FAR OFF-SHORE WIND ENERGY-BASED HYDROGEN PRODUCTION: TECHNOLOGICAL ASSESSMENT AND MARKET VALUATION DESIGNS

M. Woznicki, G. Le Solliec, R. Loisel

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- MHyWind Overview
- Components Models Overview
- Case Studies
- Future work
- Questions ?

CONTEXT

- Offshore wind **capacity** is **increasing**, **turbines** are growing **bigger**, and **floating** technologies are on their way
- Going further offshore will unlock access to a **tremendous amount of energy**
- **Transmission** over long distances may be an **issue**

- **98%** of **H_2** is produced from **fossil** fuels => Production of **1 kg** emits **10 kg of CO_2** (for oil refining, ammonia and fertilizers production, metallurgy, etc...)
- H_2 is an **energy vector** and can provide, via **fuel cells** (+storage vessels), various **electrical services** : grid services, energy storage, mobility...
- When produced via **water electrolysis** with renewable energy sources, **orders of magnitude**:

H_2 Energy content (LHV)	33.3 $kWh.kg^{-1}$
Energy requirements (η = 0.6) for production	55.5 $kWh.kg^{-1}$
Compression energy for storage	350bar: 2.1 $kWh.kg^{-1}$ 700bar: 3.5 $kWh.kg^{-1}$

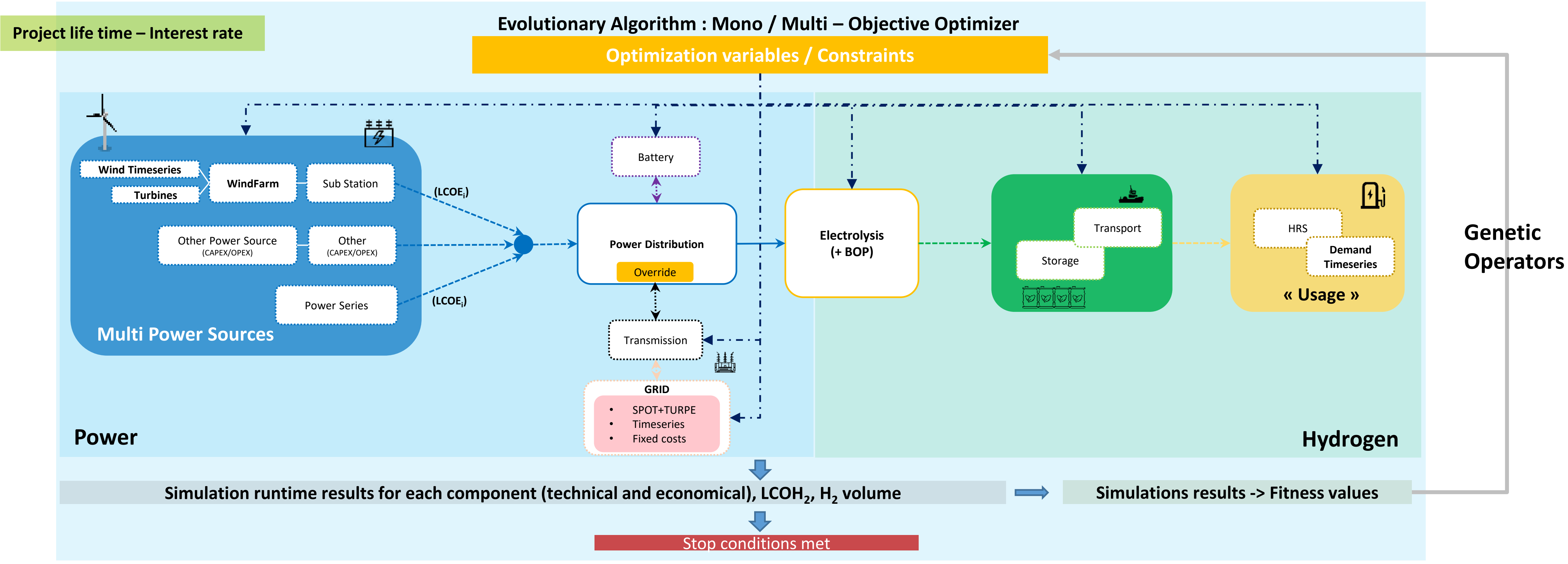
Exemple	**ICE (gasoline) car**	**Fuel cell car (H_2 from RE source)**
Fuel energy content	12.06 $kWh.kg^{-1}$	33.3 $kWh.kg^{-1}$
Engine efficiency	≈0.35	≈0.6 . 0.95 ($\eta_{FC} \cdot \eta_{EM}$)
Fuel consumption (100km)	5L / 3.68kg	1kg
CO_2 emissions (100km)	**≈10kg**	≈0g

How wind energy can be used to avoid these emissions ?

