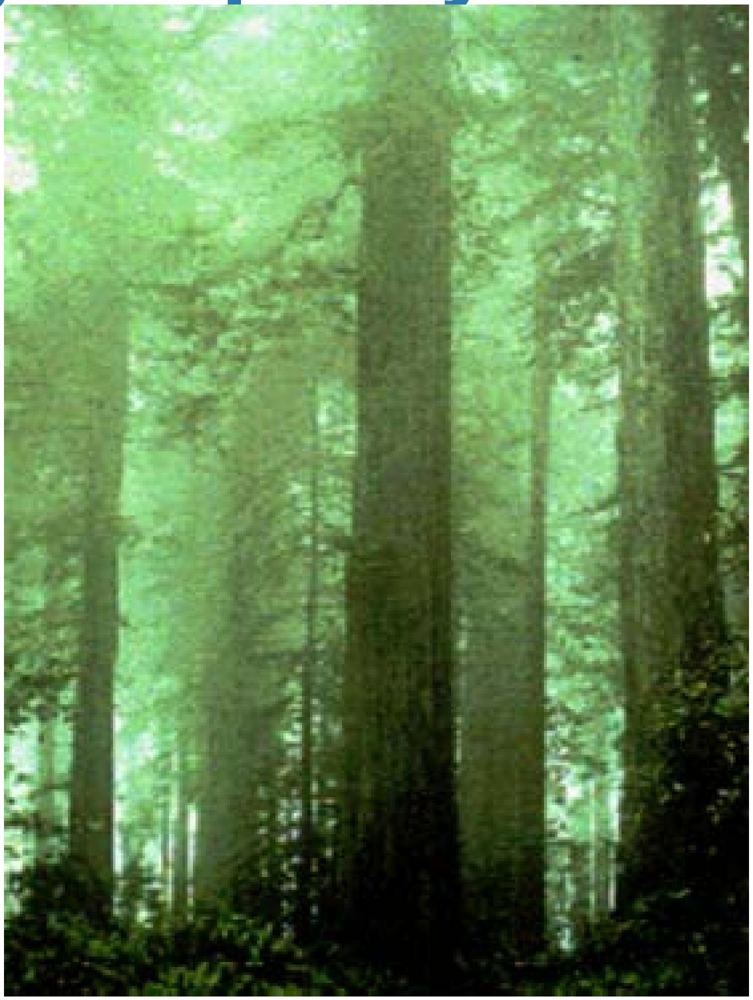
Using the full exergetic quality of solid fuels.



DCFC Workshop, NETL DOE Pittsburgh

Dr. Kas Hemmes

August 1, 2003

Faculty of Technology, Policy and Management
Section Energy and Industry

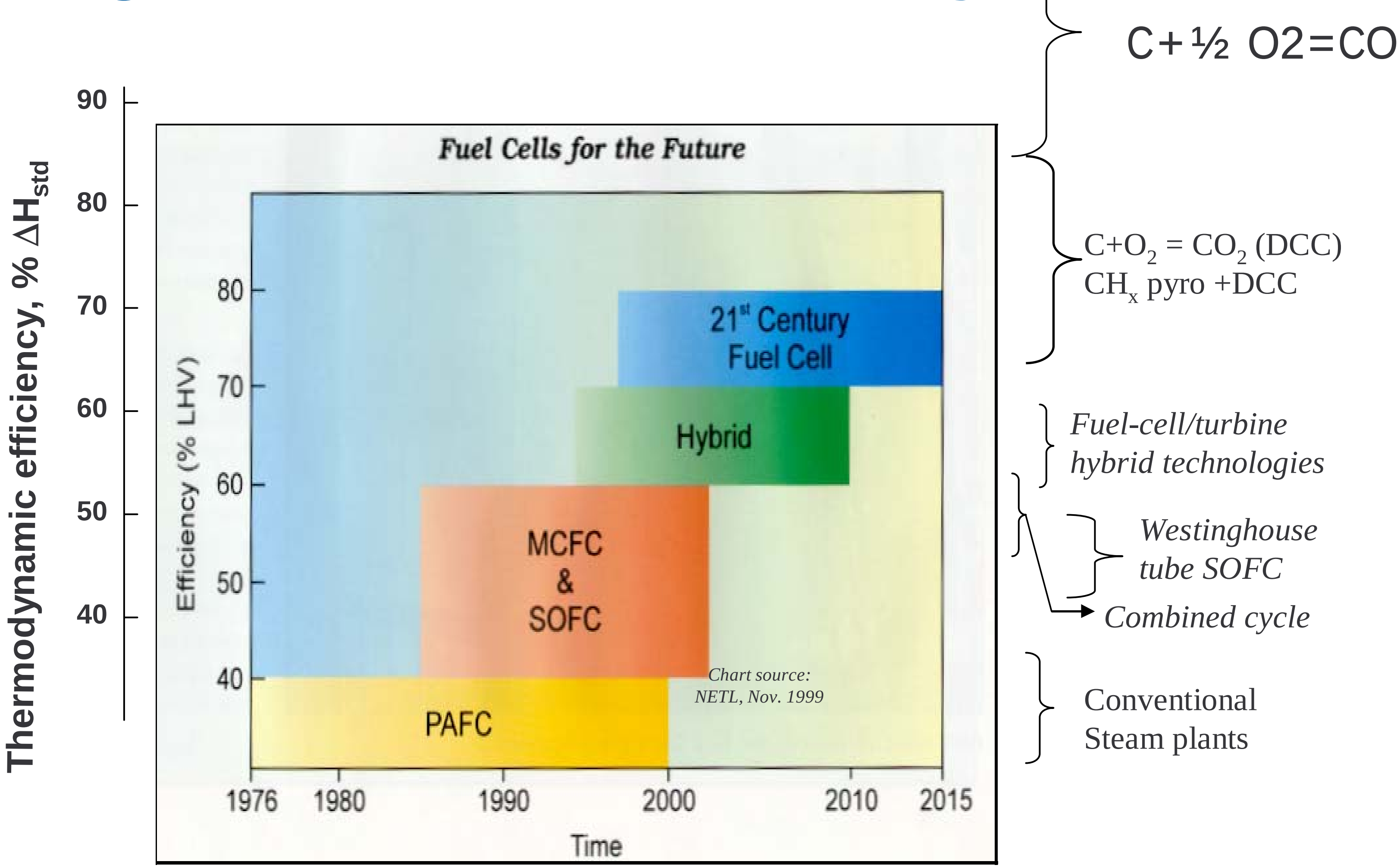
Delft University of Technology

Outline

- DOE goals
- Why emphasize solid fuels ?
- Thermodynamics, exergy and entropy production
- Direct Carbon FC
- A fuel cell that produces H_2 and converts heat into power??
- Exergy efficient integrated solar-biomass systems
- Conclusions

TU Delft

DOE goal for the 21st century fuel cell



TU Delft

Why emphasize solid fuels ?

1. Solid fuels will become more important in the future!

- Coal: abundant and cheap
- Biomass: sustainable
- Waste: negative value
- More efficient CH_4 conversion routes involve solid C

NB: Also liquids are closer to solids than to gases
in terms of their exergy value.

