“氢在可再生能源经济中的作用”

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130 年前的馬糞

1894 年倫敦的馬糞

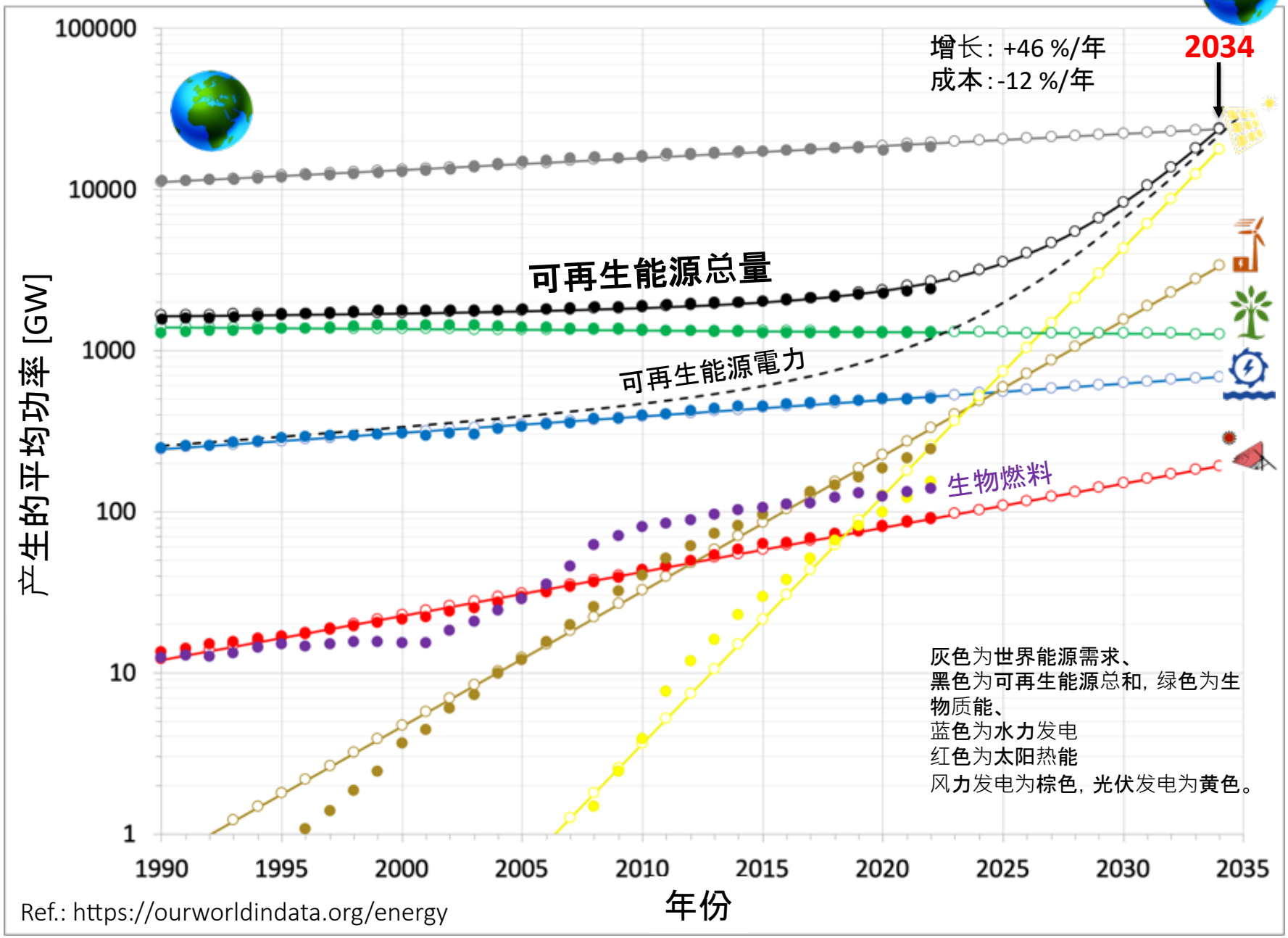
危機，我們需要減少馬匹的數量！

清除糞便

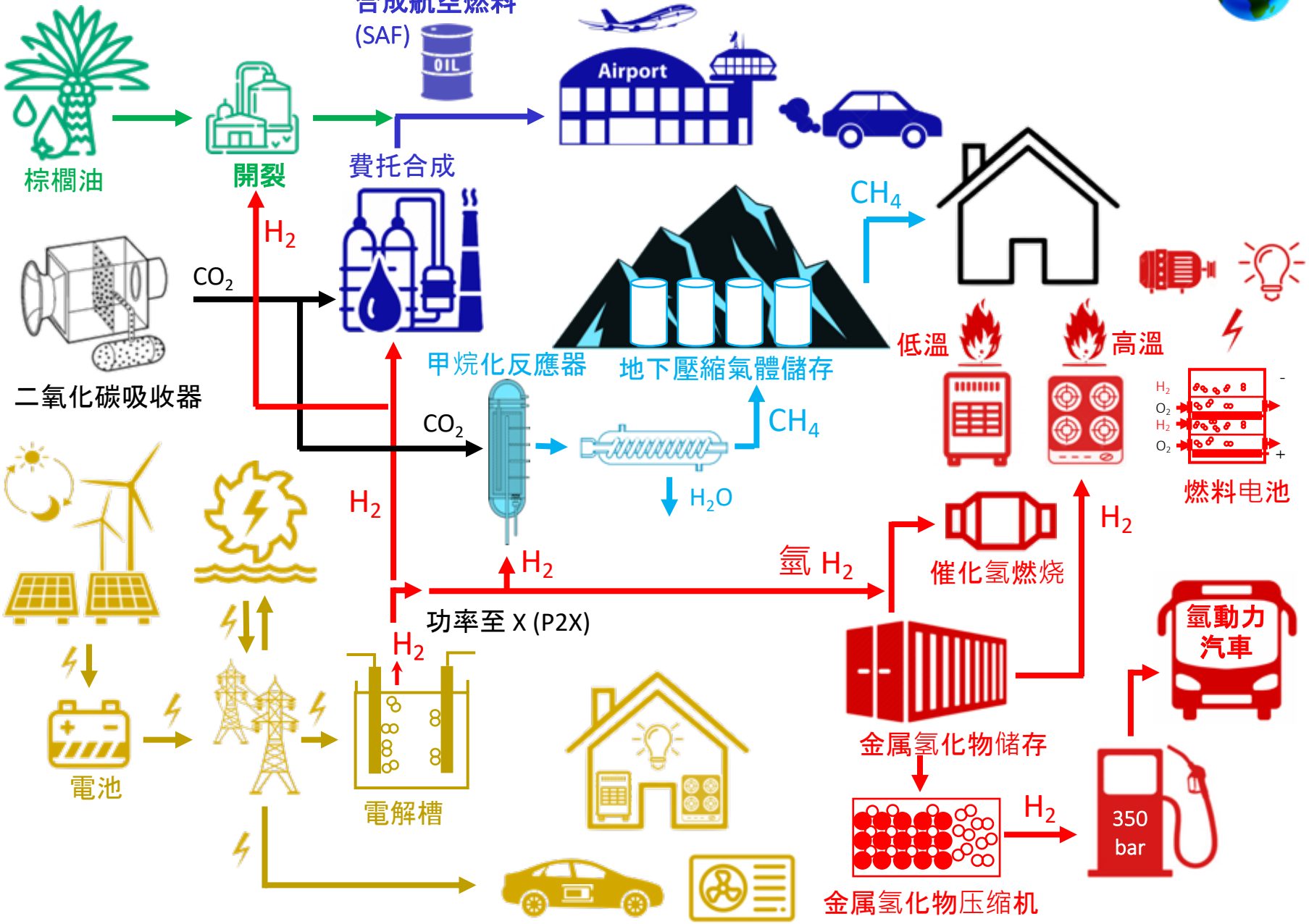
從點源收集糞肥

解決方案：新技術！

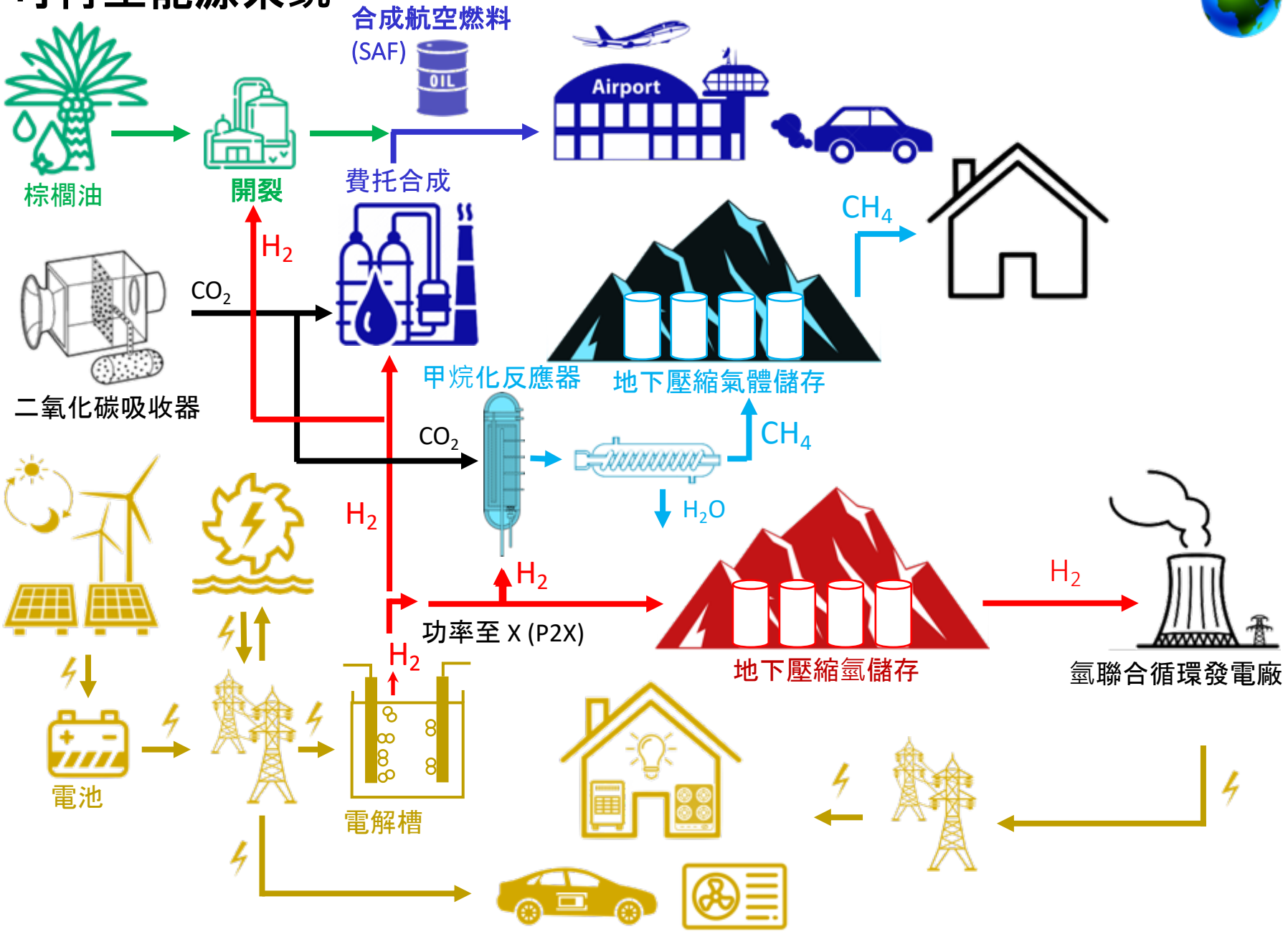
全球可再生能源產量


增长: +46 %/年
成本: -12 %/年
2034
可再生能源总量
可再生能源電力
生物燃料
灰色为世界能源需求、
黑色为可再生能源总和，绿色为生物质能、
蓝色为水力发电
红色为太阳热能
风力发电为棕色，光伏发电为黄色。
产生的平均功率 [GW]
100000
10000
1000
100
10
1
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
年份
Ref.: https://ourworldindata.org/energy

可再生能源系统


合成航空燃料
(SAF)
OIL
Airport
棕櫚油
開裂
費托合成
H_2
CO_2
CH_4
二氧化碳吸收器
甲烷化反應器
地下壓縮氣體儲存
CO_2
CH_4
H_2O
低溫
高溫
燃料电池
H_2
O_2
H_2
O_2
H_2
H_2
氫 H_2
催化氢燃烧
H_2
功率至 X (P2X)
H_2
氫動力
汽車
電池
電解槽
金属氢化物储存
H_2
350
bar
金属氢化物压缩机