Can coupling of Hydrogen and Wind be mutually beneficial ?

- **Questions**:
    - How much H_2 can be produced with Offshore Wind ?
    - How to size the plants (OWF, water electrolysis system (WE)) and define their architectures?
    - What WE technologies could be used ?
    - What strategies and levers could help minimizing H_2 production costs ?

MHYWIND OVERVIEW



Project life time – Interest rate

Evolutionary Algorithm : Mono / Multi – Objective Optimizer

Optimization variables / Constraints

Wind Timeseries

Turbines

WindFarm

Sub Station

Other Power Source (CAPEX/OPEX)

Other (CAPEX/OPEX)

Power Series

Multi Power Sources

($LCOE_i$)

($LCOE_i$)

Battery

Power Distribution

Override

Transmission

GRID

- SPOT+TURPE
- Timeseries
- Fixed costs

Electrolysis (+ BOP)

Transport

Storage

HRS

Demand Timeseries

« Usage »

Power

Hydrogen

Genetic Operators

Simulation runtime results for each component (technical and economical), $LCOH_2$, H_2 volume

Simulations results -> Fitness values

Stop conditions met

$$LCoH_2 = \frac{CAPEX + \sum_{y=1}^{pl} \frac{OPEX_y}{(1+r)^y}}{\sum_{y=1}^{pl} \frac{H2_y}{(1+r)^y}} \quad [€.kg^{-1}]$$

Optimization/simulations results

SIZING, Min ($LCoH_2$), Volume, Production aligned to forecasted demand, etc...

COMPONENTS MODELS – OVERVIEW – WIND FARM

Offshore wind farm power

$$U_{HH}(z,t) = U_{z_0}(t).\left(\frac{z}{z_0}\right)^{\alpha} \quad [m.s^{-1}]$$

Wind Speed Correction (DAVENPORT)

$$P_T\left(U_{HH}(z,t)\right) = \delta + \frac{\alpha - \delta}{\left(\varepsilon + e^{(-\beta.(U-v_0))}\right)^{\frac{1}{\gamma}}} \quad [kW]$$

(6 parameters logistic function fit)

Turbine Output Power

$$P_{owf}\left(U_{HH}(z,t)\right) = Nb_T\,.P_T\left(U_{HH}(z,t)\right) \ [kW]$$

Wind farm Output Power

$capex(distance, P_{rated})\ [€]$

$opex(distance, capex, P_{rated})\ [€/y]$

Available models :

- LEANWIND 8MW reference offshore turbine
- MHI VESTAS 4.2MW offshore turbine
- NORDEX N90 2.5MW onshore turbine
- ENERCON E53 800kW onshore turbine

Offshore Substation

$$P_{substation}(t) = \eta\left(\frac{P_{owf}(t)}{P_{substation}^{rated}}\right).P_{owf}(t)\ [kW]$$

Substation Output Power

$capex(distance, P_{rated})\ [€]$

$opex(distance, capex, P_{rated})\ [€/y]$

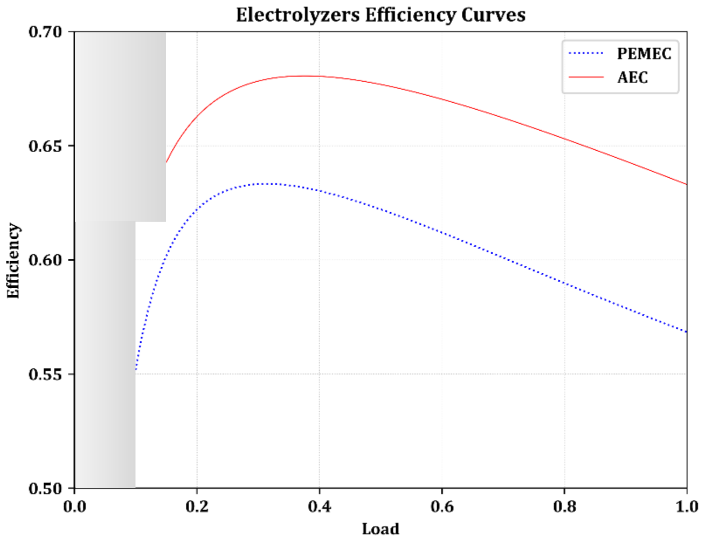
COMPONENTS MODELS – OVERVIEW – ELECTROLYZER