TU Delft

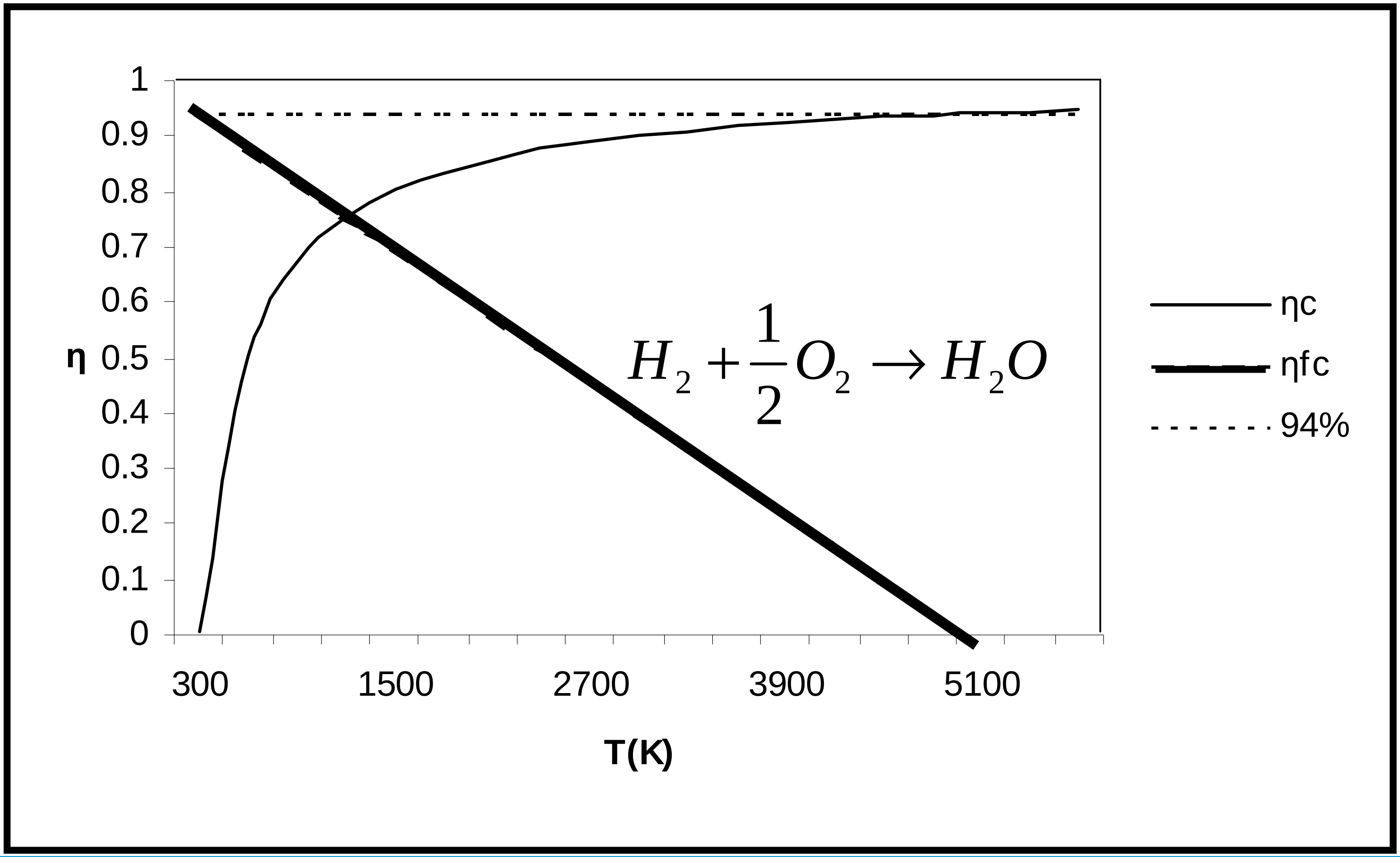
Why emphasize solid fuels ? (2)

2. Present conversion of solid fuels is <u>not</u> efficient

- Combustion (Carnot limitation)
- Gasification (Carnot & entropy production)

TU Delft

H_2 / O_2 Fuel cell and Carnot efficiency



Entropy production in conventional gasification

$C + \frac{1}{2} O_2 ==> CO + Q(heat)$

½ : 1

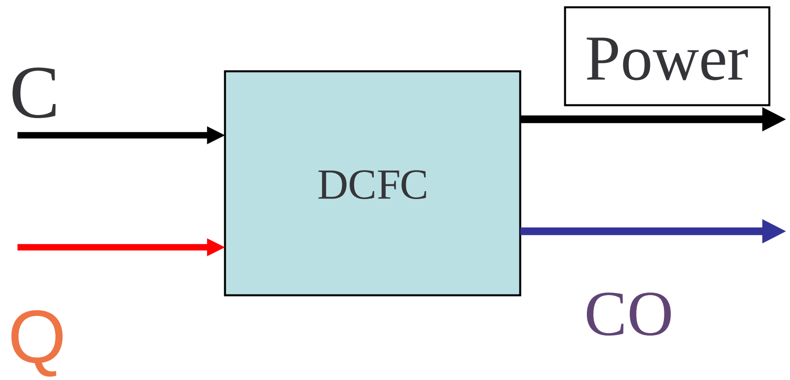
1. Doubling of the # gas molecules
2. Entropy $\Delta S = Q/T$

TU Delft

Electrochemical gasification :

$$2C + O_2 ==> 2CO \quad \Delta S>0 \quad \Delta H<0$$

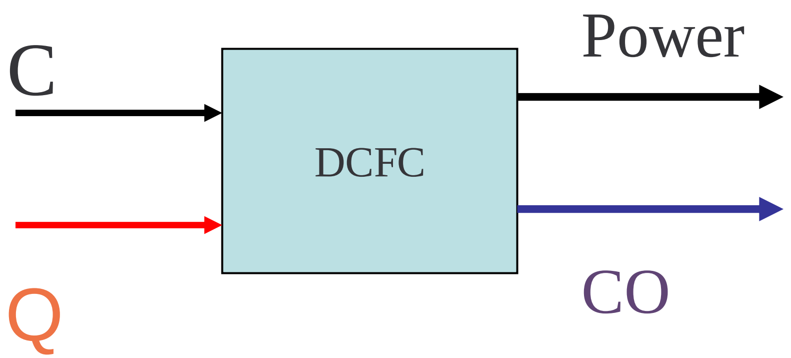
$$\eta_{fc} = 1 - \frac{T\Delta S}{\Delta H} > \underline{100\%}$$



- (Solar) Heat can be converted into power with an efficiency higher than the Carnot efficiency!
- Self regulating process

TU Delft

The ‘holy grail’ of electrochemistry : A Fuel Cell that produces hydrogen and converts heat into power !



$$\mathbf{CO} + H_2O \Longrightarrow \mathbf{H_2} + CO_2$$

TU Delft

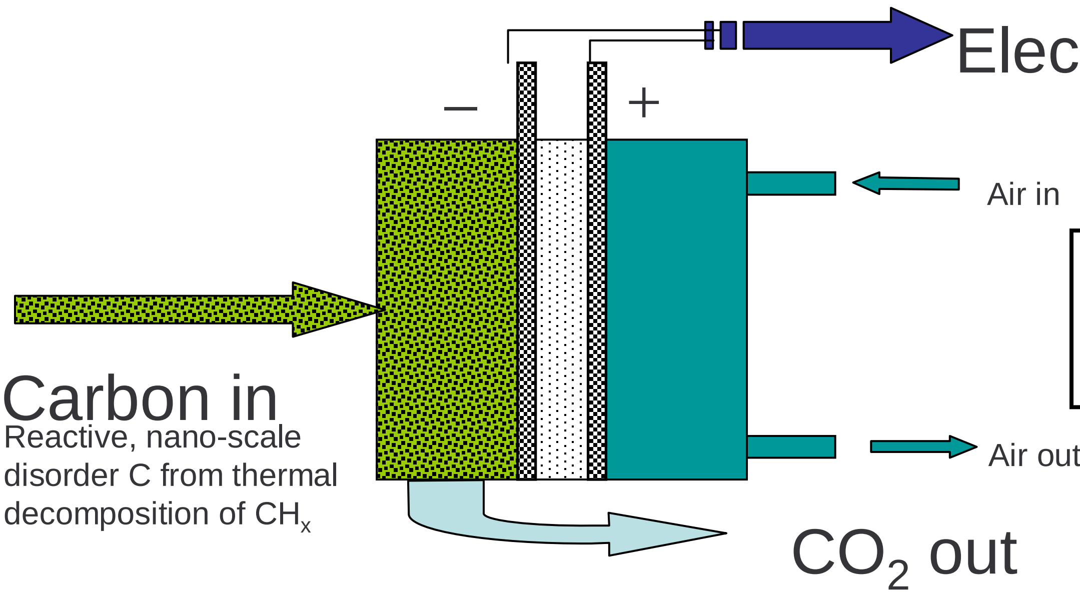
How to reach or approach this 'holy grail' ?

- Electrochemistry is the key technology because it can approach reversibility = zero entropy production = conservation of exergy.
- Use small driving forces F since $\Delta S \sim (F)^{2}$
- Solar energy is ideal renewable source to supply the heat, thereby increasing the efficiency of this technology as well.