可再生能源系统


合成航空燃料
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CH_4
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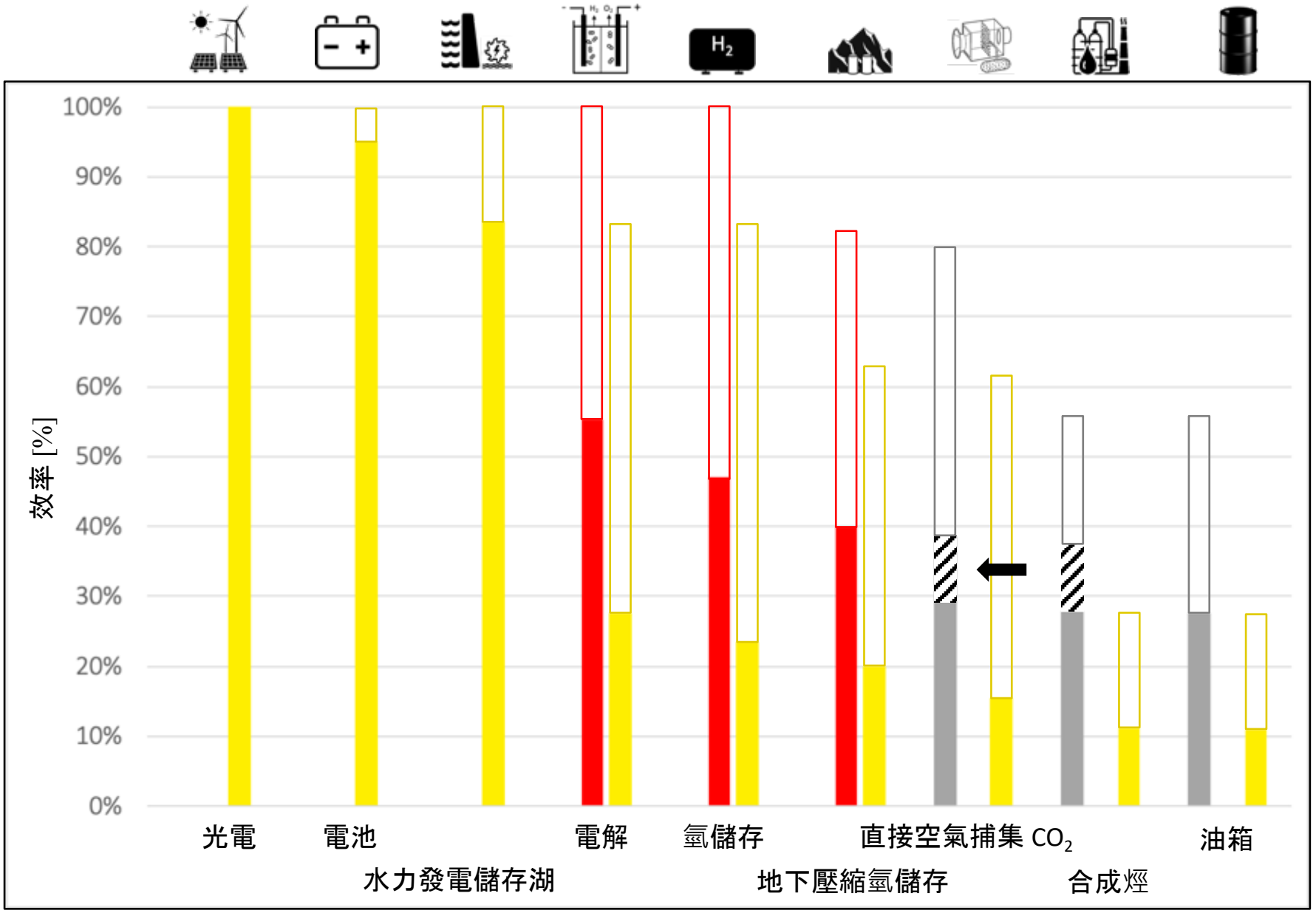
地下壓縮氣體儲存
CO_2
CH_4
H_2O
H_2
H_2
H_2
功率至 X (P2X)
地下壓縮氫儲存
氫聯合循環發電廠
電池
電解槽

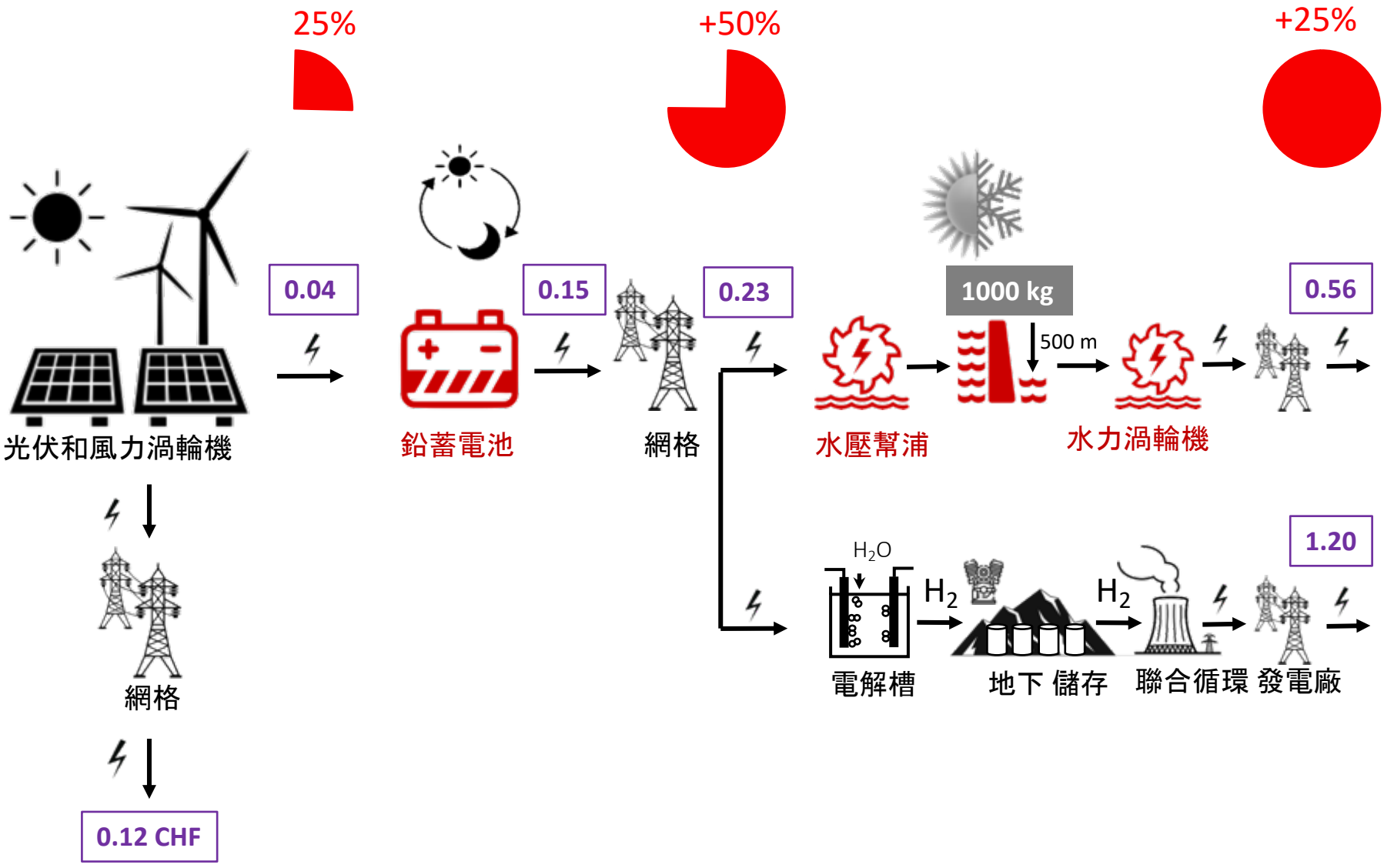
能量轉換效率

電源至 X (P2X)



