3rd Science and Energy Seminar at Ecole de Physique des Houches, March 6th-11th 2016

"Energy scenarios : which research in physics ?"

"Power to gas to power" Solution or dead lock ?

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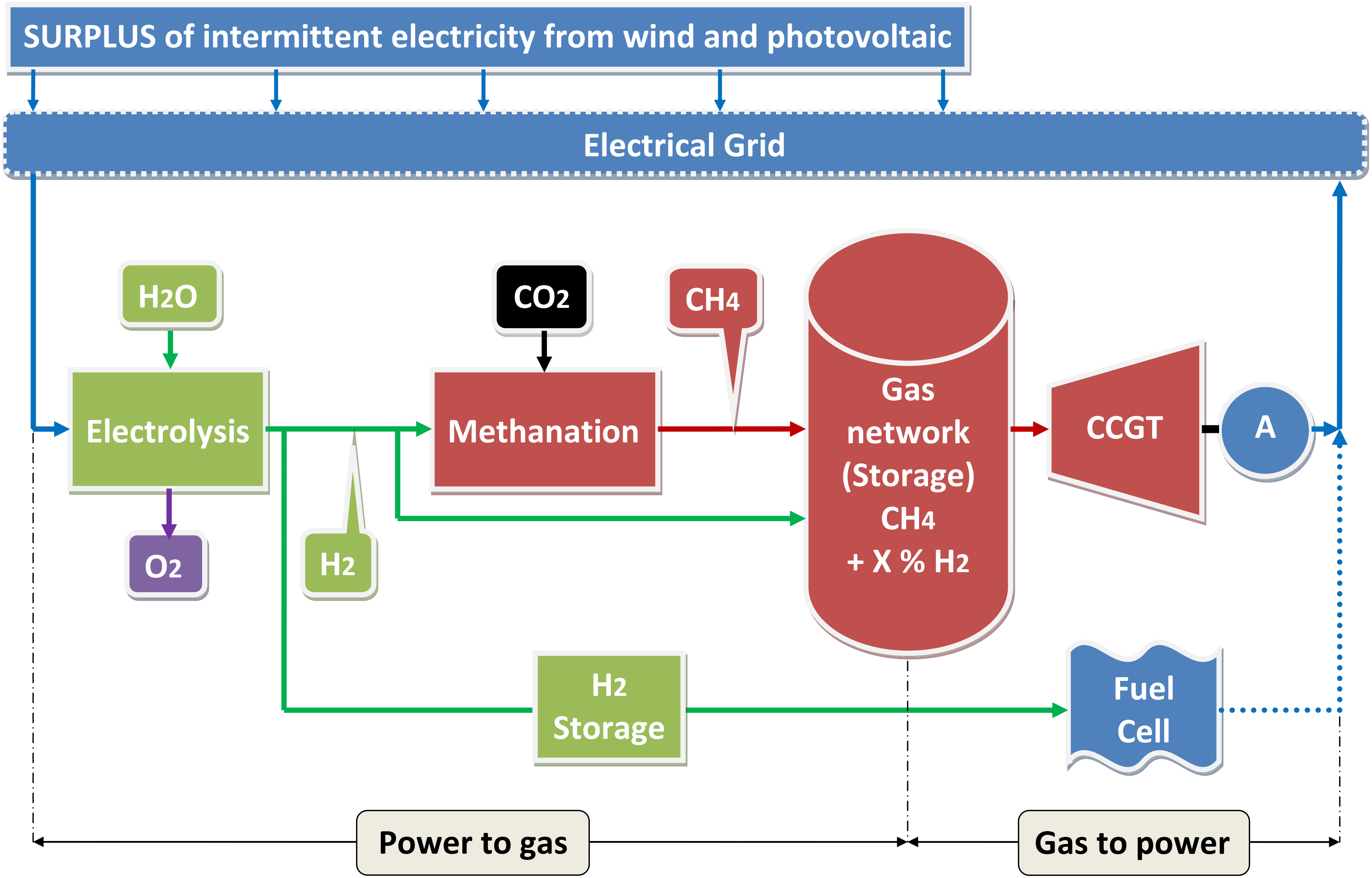
Summary

1 – Of what consists "Power to gas to power"? (Short reminder)



2 – Why is this solution envisaged ? Advantages and inconveniences

*** Goal : a possible solution to store the intermittent electricity SURPLUS from wind and photovoltaic by transforming them into chemical energy contained in gases. And vice versa to produce again some electricity**

*** Several advantages as a "paper solution" :**

- Easy storage in the existing domestic Gas network without real quantitative limits :

° Huge capacities still available in existing natural cavities used for natural gas storage ➔ Possibility of long-term (inter seasonal) storage

° Methane from synthesis : direct substitution to natural gas

> To be noted : **hydrogen** can also be **directly injected** to some extent **in the gas network :** up to **5 %** from now (subject to minor modifications and cautions), up to **20 %** expected (subject to complementary studies still in progress)

- No real industrial limits on storage and/or destocking capacities and power & limited impact on the available surfaces (Compactness of the installations)

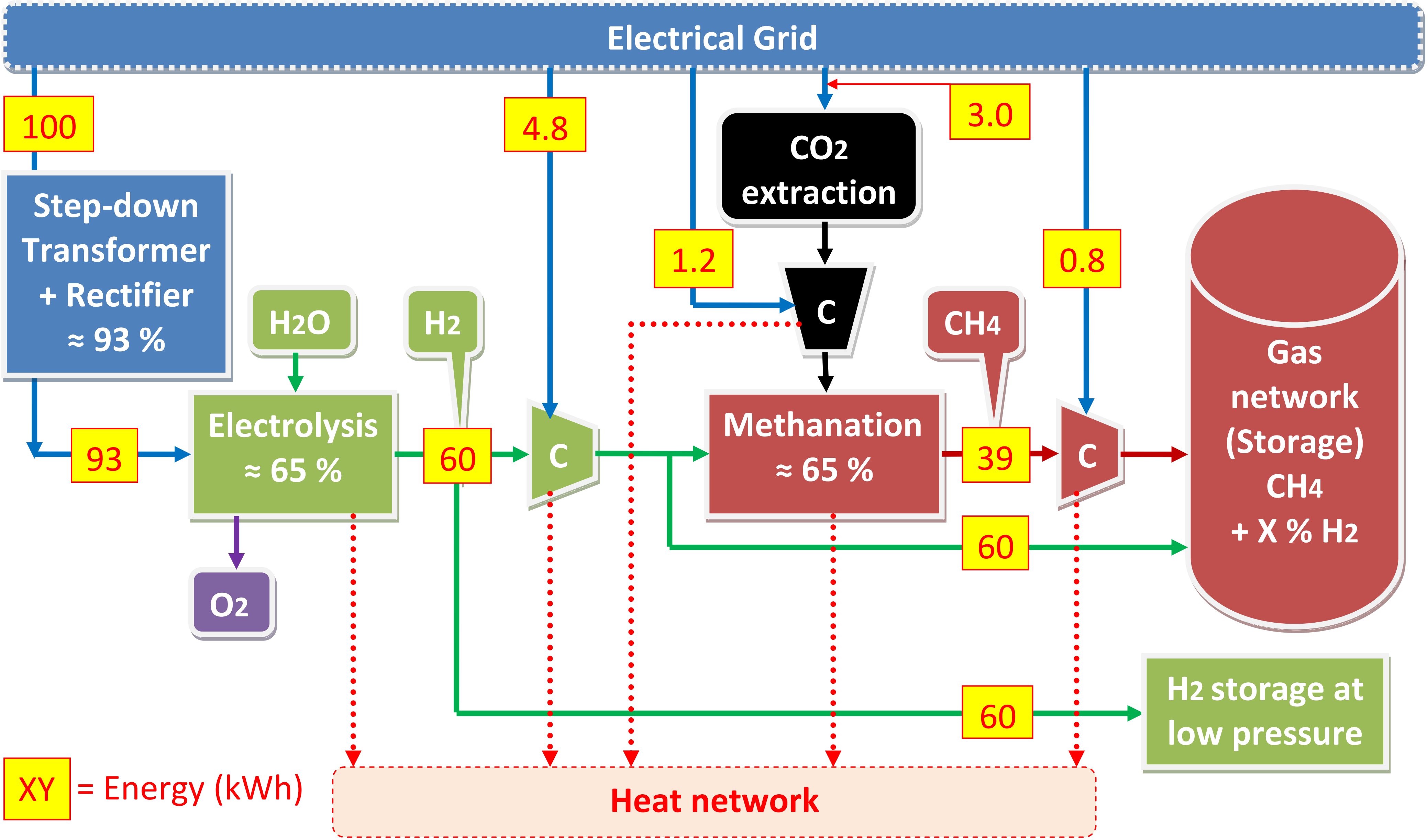
*** But a MAJOR inconvenience : massive energy losses ➔ very low global Energy Efficiency :**