TU Delft

How to reach or approach this 'holy grail' ? (1)

1. Direct Carbon Fuel Cell:

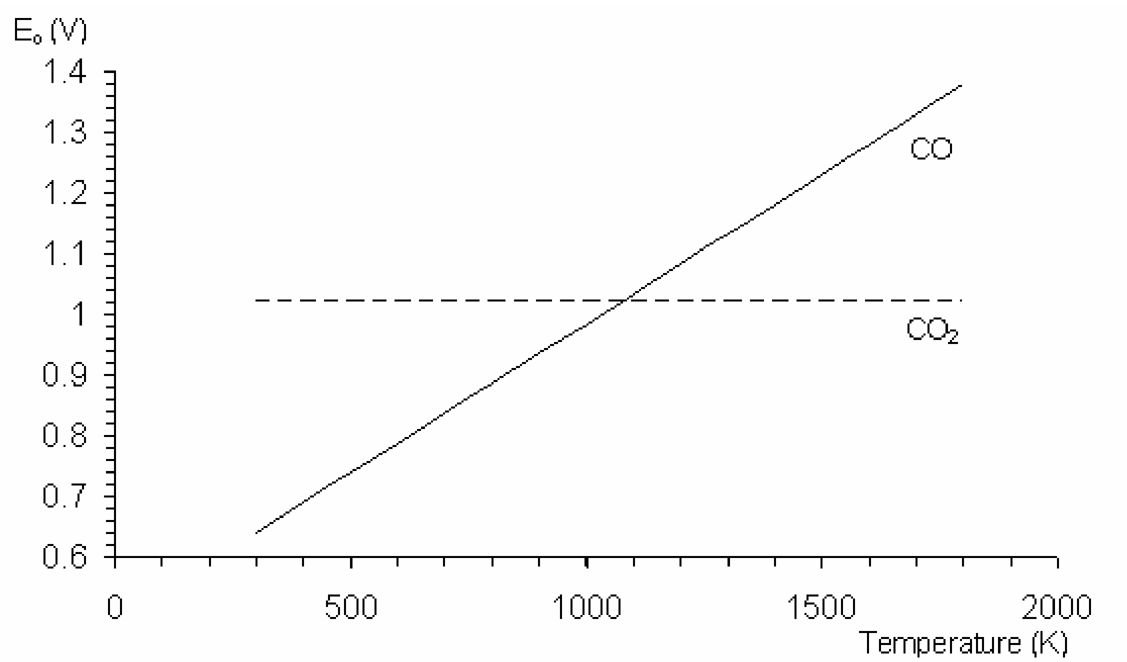


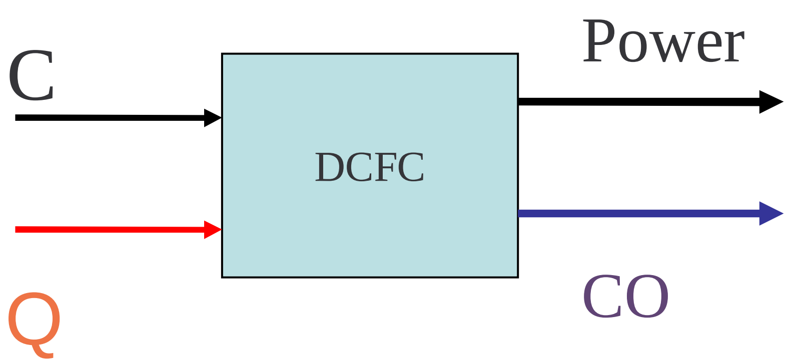
Net reaction:
$C+O_2 = CO_2$

TU Delft

How to reach or approach this 'holy grail' ? (2)

2. Direct Carbon Fuel Cell at **high T**: $C + \frac{1}{2} O_2 \Rightarrow CO$

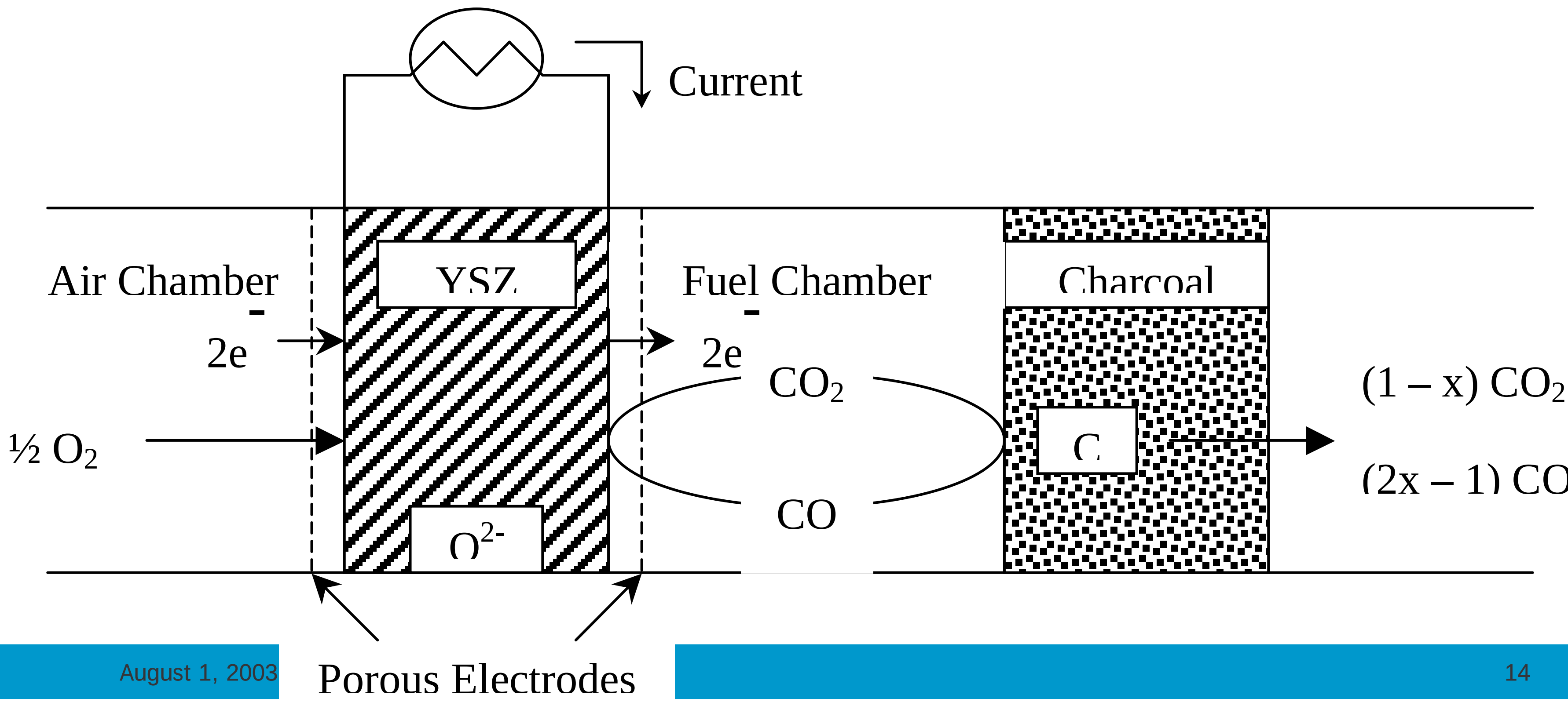




TU Delft

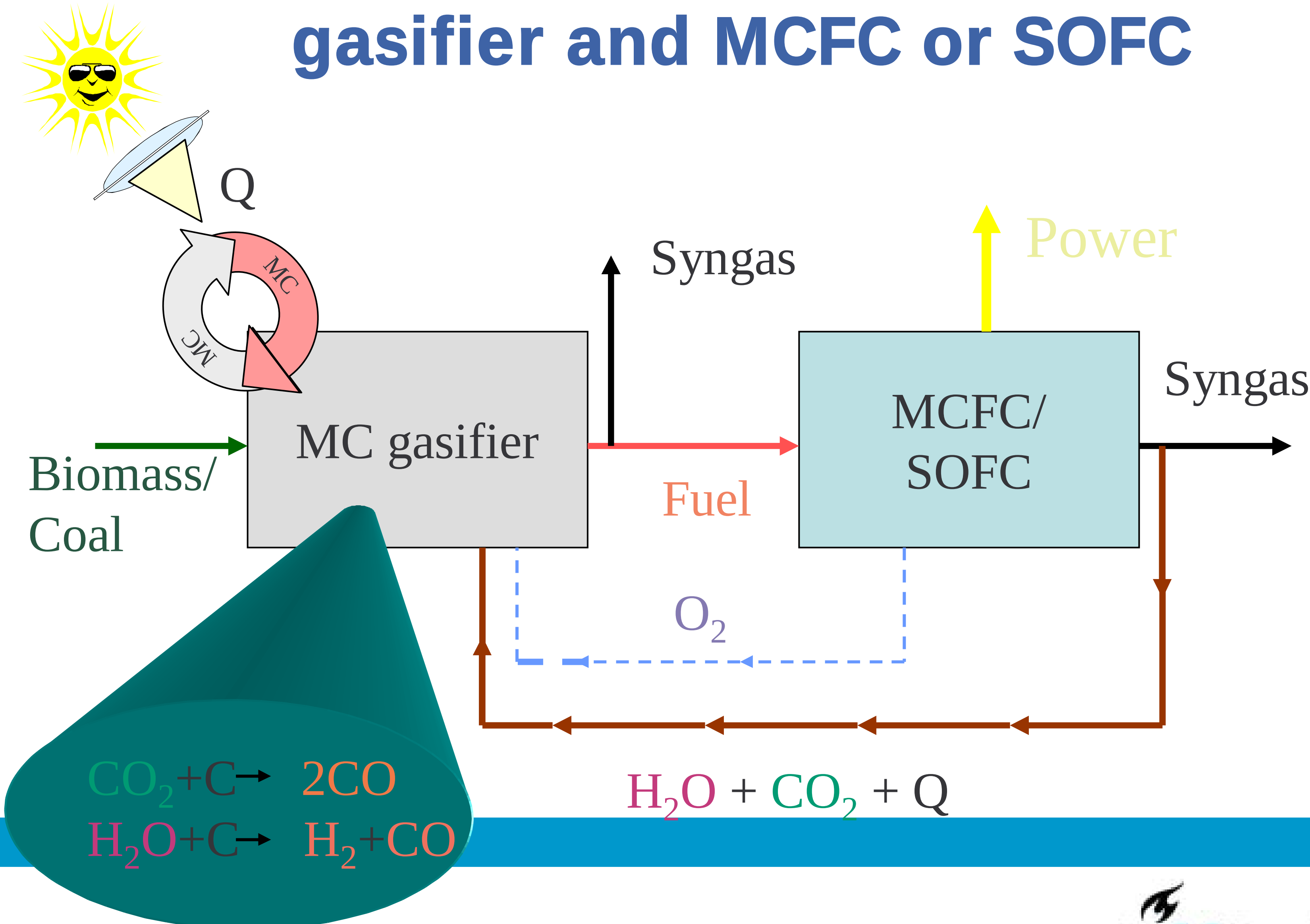
How to reach or approach this 'holy grail' ? (3)