可再生能源電力生產與儲存

以瑞士法郎/美元/歐元計算的 1 kWh 電力成本



氢循環

太陽

電力

39 kWh/kg

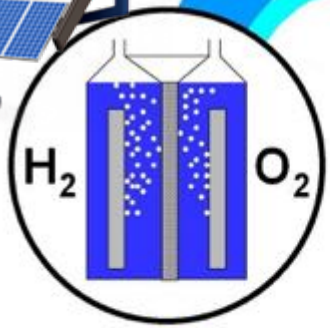
H_2

90%

储存

$M + ½H_2 \rightarrow MH$

O_2



60%

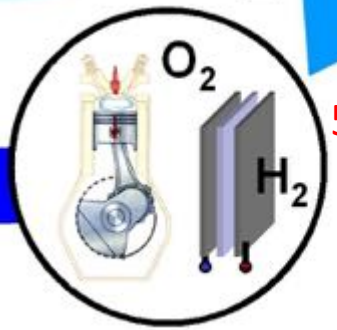
電解

$2\ H_2O \rightarrow 2\ H_2 + O_2$

H_2

O_2

H_2O



50%

能源

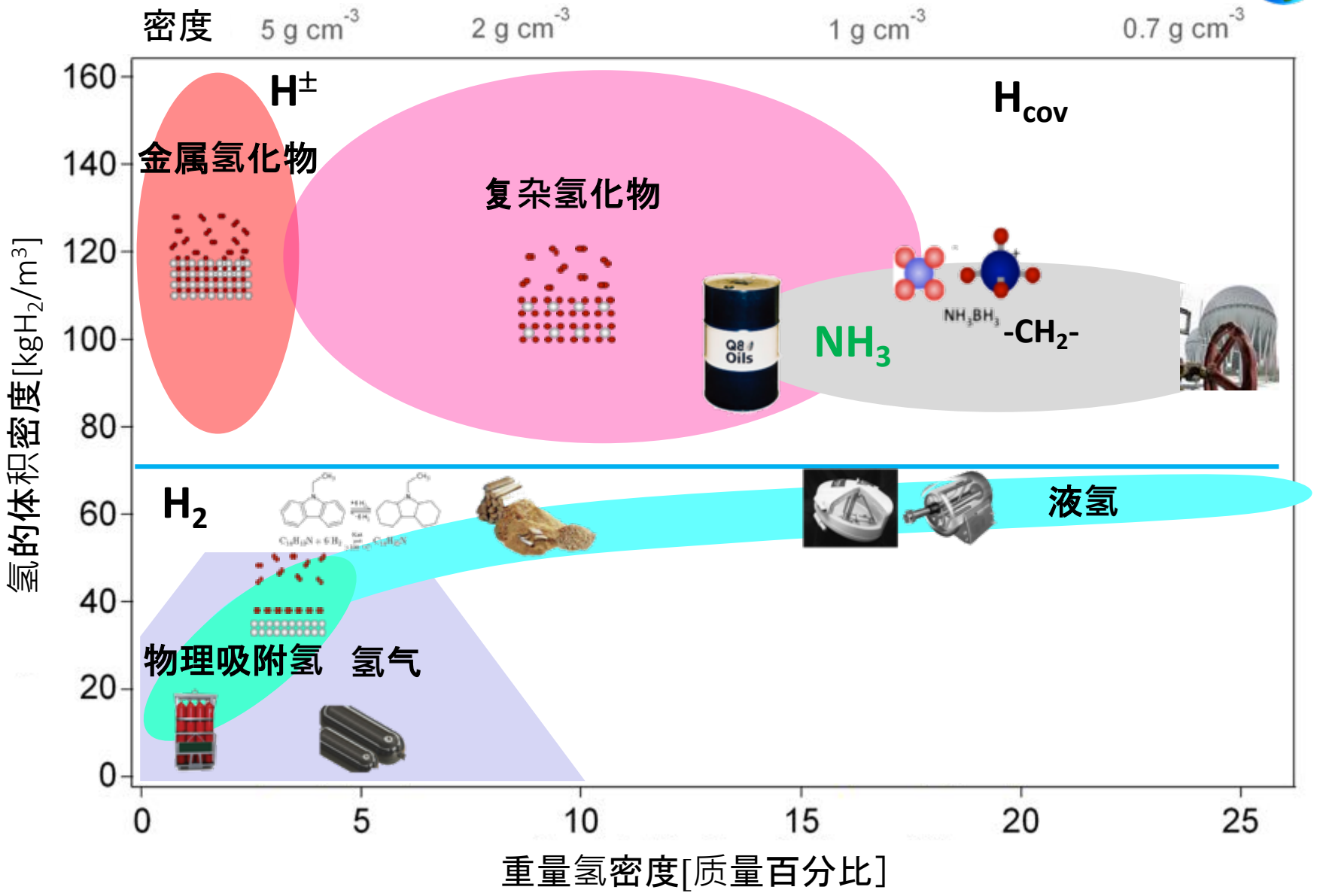
27%

电

燃燒

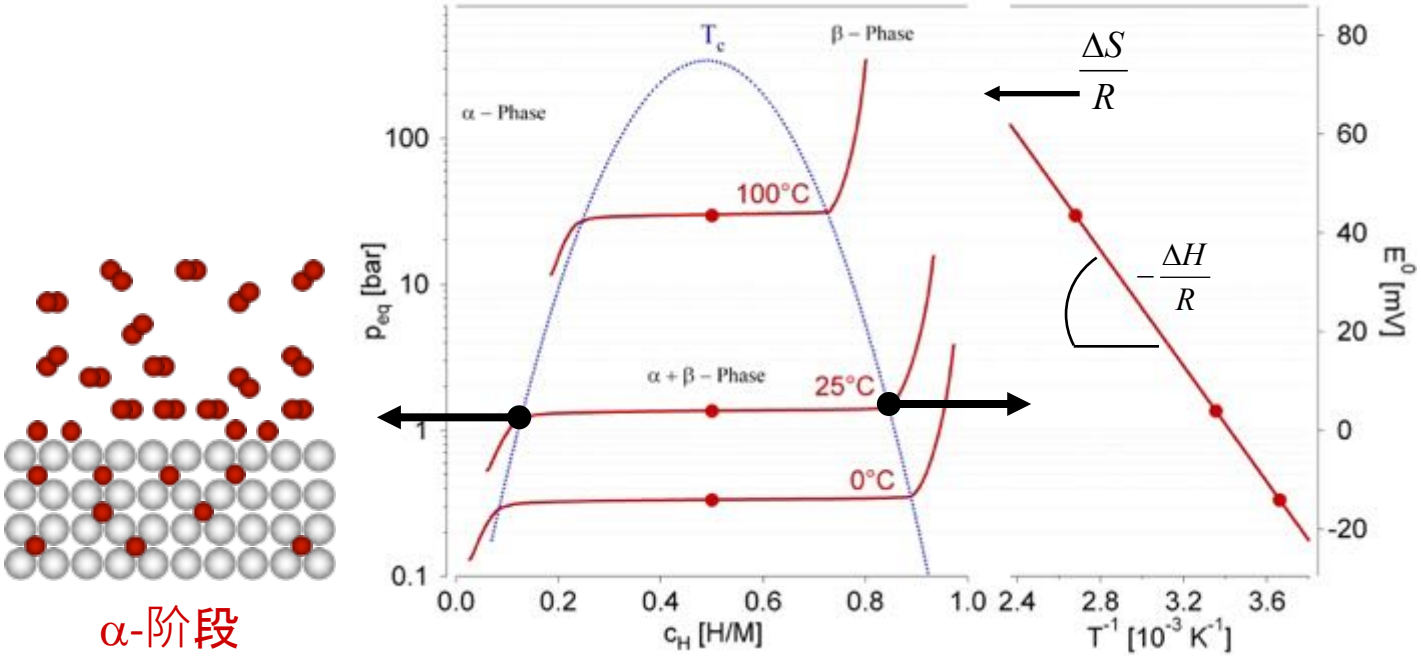
$2\ H_2 + O_2 \rightarrow 2\ H_2O$

氢密度



Ref: A. Züttel, “Materials for hydrogen storage”, materialstoday, Septemper (2003), pp. 18-27