° Massive over-sizing of installations resulting in massive financial investments

° An economic model very difficult to balance…

3 – The major inconvenience of the solution : massive energy losses

3.1 – "Power to gas" energy losses (1st part)



3.1 – "Power to gas" energy losses (Continuation)

*** Chemical internal energy of gases and associated volumes**

They are evaluated from 100 kWh (delivered by the Electrical Grid) on the basis of the two classical chemical equations :

Electrolysis : $4\ H_2O \rightarrow 4\ H_2 + 2\ O_2$

Methanation : $4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$

Quantities of gases (in Nm3) :

Gas	H_2	CO_2	CH_4
Chemical energy (kWh)	60	-	39
Lower or Higher Heat (kWh / Nm3)	LH ≈ 3	-	HH ≈ 11.7
Volume (**Nm3**)	60 ÷ 3 = **20**	20 ÷ 4 = **5**	39 ÷ 11.7 ≈ **3.3**

*** Energy losses for gas compressions**

All the gases are supposed to be compressed up to ≈ 80 bars in order to meet current industrial requirements. Two types of energy losses shall be taken into account :

3.1 – "Power to gas" energy losses (Continuation)

- **First type of losses** : **energy spent during physical compression of gases, depending on the type of compression :**

° **Isothermal compression : ➔ Smallest losses but industrially not practicable**

° **Adiabatic compression : ➔ Highest losses** (≈ 2.5 times isothermal ones at 80 bar)

° **Multistage adiabatic compression with intermediate cooling's : ➔ Practical industrial scheme** (losses are supposed to be approximately the average of isothermal and adiabatic ones : (1 + 2.5) ÷ 2 = **1.75** x isothermal losses)

- **Second type of losses** : **electro-mechanical losses in compressors used to compress gases** (assumed to be ≈ **10 %** of internal physical losses of gases)

- **Total compression losses** :

Gas	**H_2**	**CO_2**	**CH_4**
Volume (in **Nm^3**) (Previous table)	20	5	3.3
Isotherm losses W = P1 x V1 x Ln(P2/P1) (*) x 1.75 (Multistage compression losses factor) x 1.1 (Electro mechanical losses in compressors) **= Total compression losses (KWh)**	**≈ 4.8**	**≈ 1,2**	**≈ 0,8**

(*) P1 = 1 bar ; P2 = 80 bar ; Ln P2/P1 ≈ 4.38

3.1 – "Power to gas" energy losses (Continuation)

To be noted :
- Compression losses are small compared to chemical energy of gases but **not negligible**
- Chemical energy of gases (**H_2** or **CH_4**) are supposed not to be modified by the compression

* CO_2 extraction energy losses

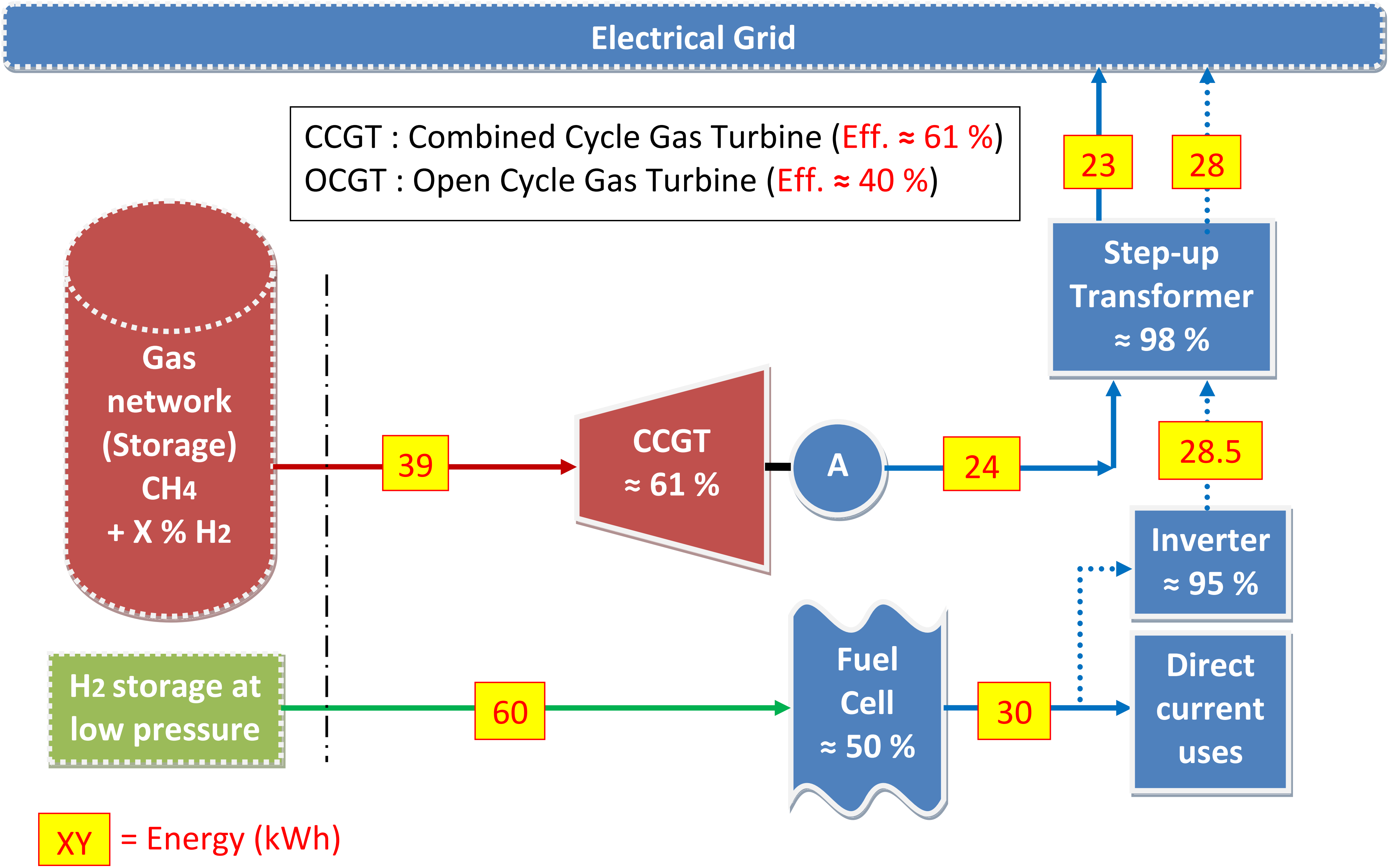
CO_2 is supposed to be extracted in post-combustion mode in the exhaust fumes of fossil fuel fired plants by means of an amine solvent (which is the **least energy intensive** process). Based on various references, this mode of **CO_2** extraction requires **≈ 0.6 kWh / Nm3**. Thus, for **5 m3 of CO_2 :** 0.6 x 5 **≈ 3 kWh**

* Recapitulation of additional electrical consumptions

Power to gas scheme	Process Efficiency	Additional electrical consumptions in kWh (1)
Power to Hydrogen (**Low** pressure)	≈ 60 %	**≈ 0**
Power to Hydrogen (**High** pressure)	≈ 60 %	**≈ 4.8**
Power to Methane (**High** pressure)	≈ 39 %	[4.8 + 1.2 + 3.0 + 0.8] **≈ 9.8**

(1) For gas compression (H_2, CO_2 and CH_4) & for CO_2 extraction from fumes

3.2 – "Gas to power" energy losses (2nd part)



3.3 – Global "Power to gas to power" energy losses

*** Global energy efficiency in operational functioning conditions**

Power to gas to power scheme	Global Efficiency in optimal constant conditions (1)	Global Efficiency in real variable conditions (2)
Power to **Hydrogen** to power (**Low** pressure)	**≈ 28 %**	≈ 28 x 0.85 to 0.9 **≈ 24 to 25 %**
Power to **Methane** to power (**High** pressure)	24 ÷ 109.8 **≈ 22 %**	≈ 22 x 0.85 to 0.9 **≈ 19 to 20 %**

(1) : stable conditions close to the optimal functioning regime.