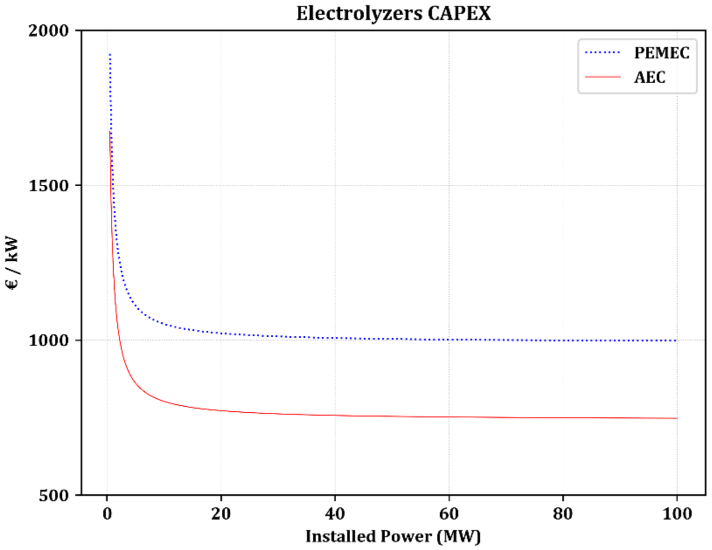
- Total electrolysis power P_{we}^{rated}
- Number of electrolyzers
- Electrolyzer technology
- $capex\left(distance, P_{we}^{rated}\right)$ [€]
- $opex\left(distance, capex, P_{we}^{rated}\right)$ $[€/y]$

Ageing (for efficiency degradation) is included and replacement costs are added to project OPEX

	AEC	PEMEC
Efficiency η	Cf. graph	Cf. graph
Working range (% nominal load)	15-100	10-100
Life time (kh)	60	50
Efficiency degradation (%/y)	0.01	0.015

$$\begin{cases} P_{we}^{out}(t) = P_{we}^{in}(t).\eta\left(\dfrac{P_{we}^{in}(t)}{P_{we}^{rated}}\right), P_{we}^{min} \le P_{we}^{in}(t) \le P_{we}^{max} \\ \dot{m}_{H2}(t) = \dfrac{P_{we}^{out}(t)}{LHV_{H2}} \end{cases}$$





COMPONENTS MODELS – OVERVIEW – H_2 STORAGE / COMPRESSION

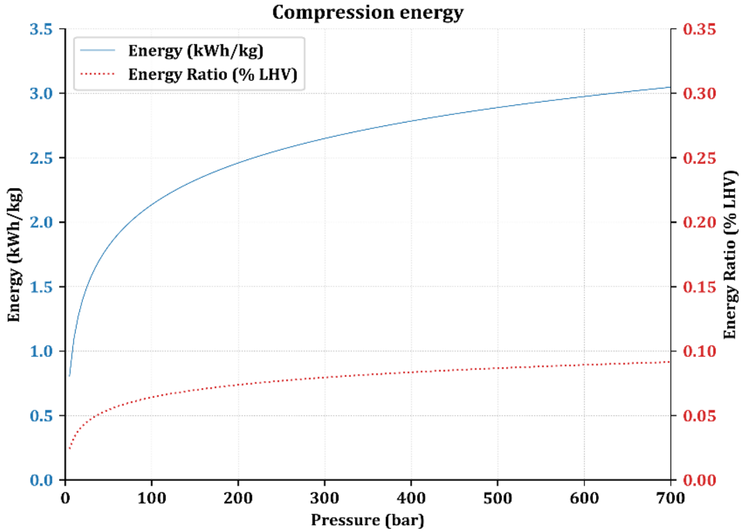
Storage is represented by:

- **Capacity** in tons,
- Cost (capex/opex) function of capacity,

2 types of storage implemented:

- Generic: energy required to store a kg of H_2 has to be provided: possibility to create any type of storage
- **Compressed**: required compression energy is derived from a compression energy curve, from a few bars to 700bars. Hence compressor rated power can be derived.