金属氢化物- 氢平衡



α-阶段
固体解决方案

α+β-阶段

β-阶段
氢化物相

$$\frac{1}{2}\ln\left(\frac{p}{p_0}\right) = k \cdot T \cdot \ln(c_H)$$

$$\ln\left(\frac{p}{p_0}\right) = -\frac{\Delta H^0}{R \cdot T} + \frac{\Delta S^0}{R}$$

$$\frac{1}{2}\ln\left(\frac{p}{p_0}\right) = k \cdot T \cdot \ln(c_H)$$

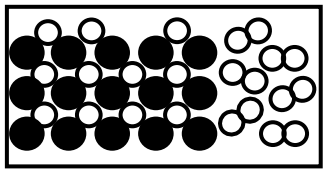
范特霍夫方程

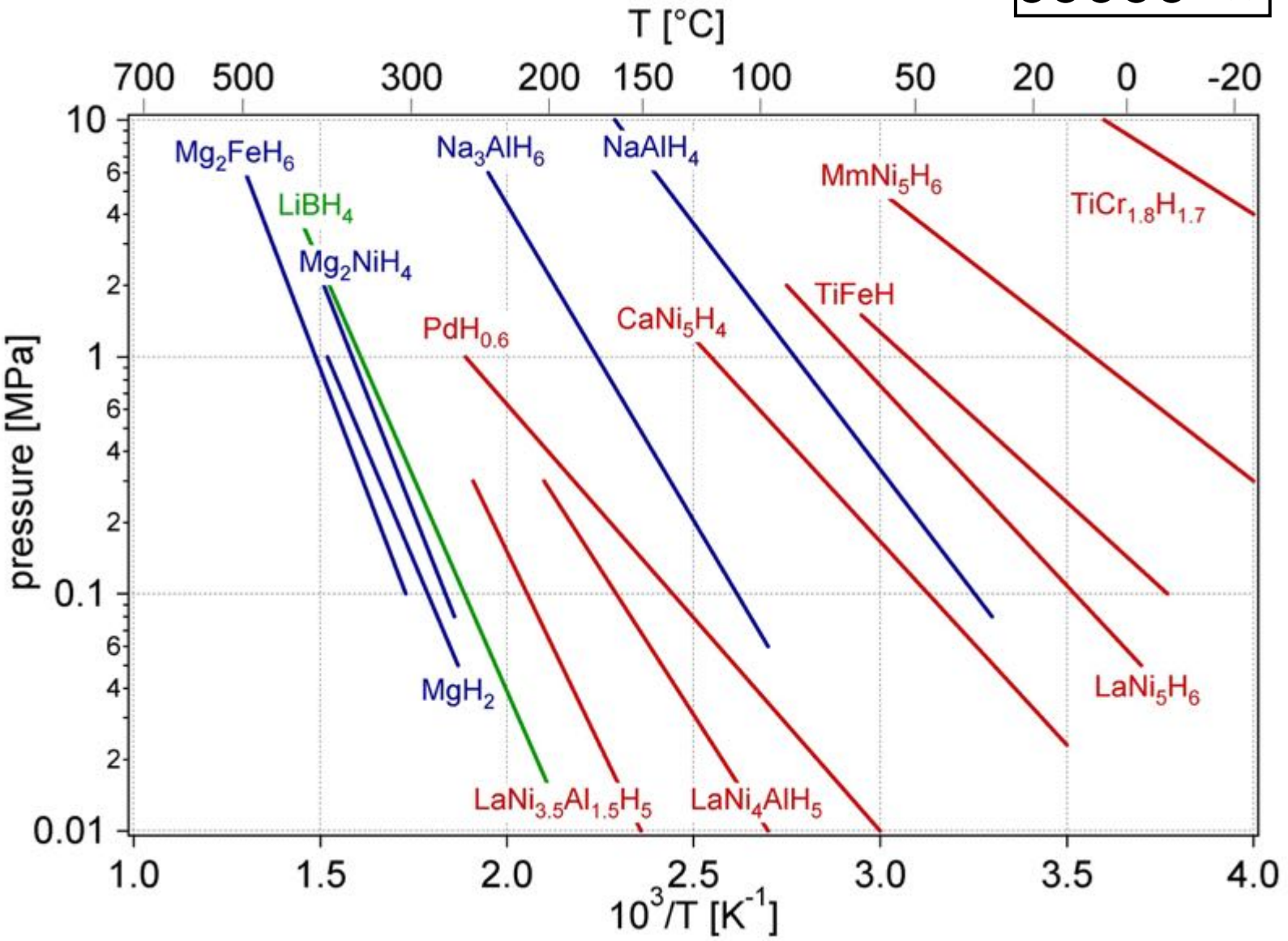
MH_x $(0 < x < 0.1)$
~~H⟷H~~, $\Delta V/V = k \cdot c_H$