(2) : variable regimes, far away from nominal conditions, especially during frequent starts and stops + wide amplitude transients required by the use of intermittent electricity. Given the lack of any feedback experience from such installations, only analogies with various other industrial processes can be used, that show additional losses up to 10 to 15 %.

*** Conclusion**

Based on the present state of technologies, global Efficiency of "Power to gas to power" is very low. As an order of magnitude and depending on the scheme :

Destocking 1 kWh requires using from ≈ 4 to 5 kWh !

4 – Which research in progress or envisaged to reduce energy losses ?

4.1 – For the main physical processes : Electrolysis & Methanation

*** Expected improvements in Electrolysis technologies and associated Efficiency and limits :**

Electrolysis technologies ➔	Improved alkaline (current) process	Proton Exchange Membrane (PEM)	Solid Oxide Electrolyser Cell (SOEC)
Efficiency obtained or expected (R&D)	≈ 79 %	≈ 84 %	Up to 90 % or... more ?
Main technical limits	* **Slow dynamic response** (However in improvement) * Use of **dangerous corrosives** products (KOH or NaOH)	* **Short lifespan** (In improvement) * Use of **rare metals** (Platinum or Iridium) * **Low unitary power**	* **Limited lifespan** (High temperatures accelerate corrosion) * Not well adapted for **intermittent ratings** * Still **very far** from the industrial stage

➔ **Average Efficiency retained for future electrolysis process by around 2030 ≈ 85 %**

To be noted : Efficiency of **Fuel cells**, that use the **inverse process of electrolysis**, will also be improved. Expected improvement up to **≈ 60 %** (Assumption)

*** Expected improvements in Methanation Efficiency (Improved current process) ≈ 80 %**

4.2 – R&D for the other physical processes : mature technologies

* Combined Cycle Gas Turbine (CCGT)

CCGT global efficiency mainly depends on the hot temperatures reached in the Gas Turbine according to Carnot Efficiency ➔

$$\text{Carnot Efficiency} = \frac{[T \text{ hot source} - T \text{ cold source}]}{T \text{ hot source}}$$

Hot temperature in GT **(° C)**	Maximum present ≈ **1 450**	Expected in a short time **≈ 1 600**
Carnot theoretical efficiency	≈ 82 %	≈ 83.5 % (+ 1.5 %)
CCGT effective efficiency (1)	≈ 61 %	≈ 62 to 63 % (+ 1 to 2 %)

(1) For the most efficient CCGT existing today, built by GE Company

* Other components (electrical and mechanical)

Components	Present efficiency	Expected efficiency improvements
Step-up & Step-down Transformers	> 97 %	≈ + 1 %
Rectifiers & Inverters	≈ 95 %	≈ + 1 to 2 %
Compressors	≈ 90 %	≈ + 1 to 2 %

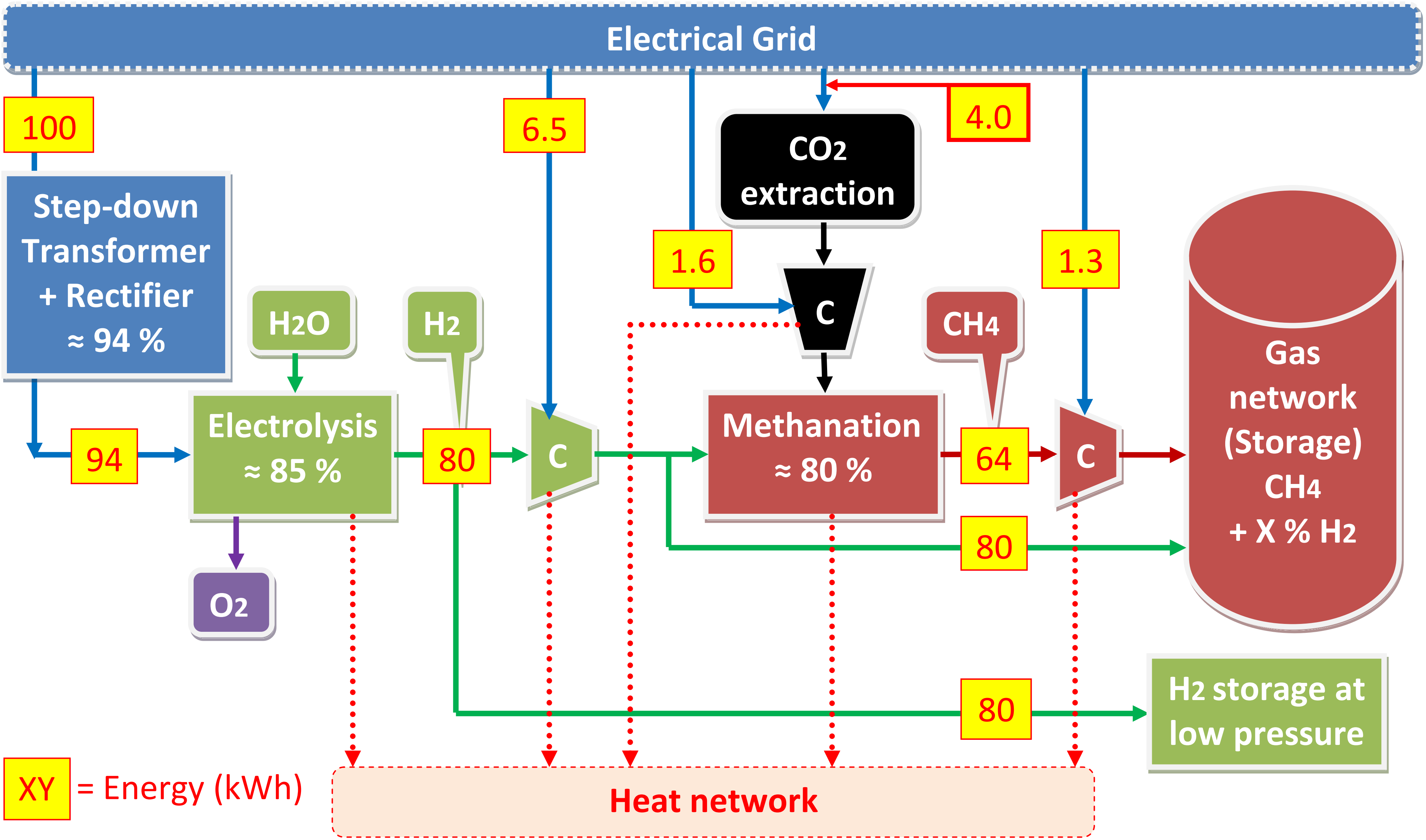
* Conclusion

Expected Efficiency improvements on mature technologies are limited to a few percents