When storage capacity is fixed, the amount of vented hydrogen is recorded

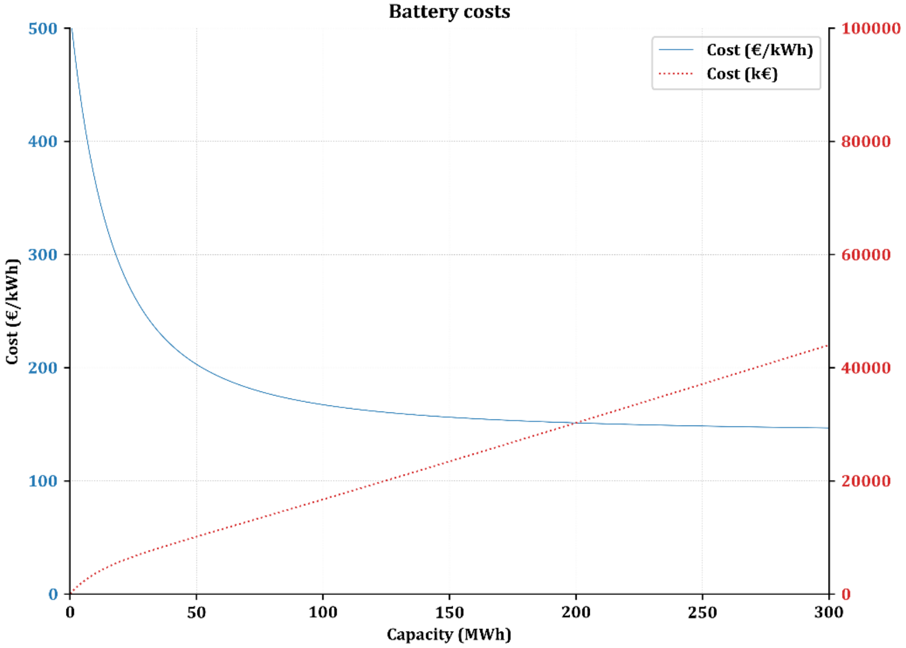


COMPONENTS MODELS – OVERVIEW – BATTERY

Battery **capacity** is a design variable

Battery parameters	Value
C-rate	2
Charge efficiency - $\boldsymbol{\eta_{charge}(load)}$	0.9
Discharge efficiency - $\boldsymbol{\eta_{discharge}(load)}$	0.95
Depth of discharge (% capacity)	0.8
Life expectancy (# of cycles)	3000
Efficiency loss over lifetime (%)	0.1

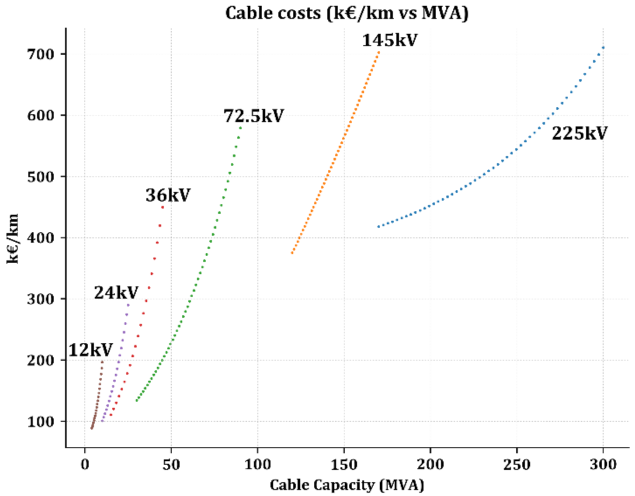
$$P_{max}^{discharge} = P_{max}^{charge} = C.capacity\ [kW]$$



COMPONENTS MODELS – OVERVIEW – OFFSHORE EXPORT CABLES

6 types of cables are defined within MHyWind, from 15MVA to 290MVA with the associated acquisition cost functions (€/m)

kV	Imax	MVA
12	1265	15.18
24	1265	30.36
36	1265	45.54
72.5	1265	91.712
145	1290	187.05
225	1290	290.02