3. In-direct Carbon Fuel Cell/integrated systems :



TU Delft

Combination of Molten Carbonate gasifier and MCFC or SOFC



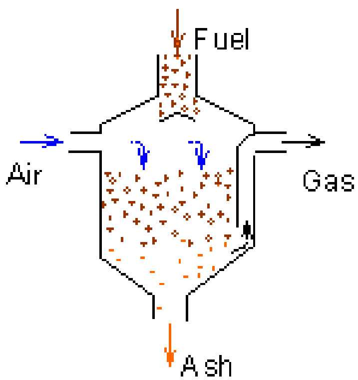
TU Delft

Explaining the difference between conventional combustion/gasification and electrochemical conversion.

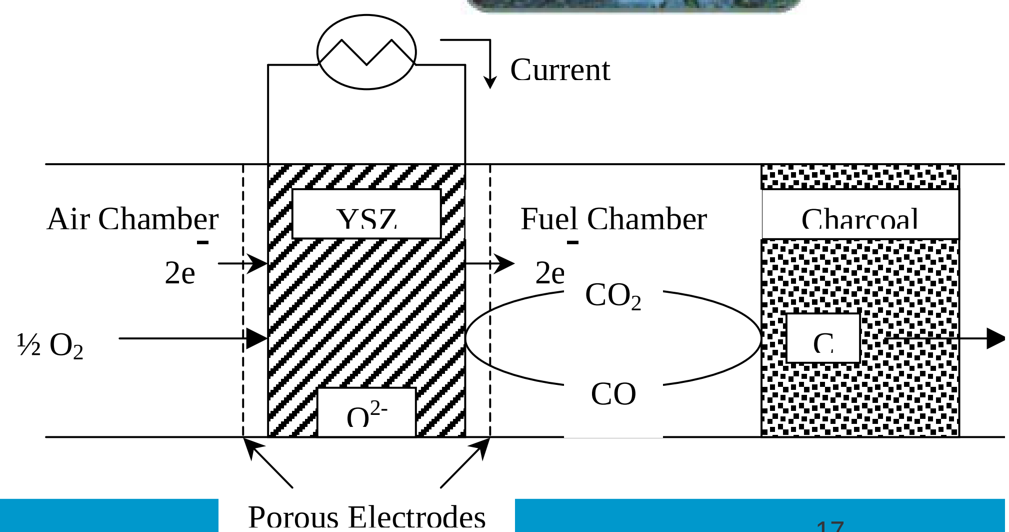
TUDelft

Chemical versus electrochemical

$$C + \tfrac{1}{2}\,O_2 \Rightarrow CO$$
$$C + O_2 \Rightarrow CO_2$$



Downdraft gasifier



TUDelft

Energy Research Policy

- Identify solar-biomass regions
- Prevent entrenchment in inefficient technologies by designing a roadmap to develop EXEFF systems
- Electrochemistry and fuel cells are key technologies
- ‘First’ systems ‘then’ components
- Demand specification of exergy efficiency
- Promote cooperation between research areas; solar biomass, coal and fuel cells and Al production industry
- Promote cooperation between Europe, USA and Japan

Countries with large potential for Solar and Biomass can become the energy (H_2) producing countries of the future.

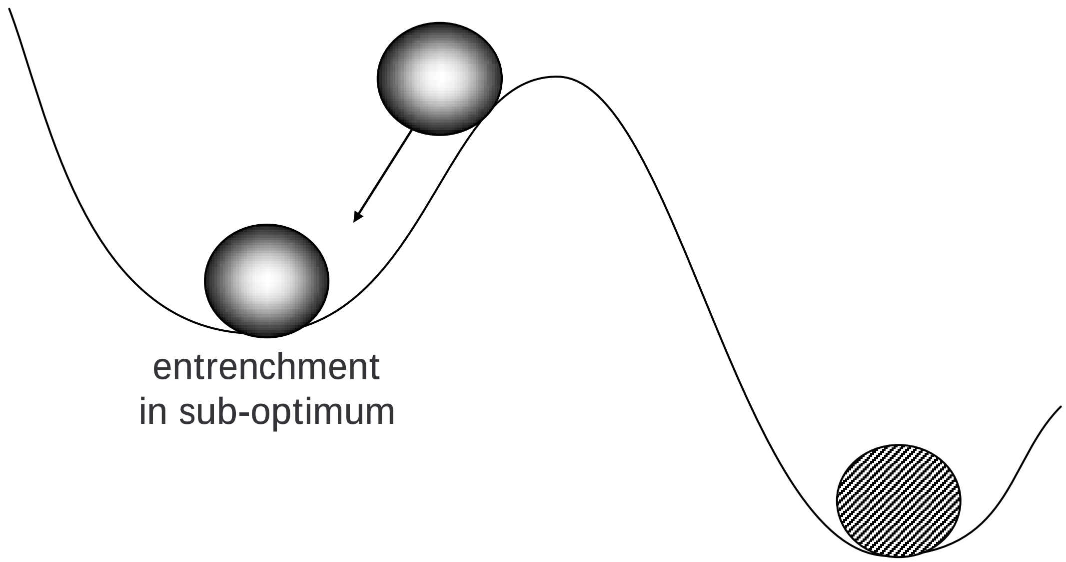
Fuel cell technology

Solar

Biomass

TU Delft

How to prevent entrenchment in conventional gasification?



TU Delft

Conclusions

- **Solid fuels will become increasingly important in the future.**
- **Present conversion systems for solid fuels are inherently inefficient.**
- **New conversion systems for solid fuels with higher (exergy) efficiency are possible; ultimately a flexible hydrogen & power producing system converting heat into power can be conceived.**
- **Fuel cell technology is a key-technology.**
- **The DCFC producing pure CO_2 is one of the very promising options**
- **A well defined roadmap is necessary to provide a framework for the development of these systems and to prevent entrenchment in inherently inefficient technologies**

Identification of R&D needs

- Design of a roadmap towards exergy efficient energy conversion systems with socio-economic analysis of flexible H2/power production
- Design and analysis of exergy efficient energy conversion systems and comparison with conventional systems to show potential benefits
- Integration of solar with gasification and fuel cells
- Steam and CO_2 gasification
- Molten salt (carbonate) gasification and in-situ gas cleaning.
- DCFC design and up-scaling
- Electrochemical oxidation of Carbon including transition from CO_2 to CO production as function of T
- Use of multi-valent ions (V) as catalyst for Carbon oxidation

TUDelft

Empty slide

Empty slide

Empty slide

TU Delft

Following slides contain additional info for question session.