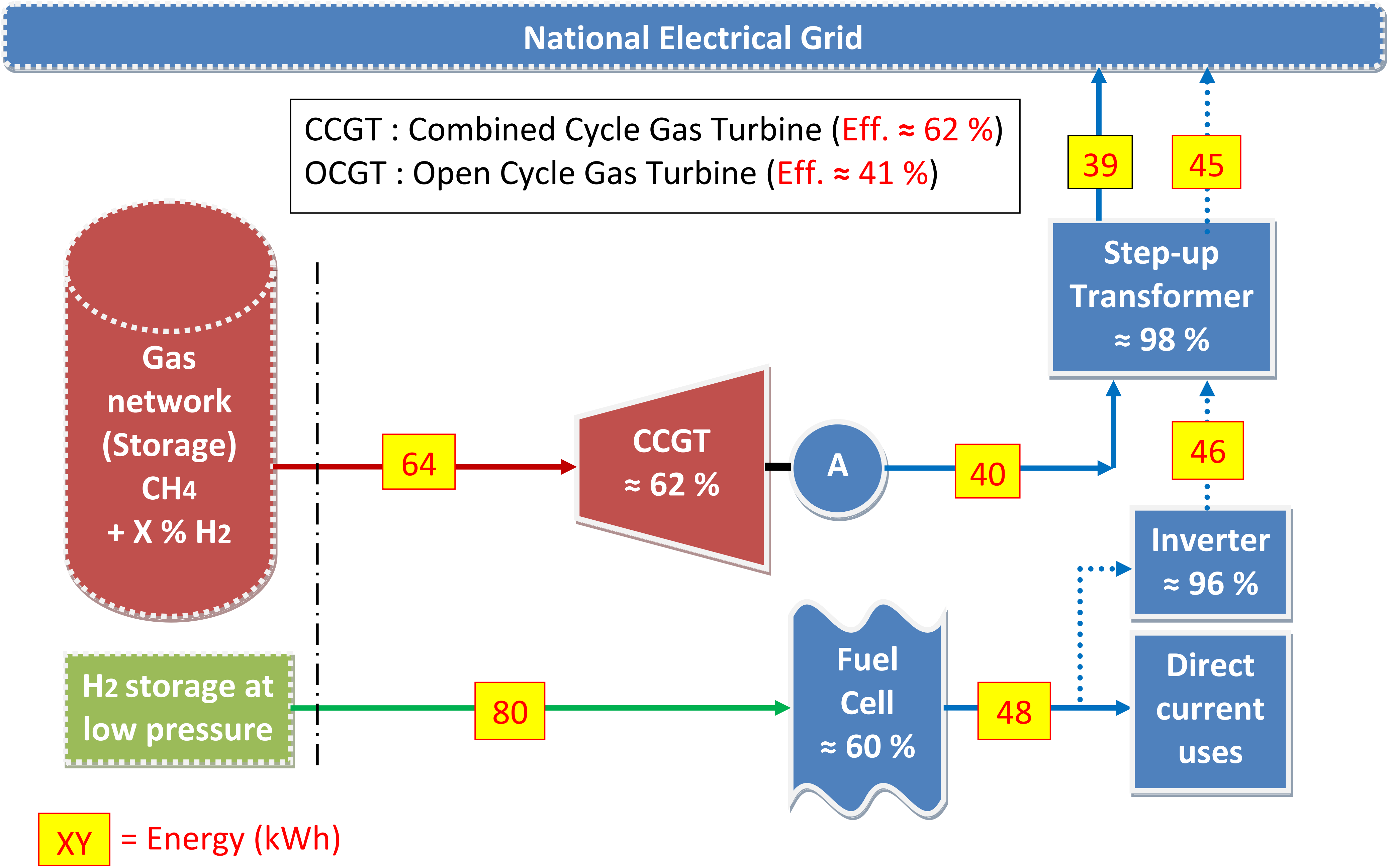
(Tentatively ≈ 3 to 5 % maximum, except in case of unforeseeable technological rupture)

4.3 – Expected global reduction of losses after R&D improvements

Improved "Power to gas" Efficiency



Improved "Gas to power" Efficiency



Improved "Power to gas to power" global Efficiency
Comparison with other studies

*** Global expected energy efficiency after R&D improvements taking into account real operational functioning conditions**

Power to gas to power scheme	Global Efficiency in optimal constant conditions	Global Efficiency in real variable conditions
Power to **Hydrogen** to power (**Low** pressure)	**≈ 45 %**	≈ 45 x 0.85 to 0.9 **≈ 38 to 41 %**
Power to **Methane** to power (**High** pressure)	39 ÷ 113.4 ≈ **34 %**	≈ 34 x 0.85 to 0.9 **≈ 29 to 31 %**

*** Comparison with other studies (Future ≈ by 2030)**

Scheme ➔	**Power ➔ H_2 ➔ Power**	**Power ➔ H_2 ➔ CH_4 ➔ Power**
This study	Today ≈ 23 to 24 % Future ≈ **38 to 41 %**	Today ≈ 19 to 21 % Future ≈ **29 to 31 %**
Fraunhofer Institute	Future ≈ **34 to 44 %**	Future ≈ **30 to 38 %**

*** Conclusion**

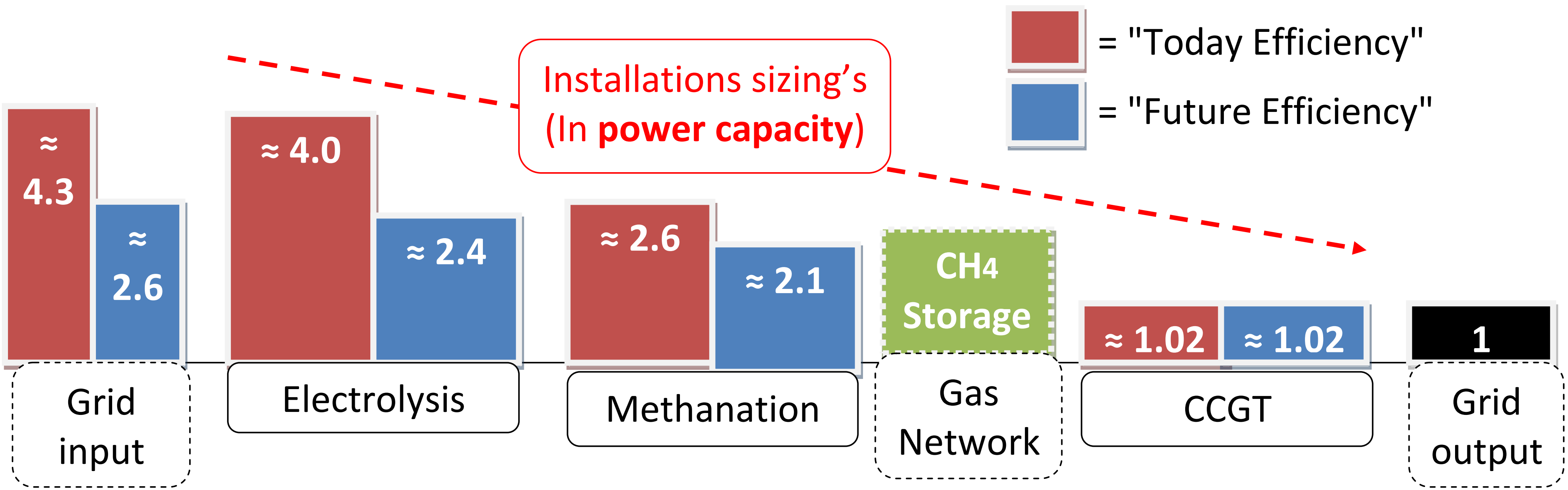
Even after expected improvements (that are not certain…) and depending on the scheme :

Destocking 1 kWh will still require using from ≈ 2.5 to 3 kWh !

5 – Industrial and economic consequences

5.1 – Sizing's of industrial installations

*** Sizing's of installations for the "Methanation scheme"**



*** Root causes of the massive energy losses of the "Methanation scheme", that result in over-sizing of the installations :**

° **Insufficient Efficiency of the main transformations** (Electrolysis, Methanation and CCGT)

° **Too many successive physical transformations** (Up to 7 !)