MH_x $x = \{1, 2, 3, \ldots\}$
H⟷H

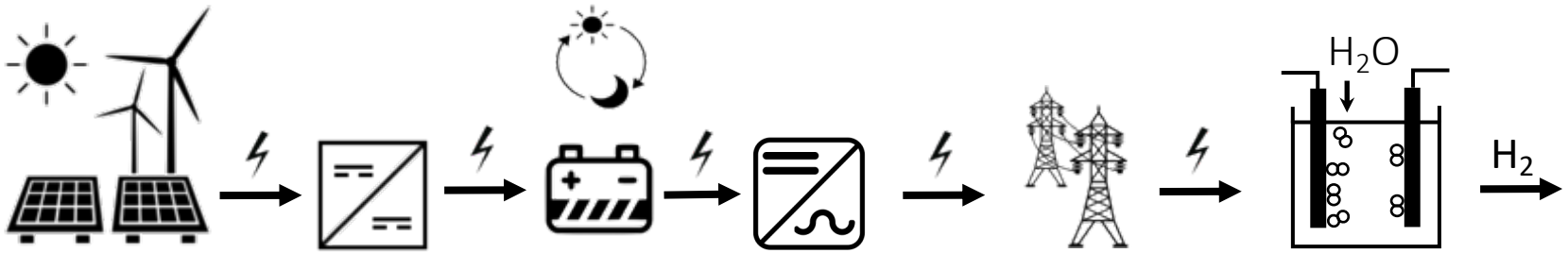
范特霍夫阴谋

$$\ln\left(\frac{p}{p_0}\right) = -\frac{\Delta H^0}{R \cdot T} + \frac{\Delta S^0}{R}$$