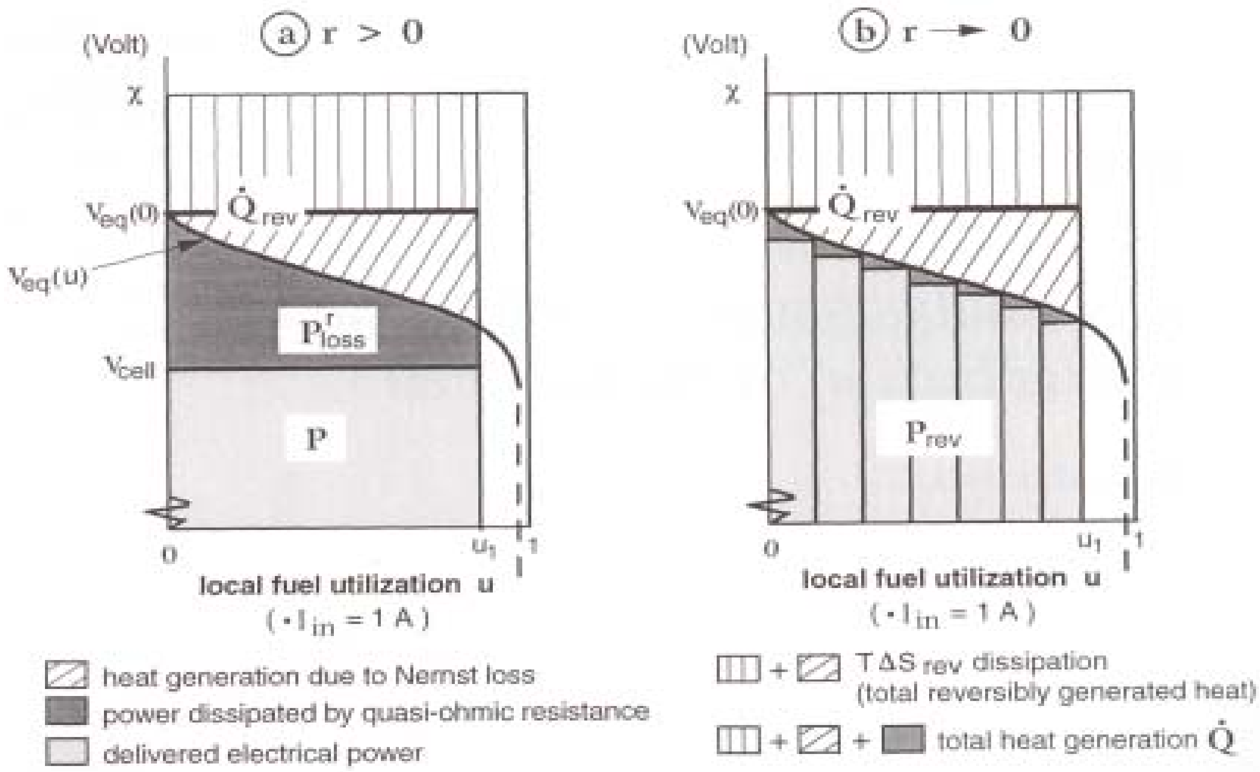
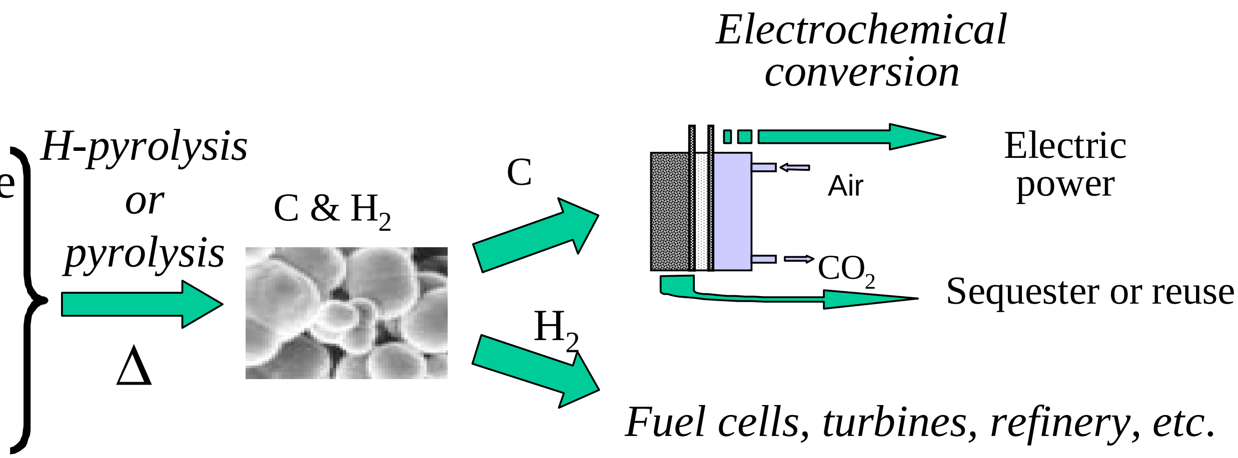


Illustration of the reversible and irreversible heat losses in a fuel cell.

Objectives

Evaluate processes for fossil conversion to electric power at efficiencies > 70 %

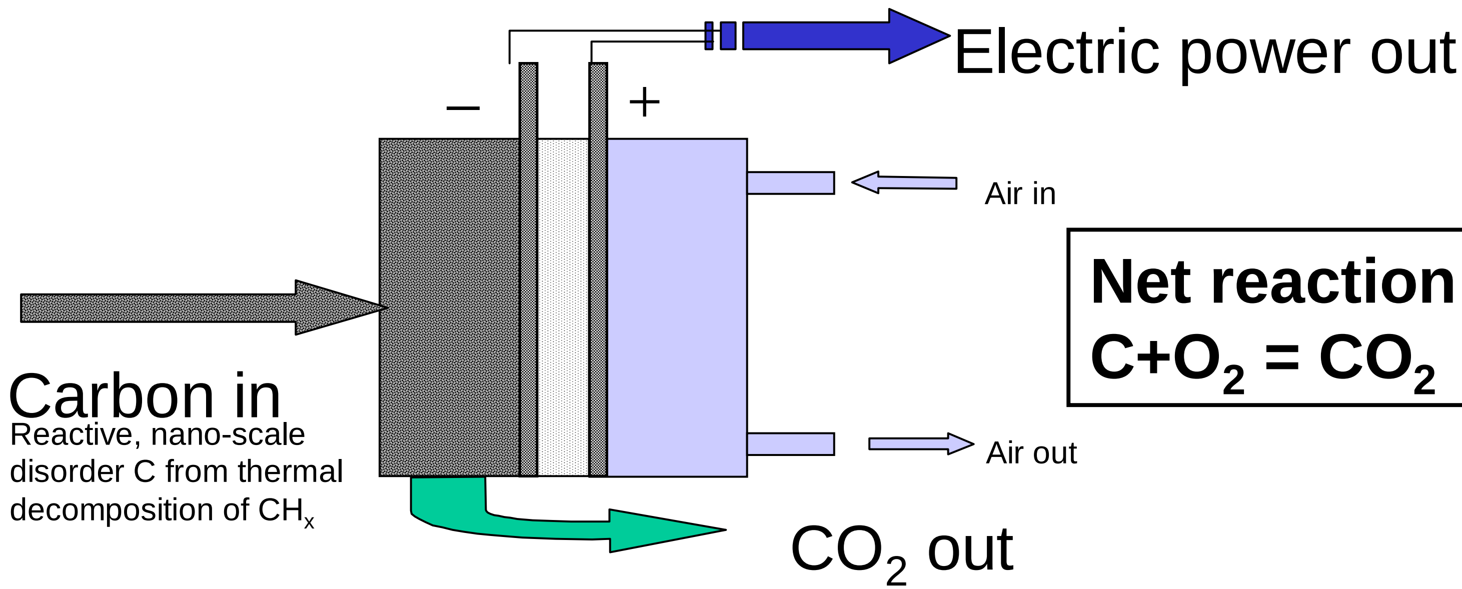
- Coal, lignite
- Natural gas
- Petroleum
- Petr. coke
- Biomass