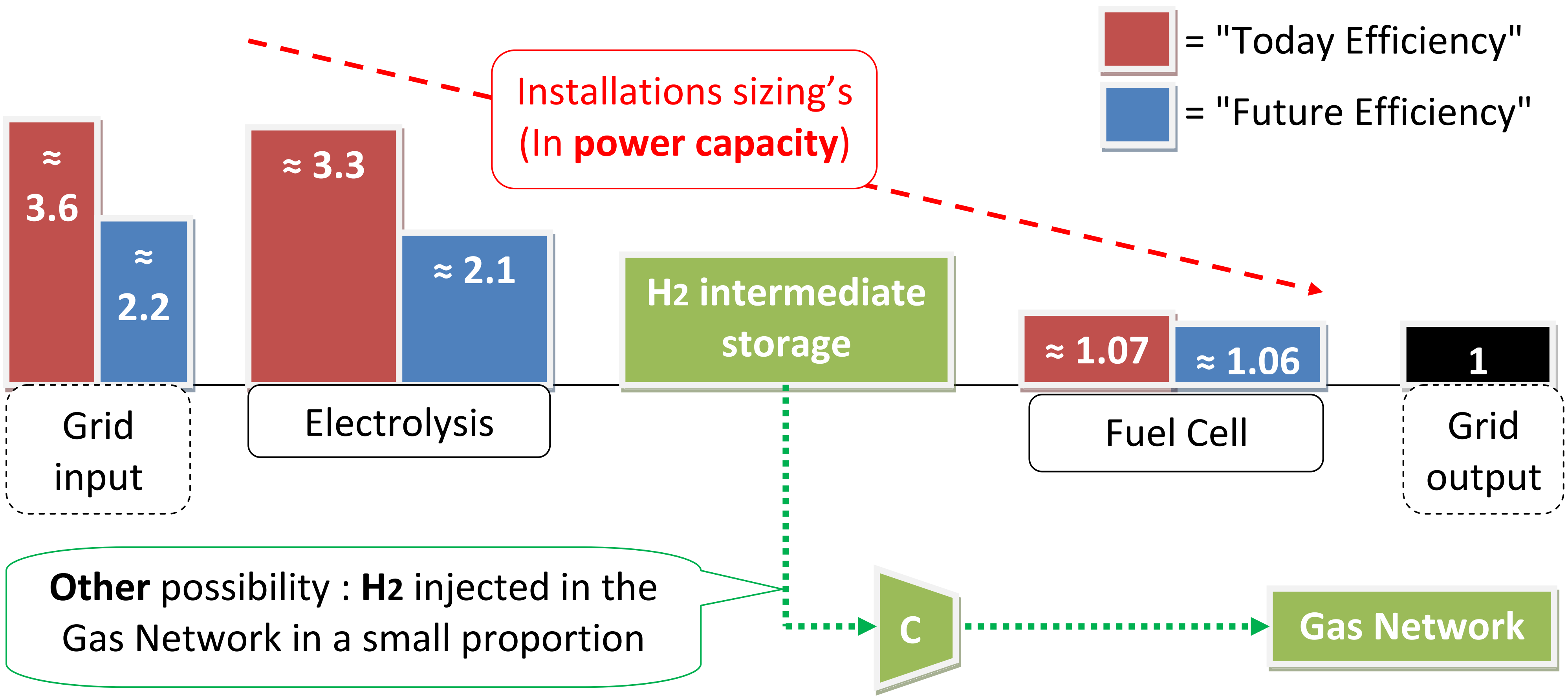
° **Too many additional energy losses** (3 for gas compressions + 1 for CO_2 extraction)

5.1 – Sizing's of industrial installations (Continuation)

*** Sizing's of installations for the "Hydrogen scheme" with minimization of auxiliary energy losses :**

° **Only two main inverse transformations**

° **Minimization of auxiliary energy losses : avoiding compression losses** (through **metal hydrides** storage solution) except if directly injected in the Gas Network.



5.2 – An economic model very difficult to balance…

CAPEX of the "chain" of physical transformations : "Power to gas" part

Methanation scheme →	Electrolysis	Methanation	TOTAL
Unitary CAPEX in € / Installed kW	≈ 1,000 (1)	≈ 1,000	-
Number of installed kW (Today Efficiency)	4.0	2.6	-
Global CAPEX of the "chain" (Today Efficiency) (For 1 kW capacity at the grid output)	4,000	2,600	≈ 6,600
Number of installed kW (Future Efficiency)	2.4	2.1	-
Global CAPEX of the "chain" (Future Efficiency) (For 1 kW capacity at the grid output)	2,400	2,100	≈ 4,500

Hydrogen scheme →	Electrolysis	Gas storage	TOTAL
Unitary CAPEX in € / Installed kW	≈ 1,000 (1)	(2)	-
Number of installed kW (Today Efficiency)	3.3	-	-
Global CAPEX of the "chain" (Today Efficiency) (For 1 kW capacity at the grid output)	3,300	-	≈ 3,300
Number of installed kW (Future Efficiency)	2.1	-	-
Global CAPEX of the "chain" (Future Efficiency) (For 1 kW capacity at the grid output)	2,100	-	≈ 2,100

(1) Today alkaline technology

(2) Intermediate storage of gases is considered here as free of charges in order to simplify

5.2 – An economic model very difficult to balance…

CAPEX of the "chain" of physical transformations : "Gas to power" part

Methanation scheme →	CCGT	TOTAL
Unitary CAPEX in € / Installed kW	≈ 1,100	-
Number of installed kW **(Today Efficiency)**	1.02	-
Global CAPEX of the "chain" **(Today Efficiency)** **(For 1 kW capacity at the grid output)**	1,120	**≈ 1,100**
Number of installed kW **(Future Efficiency)**	1.02	-
Global CAPEX of the "chain" **(Future Efficiency)** **(For 1 kW capacity at the grid output)**	1,120	**≈ 1,100**

Hydrogen scheme →	F. Cell	TOTAL
Unitary CAPEX in € / Installed kW	≈ 1,400	-
Number of installed kW **(Today Efficiency)**	1.07	-
Global CAPEX of the "chain" **(Today Efficiency)** **(For 1 kW capacity at the grid output)**	1,498	**≈ 1,500**
Number of installed kW **(Future Efficiency)**	1.06	-
Global CAPEX of the "chain" **(Future Efficiency)** **(For 1 kW capacity at the grid output)**	1,484	**≈ 1,480**

(1) Today alkaline technology

5.2 – An economic model very difficult to balance… (Continuation)
Simplified Business Plan for integration in the electricity market

*** Assumptions** :

° Installation's lifespan ≈ **20 years** – Interest rate ≈ **2 %** – Annual OPEX ≈ **5 % of annual CAPEX**

° **Annual load factor rough estimates** (at equivalent full capacity) **:**

- **For input electricity : ≈ 20 %** or **≈ 1,750 hours / year (Intermittent electricity SURPLUS ONLY)**
- **For output electricity : ≈ 4 %** or **≈ 350 hours / year (Peak-demand conditions ONLY)**

*** CAPEX + OPEX amortization :**

Amortization base ➔		**Annual** CAPEX + OPEX by **installed output kW** (€/kW/year)	CAPEX + OPEX by **SOLD kWh** (1) (c€/kWh)
Methanation scheme	**Today Efficiency**	**≈ 420 + 70 = 490**	**≈ 24 + 20 = 44**
Methanation scheme	**Future Efficiency**	**≈ 290 + 70 = 360**	**≈ 17 + 20 = 37**
Hydrogen scheme	**Today Efficiency**	**≈ 210 + 96 = 306**	**≈ 12 + 27 = 39**
Hydrogen scheme	**Future Efficiency**	**≈ 135 + 95 = 230**	**≈ 8 + 27 = 35**

(1) **1,750 hours / Year** for "Power to gas" & **350 hours / Year** for "Gas to Power"

5.2 – An economic model very difficult to balance… (Continuation)
Simplified Business Plan

*** Other costs by SOLD kWh :**

Selling 1 kWh requires buying from 5 to 2.5 kWh's (according to the scheme) which implies to pay :

° The buying price for 5 to 2.5 kWh's input electricity from the market, when its price is sufficiently low (< 2 c€/kWh by hypothesis)

° The Grid transportation tariffs and taxes for 5 to 2.5 kWh's (up to ≈ 4 c€/kWh now)

*** Total cost by SOLD kWh :**

Cost breakdown / Efficiency	CAPEX + OPEX by **output** kWh **(c€/kWh)**	Number of kWh's to be bought	**T**ransportation tariff + **B**uying costs of **input** kWh's **(c€/kWh)**	**Minimum** total **cost of SOLD** kWh's **(c€/kWh)**
Methanation scheme				
Today ≈ 20 %	**≈ 44**	**≈ 5**	**T ≈ 20 + B < 10**	**Up to ≈ 74**
Future ≈ 30 %	**≈ 37**	**≈ 3.3**	**T ≈ 13 + B < 6.6**	**Up to ≈ 57**
Hydrogen scheme				
Today ≈ 25 %	**≈ 39**	**≈ 4**	**T ≈ 16 + B < 8**	**Up to ≈ 63**
Future ≈ 40 %	**≈ 35**	**≈ 2.5**	**T ≈ 10 + B < 5**	**Up to ≈ 50**