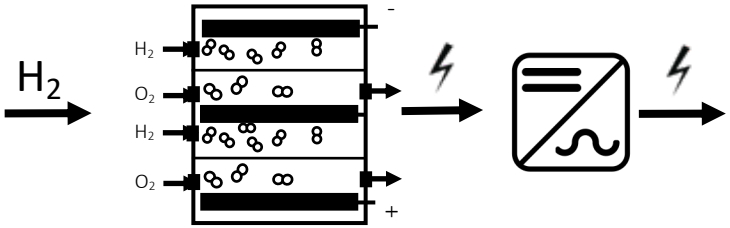


光伏、制氢和储氢、电力

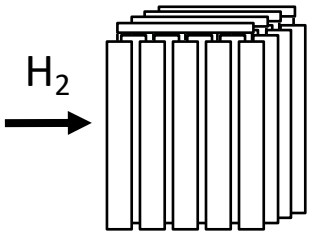


光伏和风力涡轮机　直流-直流 变流器　电池　直流-交流 变流器　网格　电解槽

压缩机　冷却器　压缩氢储存



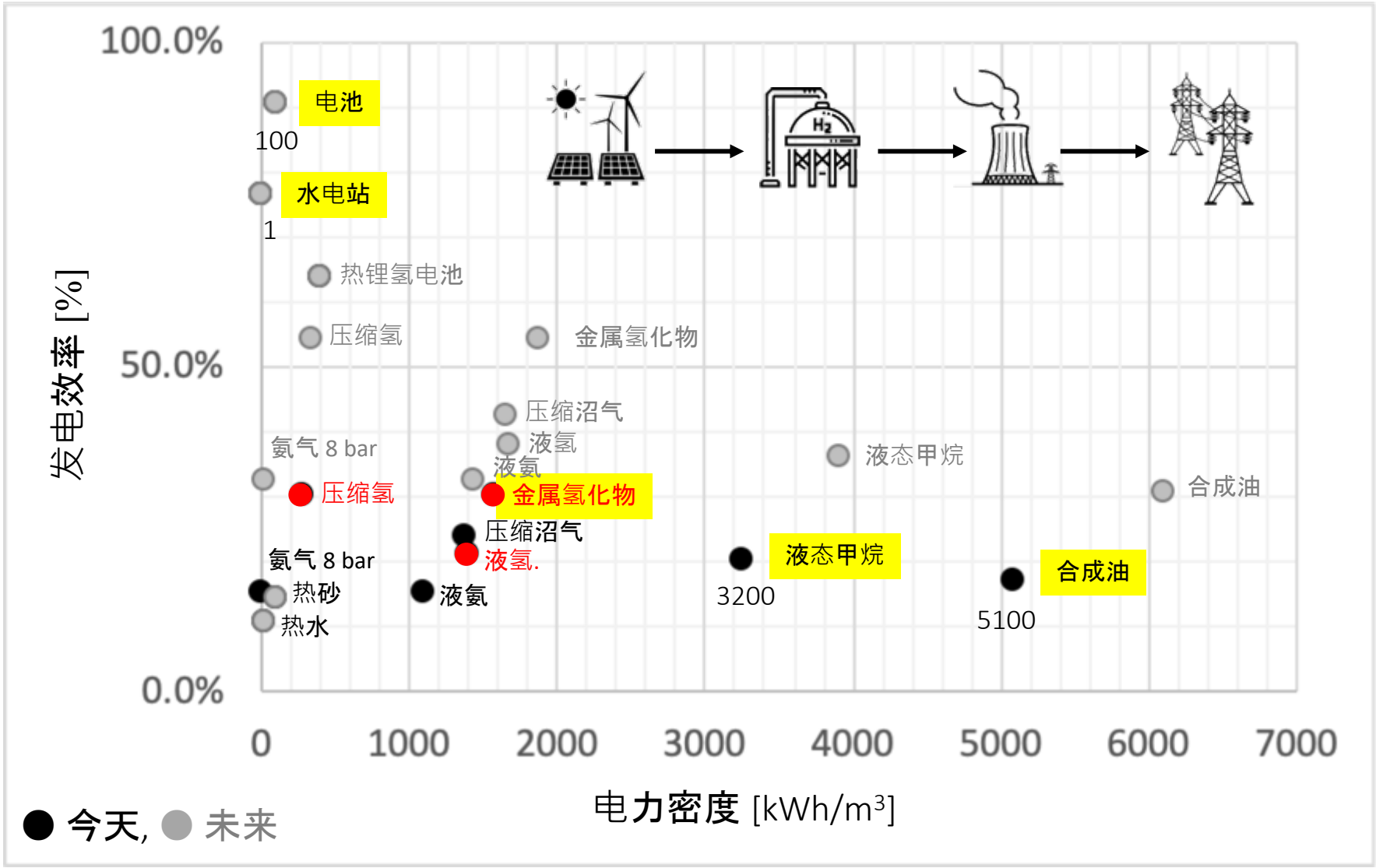
燃料电池



金属氢化物储存

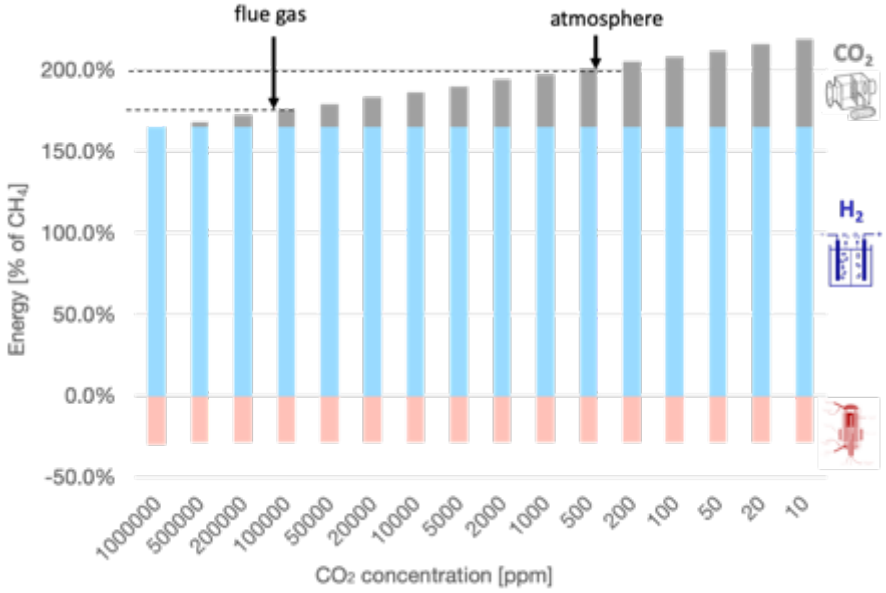
紧凑型
安全
充满活力

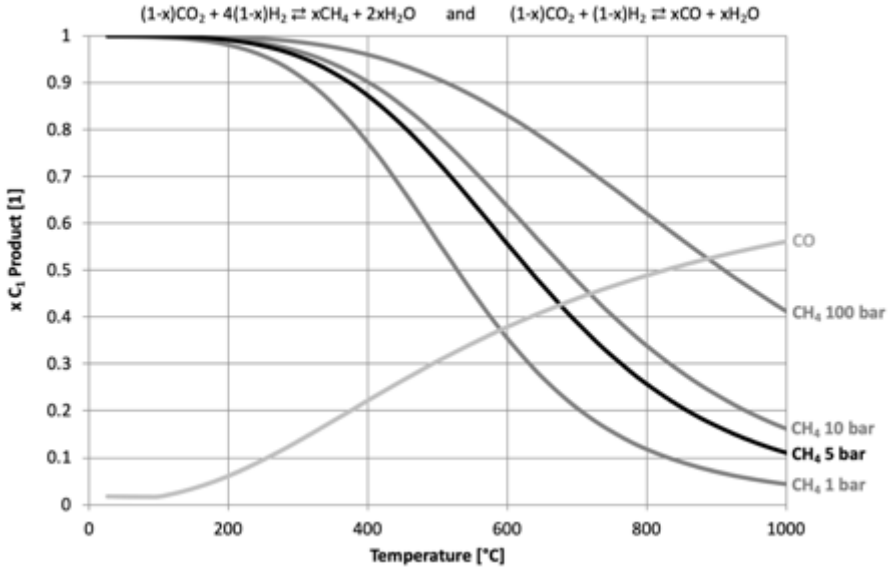
可再生能源电力的效率和储存密度

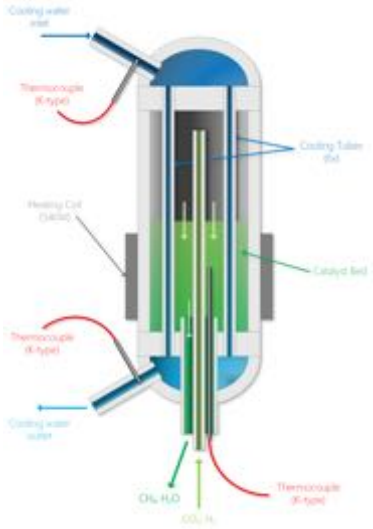


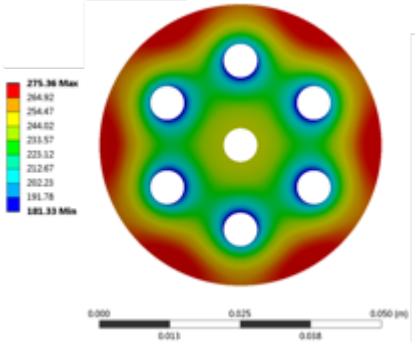
Ref.: Andreas ZÜTTEL, Christoph NÜTZENADEL, Louis SCHLAPBACH, Paul W. GILGEN "Power plant units for CO_2 Neutral Energy Security in Switzerland", Frontiers in Energy Research: Process and Energy Systems Engineering, 12:1336016 (2024).

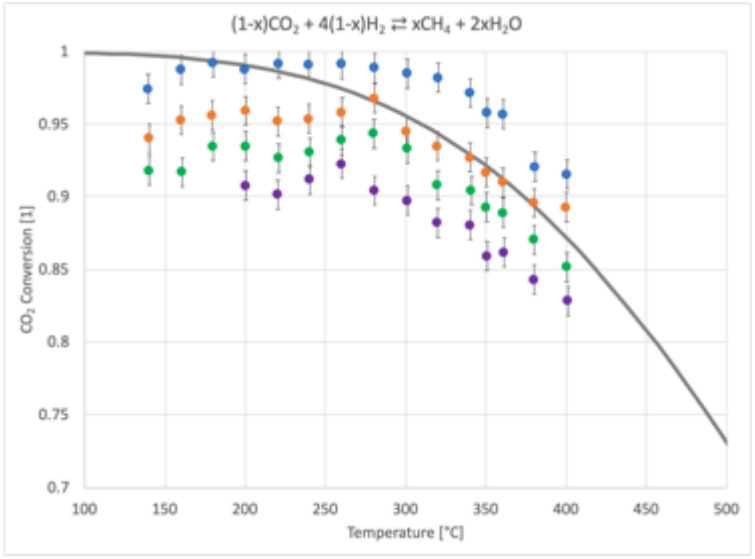
甲烷合成：$CO_2 + 4H_2 \rightleftarrows CH_4 + 2H_2O$