Target: 70 – 80 % efficiency

- **The pyrolysis of CH_x => C + (x/2)H_2 consumes 3-8% of fuel value; no ash**

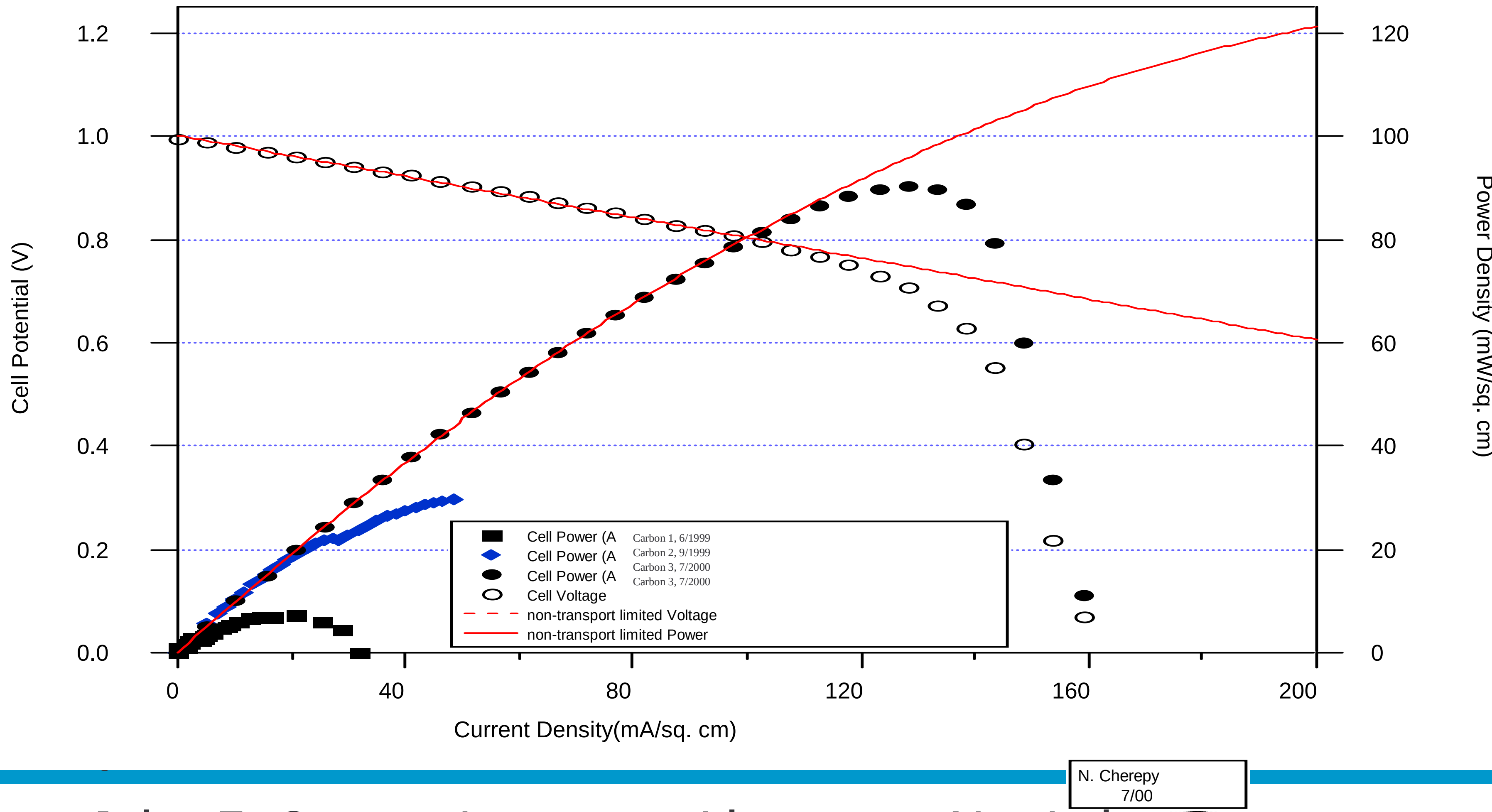
Concept Direct Carbon Conversion (DCC): electric power from electrochemical reaction of C and O_2



Net reaction:
$C+O_2 = CO_2$

- **Total efficiency ~ 80% of ΔH_{std}**
- **Pure CO_2 product for reuse/sequestration**
- **Use highly reactive carbons from CH_x pyrolysis**
- **Inherent simplicity**

LLNL Carbon/air cells operate at sufficiently high power density for base-load applications



John F. Cooper Lawrence Livermore Nat Lab.

TU Delft

Outline

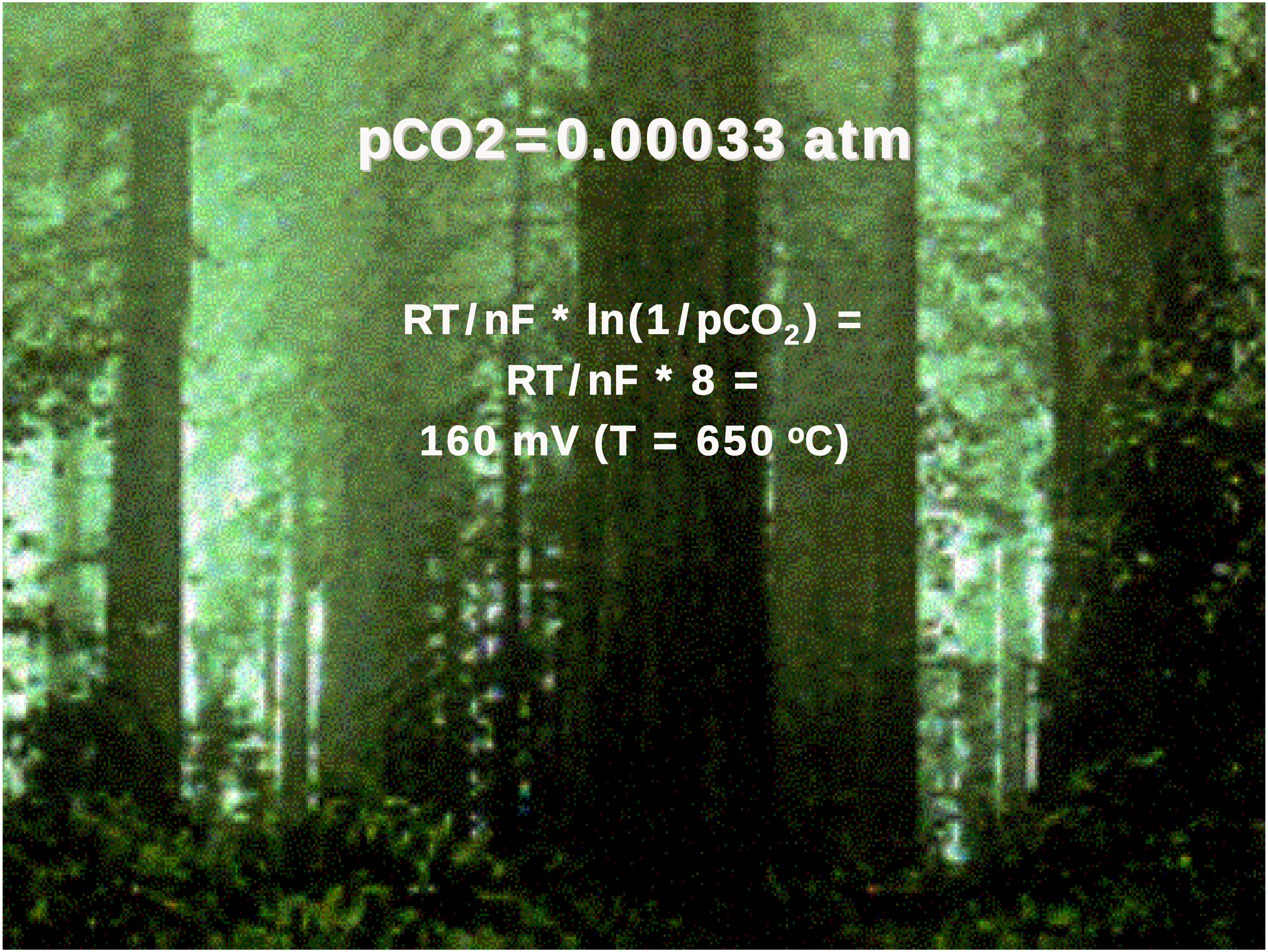
Table 3 Order of magnitude comparison between the electrochemical conversion efficiencies of C, H_2 and CH_4 (Cooper, J. F. et al 2000)

Fuel	η_{fc}	$\eta_{Nernst\ loss}$	η_{irr}	η_{tot}
C	1.0	1.0	0.8	0.8
H_2	0.7	0.8	0.8	0.45
CH_4	0.89	0.8	0.8	0.57

Looking for ways to use the full exergetic quality of solid fuel !!

- Solid fuels become increasingly more important (security of supply).
- Coal because it's abundant.
- Biomass because it is CO_2 neutral.
- Waste.
- Also liquids are closer to solids than to gases in terms of their exergy value.