5.2 – An economic model very difficult to balance… (Continuation)

*** FOUR conditions that should be met to have a chance to balance the economic model :**

° **Reduce Grid transportation tariffs and taxes for electricity dedicated to storage**

° **Buy the largest part of input electricity at very low prices (If possible close to 0 and in any case < 2 c€/kWh) during surplus conditions**

° **Sell the largest part of output electricity at the highest prices occurring during peak-demand conditions**

° **Buy & sell enough electricity to amortize fixed charges of installations**

*** Are such conditions met ?**

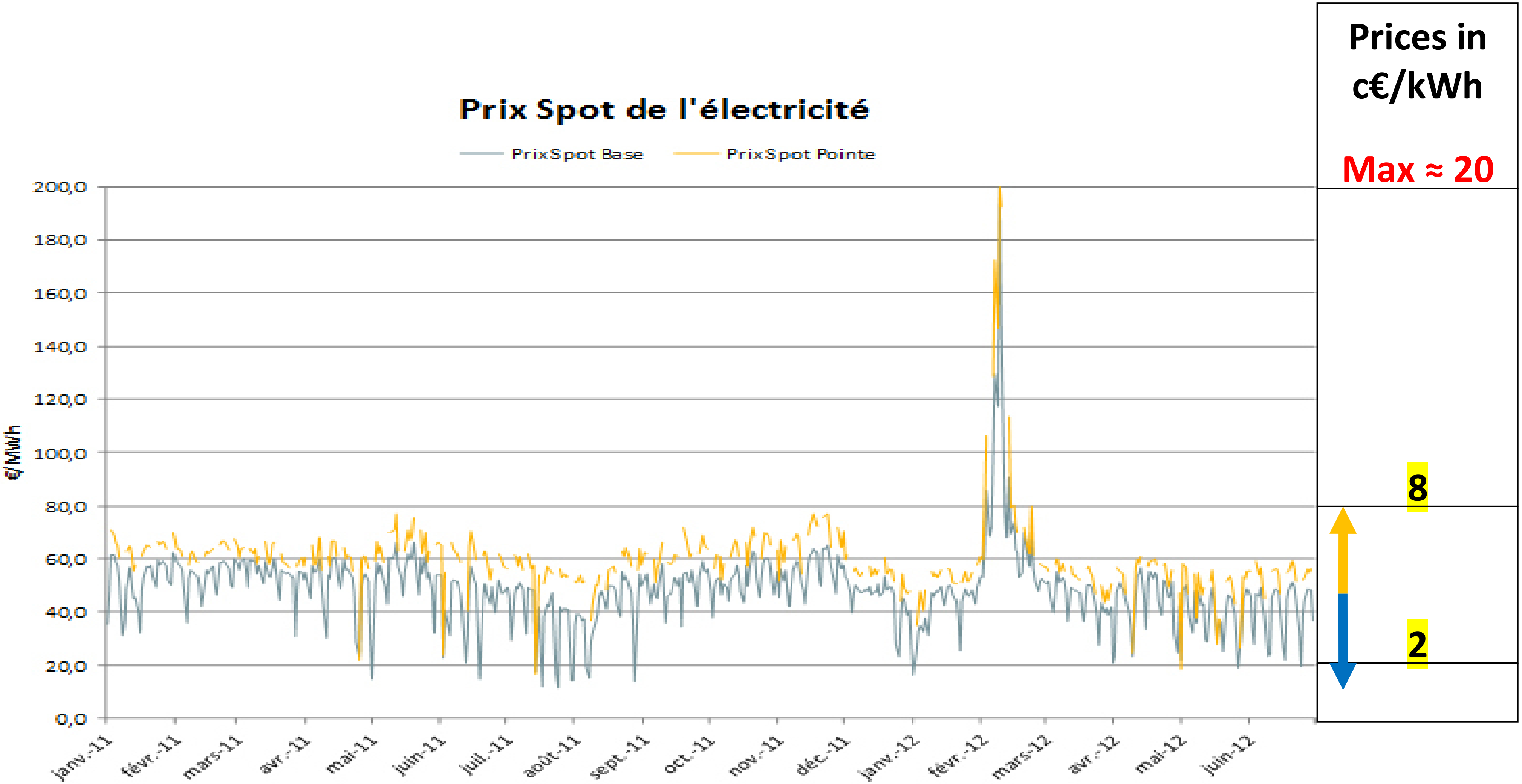
The answer is in the electricity prices on the spot market in present conditions (next slides) which clearly show that :

° **Even in ultra-peaks electricity demand conditions (case of February 9th, 2012) the spot prices remain below 25 c€/kWh**

° **Most of the spot prices evolve from about 1 to 8 c€/kWh (Recent trend : a severe fall of market prices : average < 3 c€/kWh) → Not sustainable for the European electric system !**

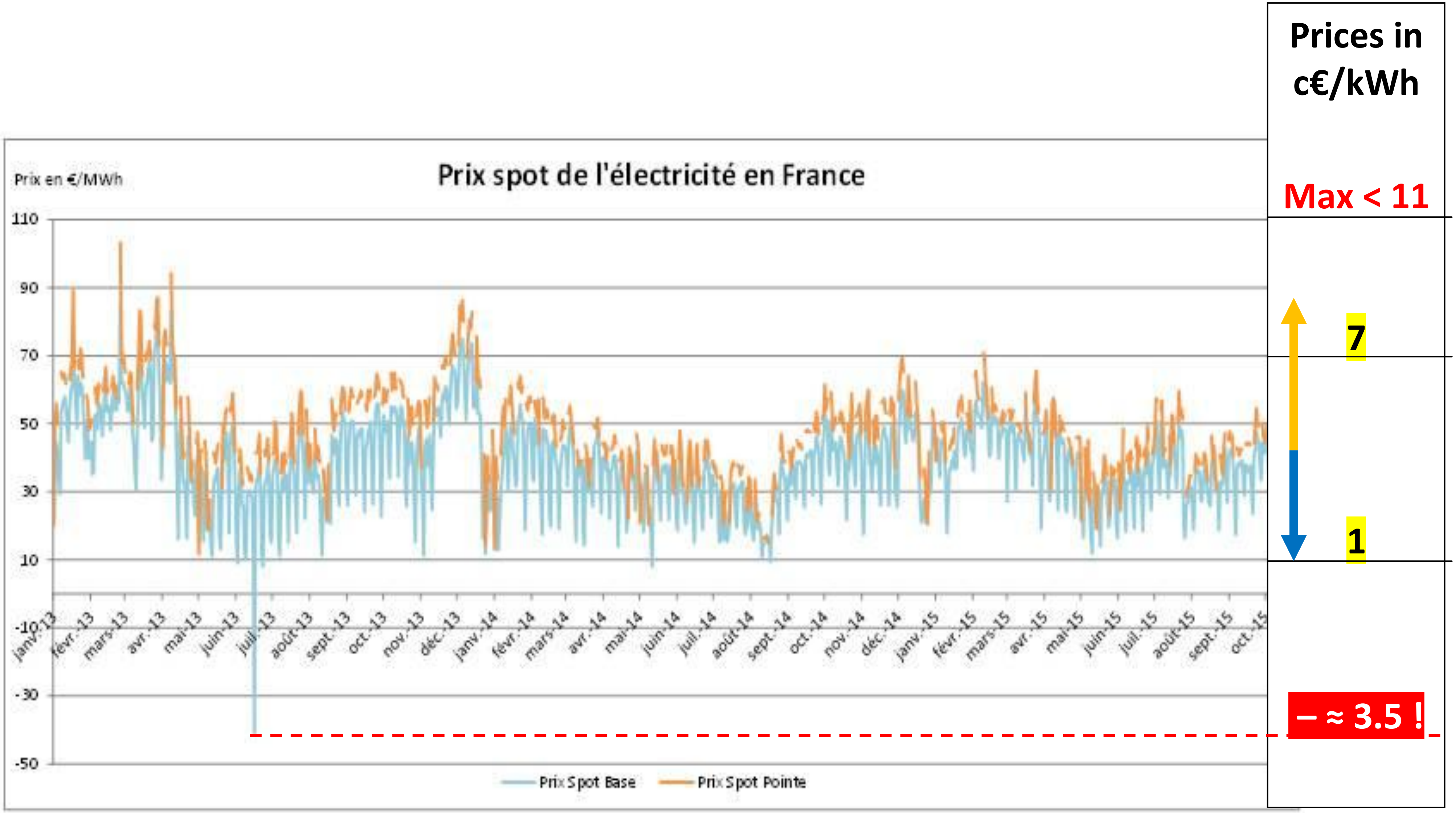
→ **The economic model cannot match market conditions today !**