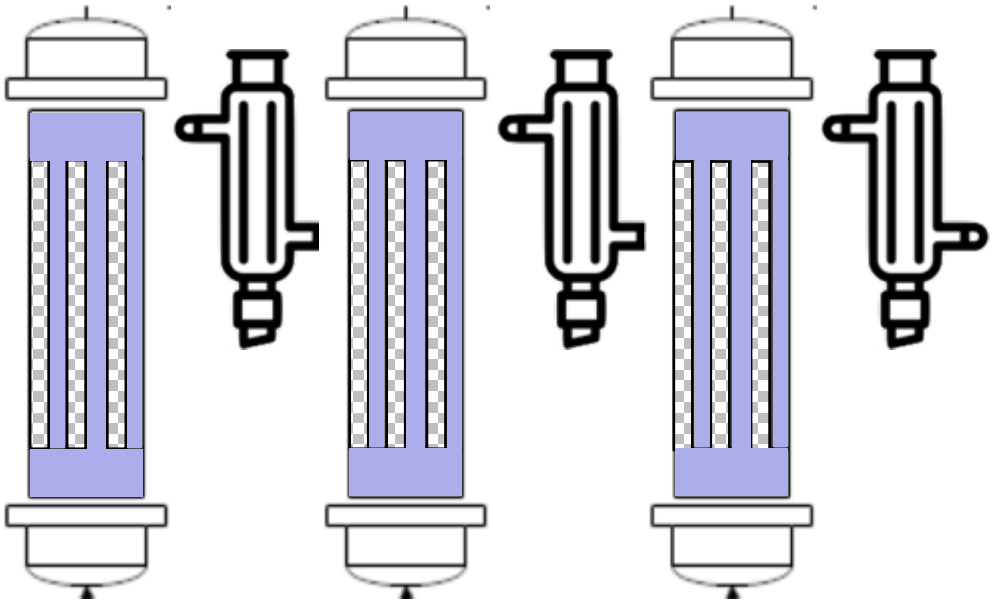


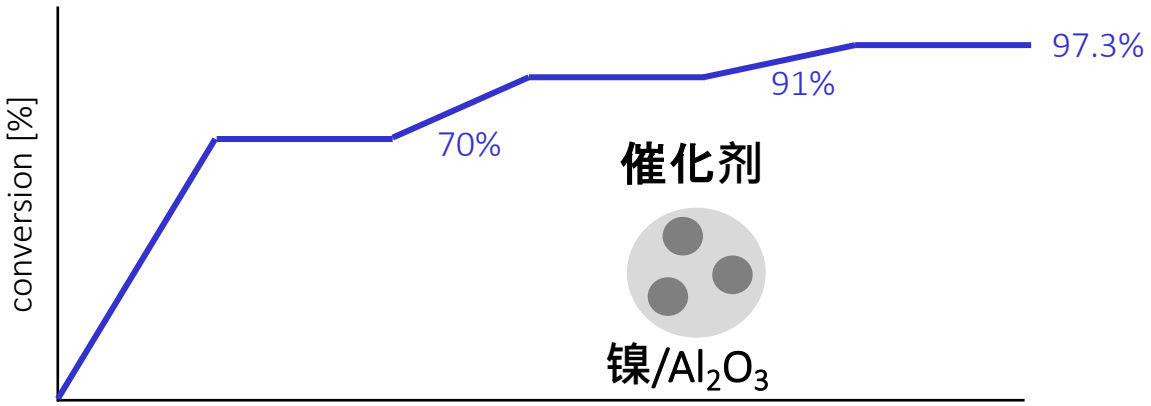


Ref.: Noris Gallandat, Robin Mutschler, Vincent Vernay, Heena Yang, Andreas Züttel, “Experimental Performance Investigation of a 2kW Methanation Reactor”, Sustainable Energy Fuels, 2 (2018), pp. 1101 - 1110

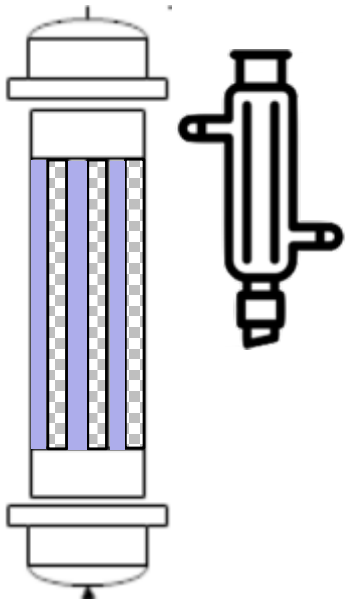
二氧化碳甲烷化: $CO_2 + H_2 \rightleftarrows CH_4 + 2\ H_2O$

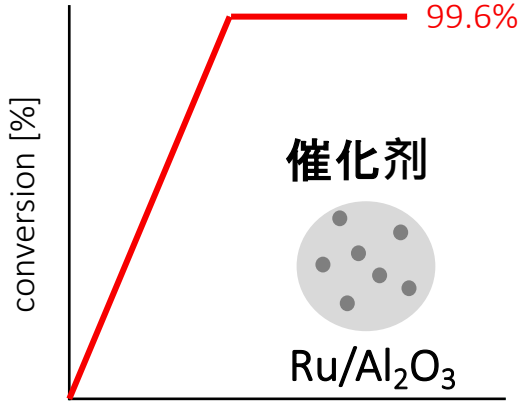
传统的





新反应器和催化剂



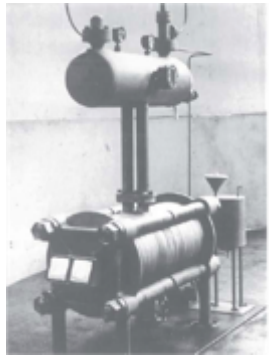


Ref.: René Bautz; Gilles Verdan, Andreas Züttel, "Installation Power-to-Gas Novatrice", AQUA & GAS No 3 (2021), pp. 48-53

瑞士氢气历史

第一台氢气内燃机 1807 年
Francois Isaac de Rivaz

水电站 Gampel 1898



Ewald Zdansky 1949

碱性电解槽 4MW, 1980
Giovanola, Lurgi, IHT

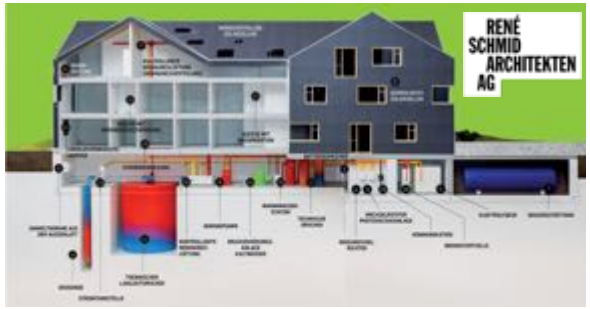
光伏、电解、汽车、炉灶
Markus Friedli 1991

氢气储存 1997
in Monthey

2001

雪地移动金属氢化物
和内燃机 2004

扫街机
压缩氢 和燃料电池 2009



能源自给自足的房屋 2016

质子交换膜燃料电池 2004-17

Hyundai 氢气卡车 2020

金属氢化物储存、压缩、甲烷化 2021

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