TUDelft


pCO2=0.00033 atm
$RT/nF * \ln(1/pCO_2)$ =
RT/nF * 8 =
160 mV (T = 650 ^oC)

In-Direct Carbon Fuel Cell

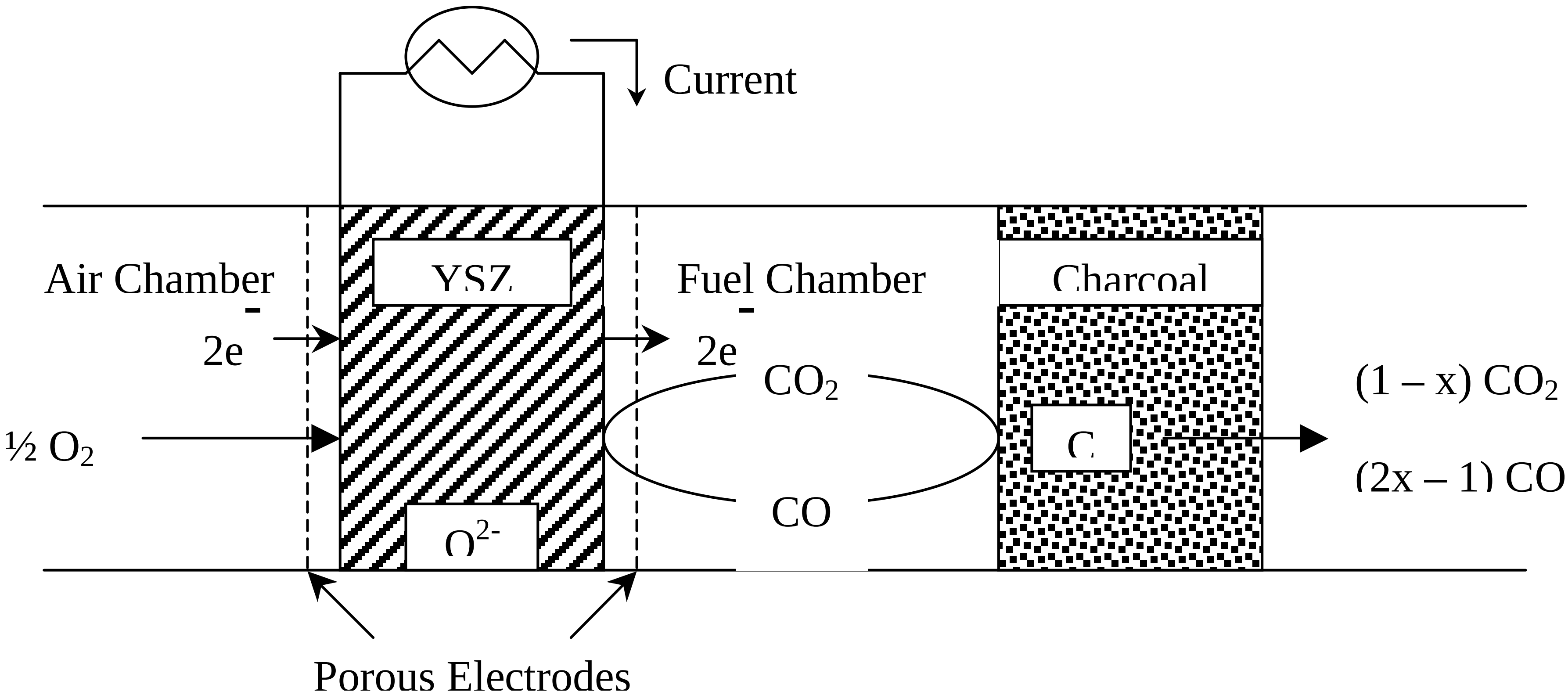
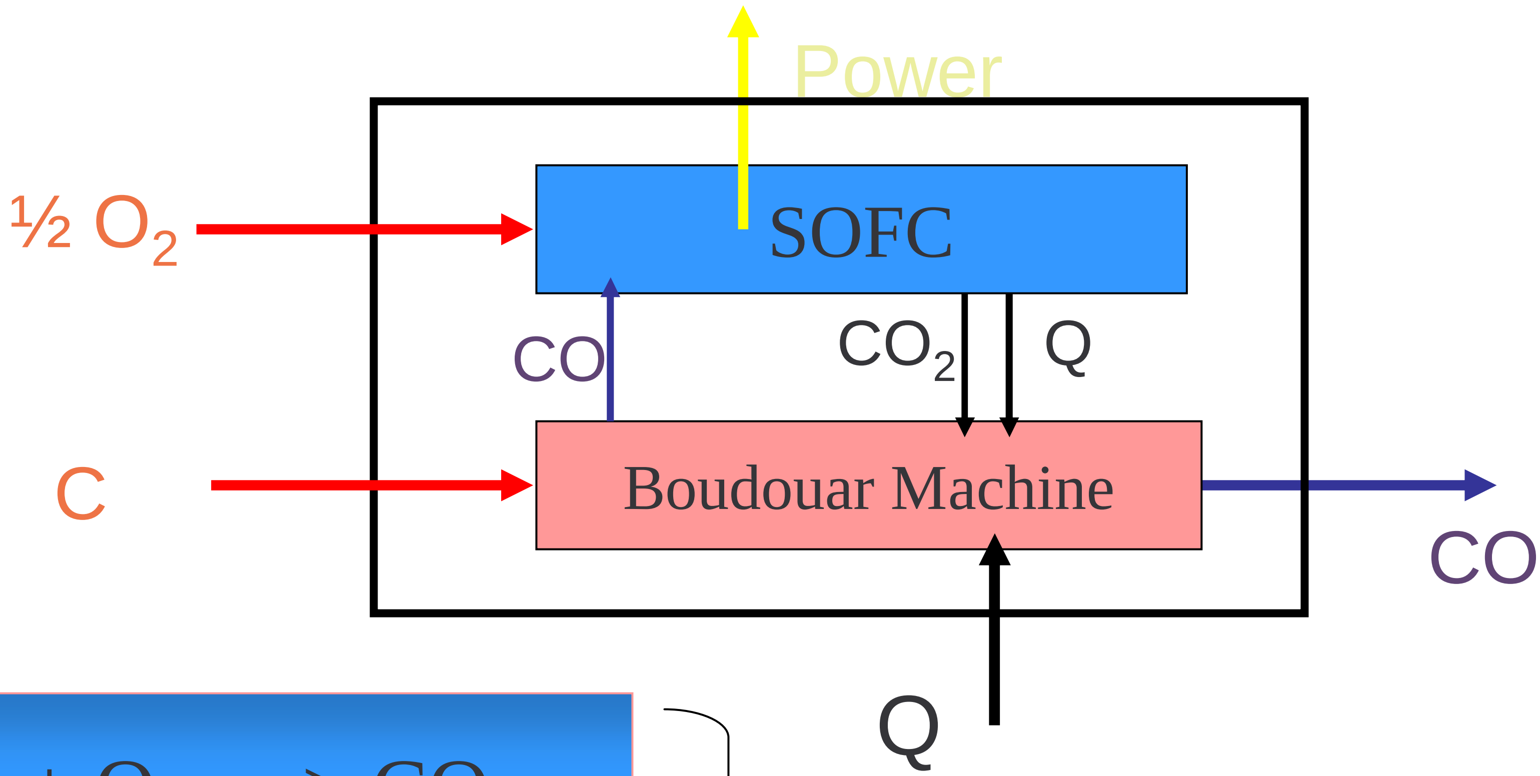


Figure 6 Indirect Carbon Fuel Cell concept by Nakagawa and Ishida (Nakagawa, N. and Ishida, M. 88)