5.2 – An economic model very difficult to balance… (Continuation)
Electricity prices on the spot market (From January 2011 to June 2012)



Blue line = base spot price – Yellow line = peak spot price (Source : RTE)

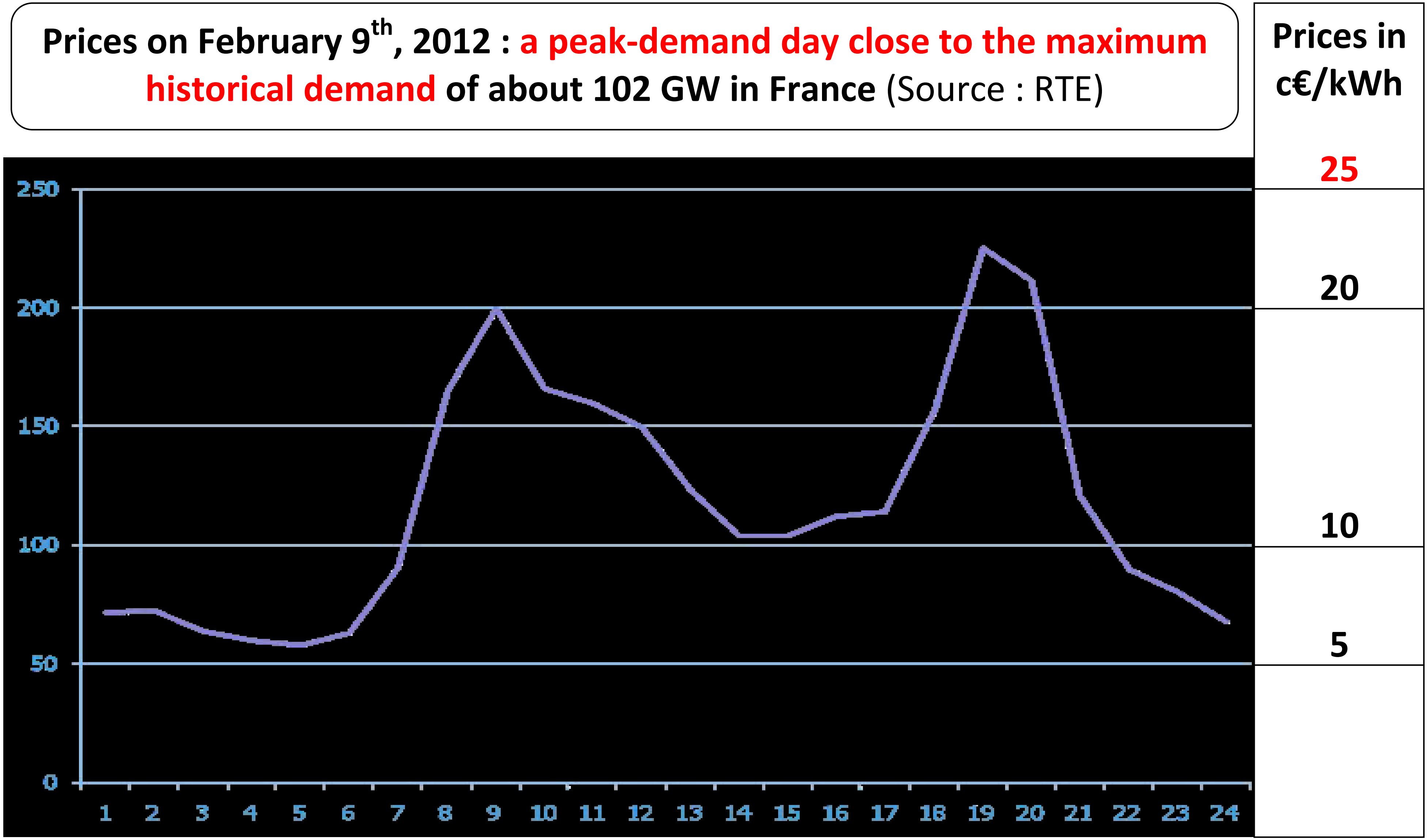
5.2 – An economic model very difficult to balance… (Continuation)
Electricity prices on the spot market (From January 2013 to October 2015)



Blue line = base spot price – Yellow line = peak spot price (Source : RTE)

5.2 – An economic model very difficult to balance... (Continuation)
Electricity prices on the spot market (On a peak-demand day)

Prices on February 9th, 2012 : a peak-demand day close to the maximum historical demand of about 102 GW in France (Source : RTE)



6 – Which R&D priorities for which best scheme ?

*** The best scheme : Hydrogen one**

Beyond the extremely low load factor which increases the CAPEX per installed output kW in both cases, the Hydrogen scheme has two particular weak points :

° Its use implies greater difficulties : specific storages, increased risks of leakages and their potential consequences : explosions and/or fires (➔ Additional safety cautions)

° The Fuel cells have a rather high CAPEX

° BUT it is less complex and more Energy Efficient than the Methanation scheme

° And R&D improvement are expected for both Electrolysis & Fuel Cells performances

*** Two major targets for R&D improvements :**

MAJOR REDUCTION of Energy losses	+	MAJOR REDUCTION of CAPEX
° New designs, process improvements & optimization, **heat recuperation**, etc. ° Energy losses reduction during **variable regimes** (flexibility improvements) **Target : Reach an Energy Efficiency of at least 40 % in variable regimes**		° Minimization of **expensive materials** use (such as platinum or iridium) in **Electrolysers & Fuel Cells** ° Miscellaneous other CAPEX reductions **Target : Divide the present [CAPEX + OPEX] per installed kW by at least 2 to 3**

7 – Other conditions for a possible future

*** Industrial contribution to costs reductions & validations :**

° **Costs reductions** through usual **industrial tools** (Optimization, productivity, series effects, etc.)

° **Construction of pilot installations at industrial scale to get real experience feedback** in order to **calibrate real performances and costs** (Several demonstrators are now in progress in Europe, but for very limited scales : << 1 MW for most of them)

*** Integration as an energy storage tool in electrical networks :**

Two very different cases

Integration in widely interconnected electrical networks
(Ex : Europe)

Integration in electrical networks NOT interconnected
(Ex : isolated islands)
or
Integration in electrical systems without (real) network
(Ex : undeveloped countries)

7 – Other conditions for a possible future (Continuation)

*** Comparison of integration cases** :

Case	Interconnected networks	Isolated networks (1) or no network (2)
Level of competition of storage solutions with : ° Grid transportation ° Direct production means of electricity	 Very high (3) Possibly high	 Optimized (1) or null (2) Optimized (1) or null (2)
Level of electricity prices (average)	Low /Very Low	High /Very high
Cost impact of Grid transportation tariffs & taxes for electricity dedicated to storage	Very high	Optimized (1) or null (2)
Market conditions : available quantities of electricity for : ° Purchase at very low prices ° Sale at very high prices	Unpredictable !	No market = integration and optimization of use of all the means → Higher load factor
→ Level of investors' risks	Extremely high	Limited & more foreseeable

(3) Grid transportation is by far less costly than storage solution

7 – Tentative conclusion

As an energy storage solution "Power to gas to power" suffers of :

* Very important energy losses

* Very high consequential costs

* Very important difficulties to match electricity market conditions

However :

* It's integration in isolated networks or in local electrical systems without networks may make sense depending on local conditions. But even there, it will be in competition with other energy storage technologies…

* Keeping only the "Power to gas" stage may also be meaningful for other uses (cogeneration, mobility)

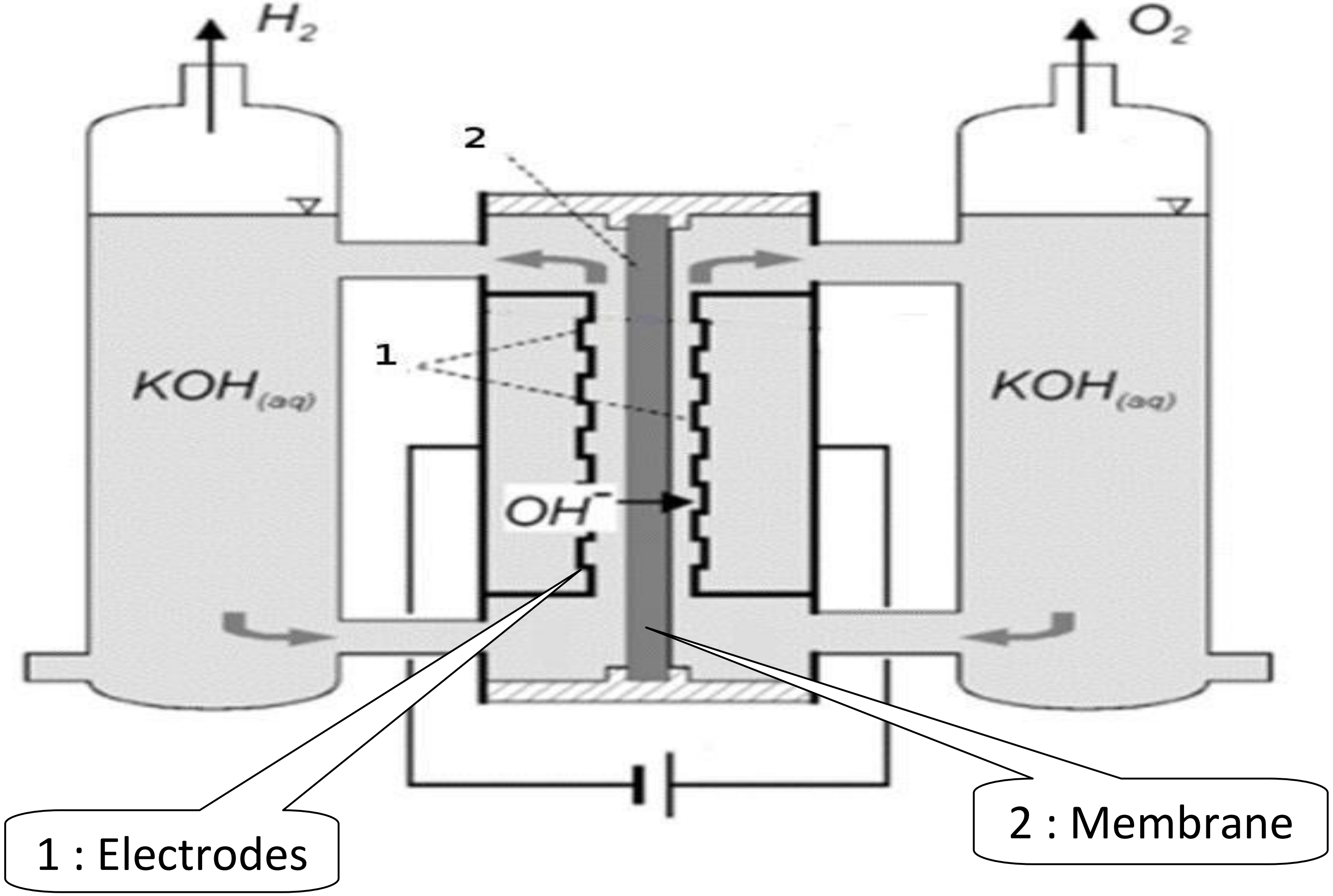
➔ In any case, its future seems to be limited, however subject to results of R&D improvements & Experience feedback

THANK YOU FOR YOUR ATTENTION

Appendix
Simplified schemes of existing electrolysis processes

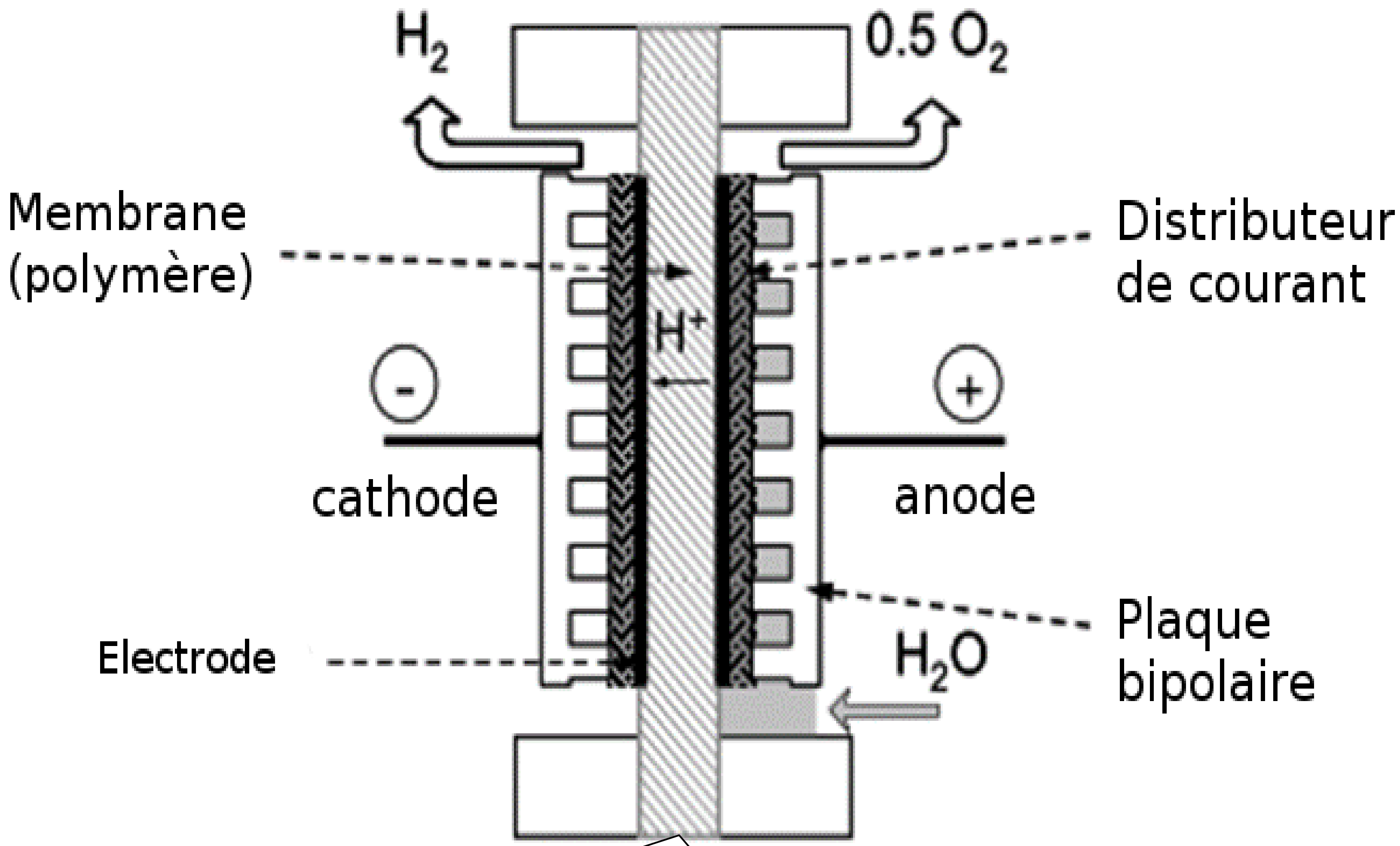
1 - Alkaline (current) scheme

(Low temperature + Low to medium pressure : 1 to 10 / 30 bars)



2 - Proton Exchange Membrane (PEM) scheme

(Low temperature [< 80 ° C] + Low-pressure process)



Semi permeable membrane (polymer electrolyte) designed to conduct protons only (but not gases such as hydrogen or oxygen)

3 - Solid Oxide Electrolyser Cell (SOEC) scheme

(High temperature + High-pressure process)