TUDelft

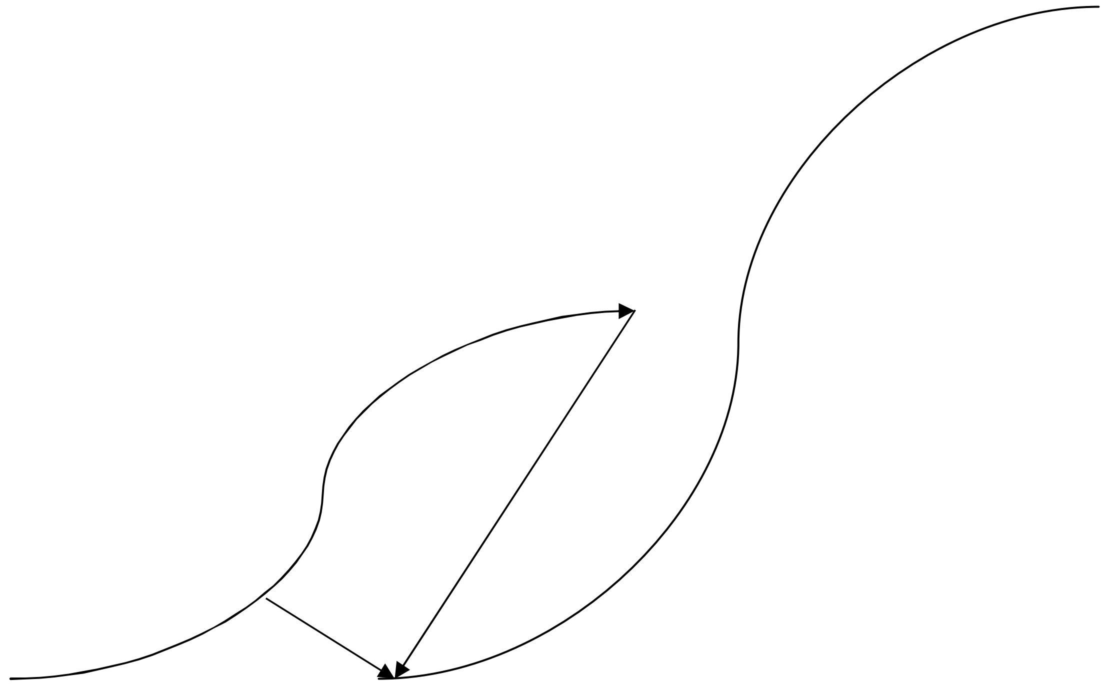
In-Direct Carbon Fuel Cell



$$C + O_2 ==> CO_2$$

$$C + CO_2 ==> 2CO$$

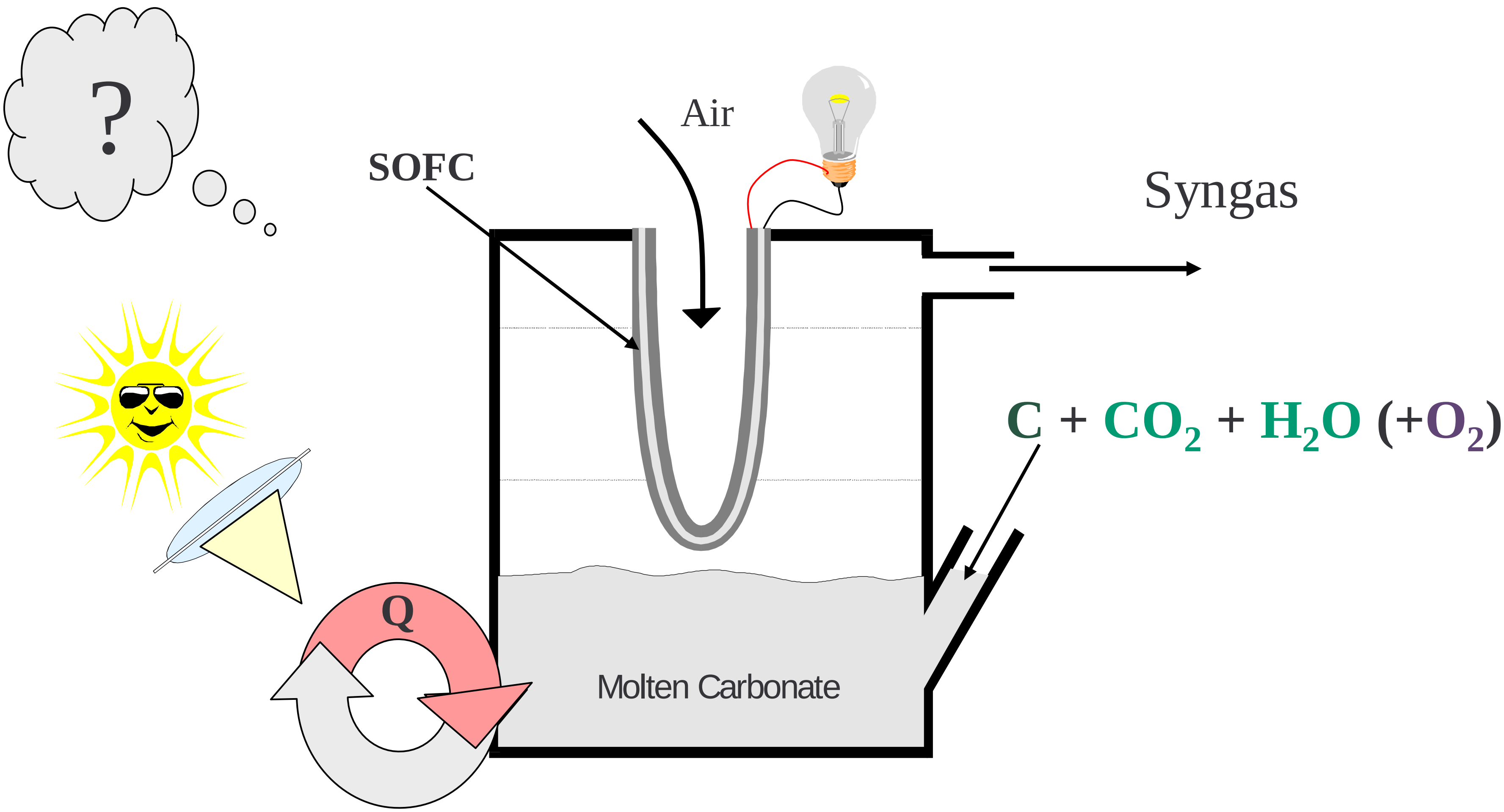
$$C + CO_2 ==> 2CO$$



Learning curves of conventional and potentially more efficient technology
When to make a transition?

TU Delft

Indirect Carbon SOFC & gasifier with molten carbonate assistance.

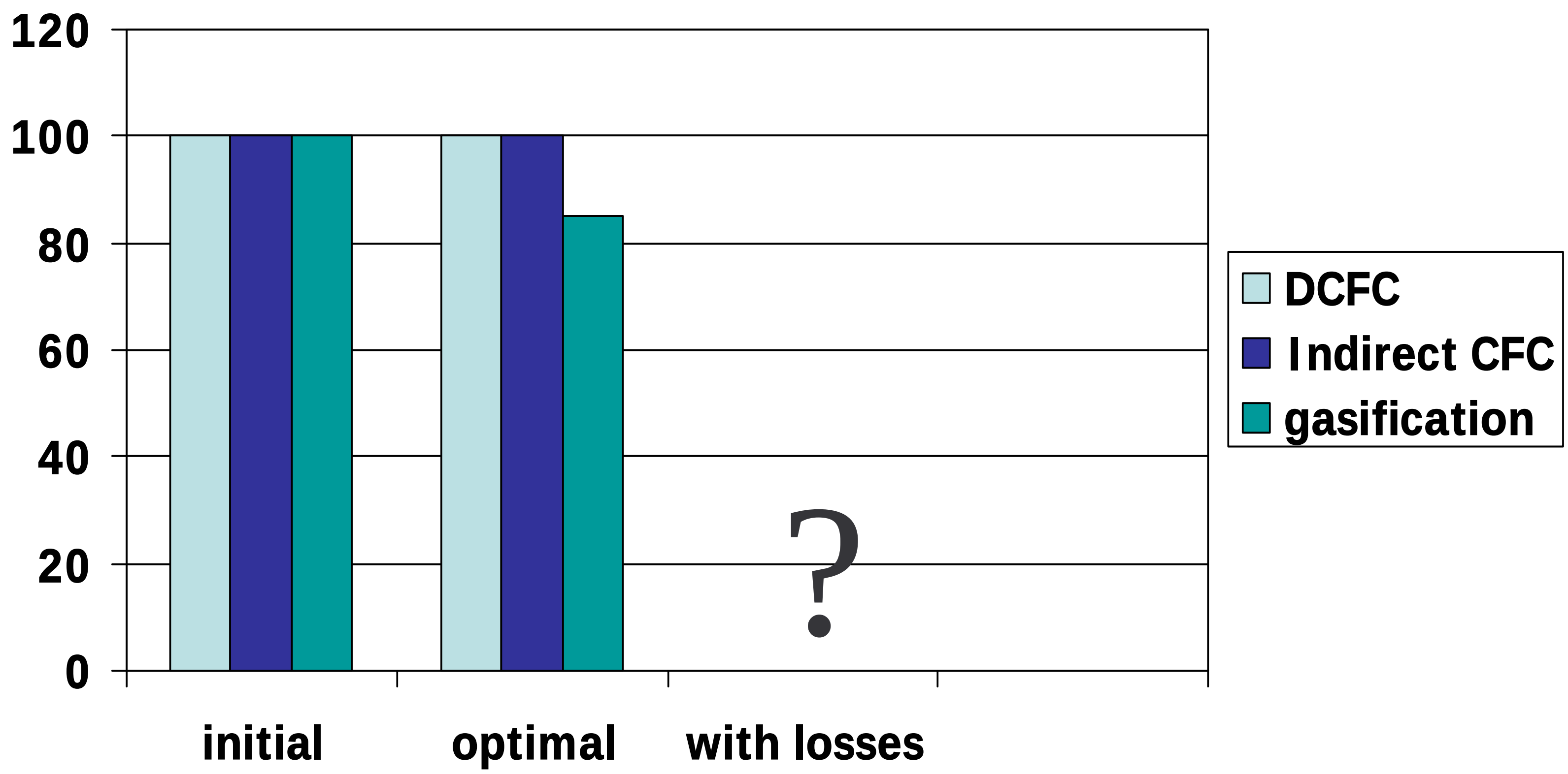


TU Delft

Combination of Molten Carbonate coal/biomass gasifier and MCFC

- In the syngas (hydrogen) producing integrated system the Fuel Cell can operate at low utilization.
- Hence low Nernst loss and high fuel cell efficiency.

Exergy efficiency of Coal/Biomass conversion



TU Delft

Solar Exergy (approx.)