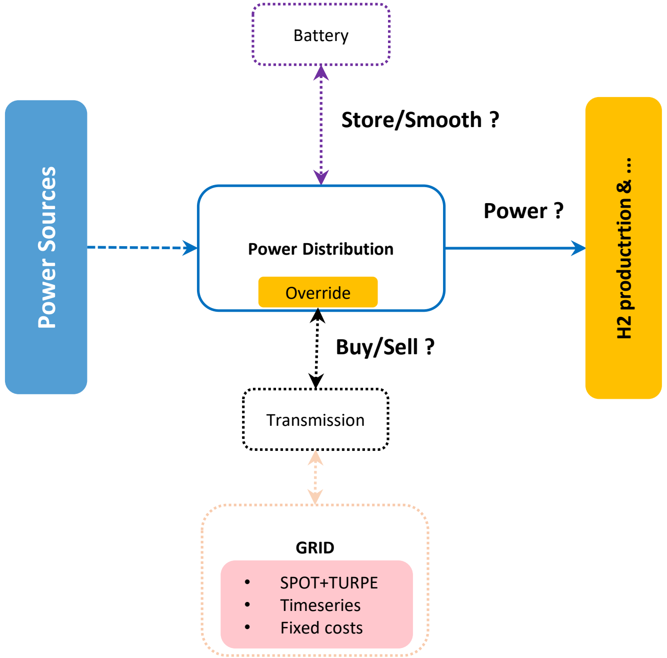


Cables **capacity** and **number** can be chosen, otherwise, the best configuration adapted to the wind farm rated power will be used.

Grid connection

- Electricity can be **sold** or **purchased** on the EPEX SPOT market, depending on power distribution heuristic and plant architecture
- Fees related to the use of the national electricity transport network (RTE in France) are computed as well (TURPE)

COMPONENTS MODELS – OVERVIEW – POWER DISTRIBUTION



Power distribution heuristic

Conditions	Distribution
$P_{owf} + P_{batt} < P_{we}^{min}$	P_{owf} is redirected sequentialy to the battery then to the grid, if applicable
$P_{we}^{min} \leq P_{owf} + P_{batt} \leq P_{we}^{max}$	All power available is used to feed the electrolysis system (wind + battery)
$P_{we}^{max} < P_{owf}$	Excess power is redirected to the battery, then to the grid, if available

CASE STUDIES

CS1: **Not Connected** - Offshore Wind Farm – **Offshore** Electrolysis

CS2: **Connected** - Offshore Wind Farm – **Offshore** Electrolysis

CS3: **Connected** - Offshore Wind Farm – **Onshore** Electrolysis

Optimization objective: minimizing $LCoH_2$
Provided with 2011 offshore wind speeds timeseries

Plants architecture & design variables

Case study ID	**CS1**	**CS2**	**CS3**
Hydrogen Production	**Offshore**	**Offshore**	**Onshore**
Grid connection / Export Cable	**No**	**Yes**	**Yes**
Number of turbines	50-100	50-100	50-100
P_{we} (MW)	$[0.1\text{-}1].P_{owf}$	$[0.1\text{-}1].P_{owf}$	$[0.1\text{-}1].P_{owf}$
Battery Capacity (MWh)	10-200	10-200	10-200
# Electrolyzers	1-5	1-5	1-5
Export Cable Capacity (MVA)	**-**	**$[0.1\text{-}1].P_{owf}$**	**P_{owf}**
Electrolyzers installation costs ratio	**1**	**1**	**1/3**

Common parameters

Project Life (y) / Interest Rate (%)	15 / 7
Hydrogen Storage Pressure	350bar
Turbine power (MW)	4.2
Turbine capex - €/kW	2880
Compressor efficiency	0.7
Export cable efficiency	0.96
Substation capex - €/kW	155
Substation installation costs - €/kW	41
Electrolyzer installation costs - €/kW	41

CASE STUDIES – OPTIMIZATION RESULTS

CS1: **Not Connected** - Offshore Wind Farm – **Offshore** Electrolysis

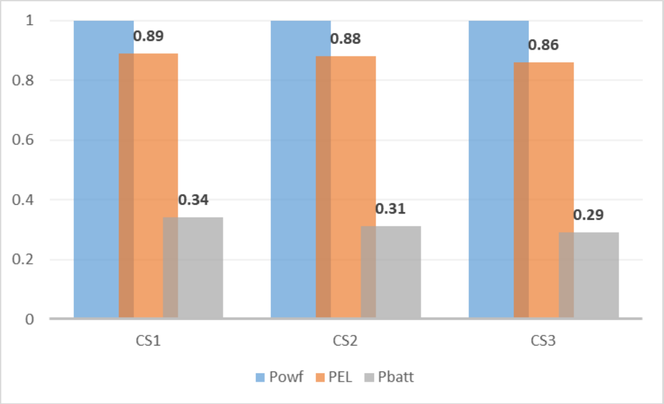
CS2: **Connected** - Offshore Wind Farm – **Offshore** Electrolysis

CS3: **Connected** - Offshore Wind Farm – **Onshore** Electrolysis

	CS1	**CS2**	**CS3**
Wind Farm Power (MW)	**420**	**420**	**420**
WE technology	**AEC**	**AEC**	**AEC**
Electrolyser Power (MW)	374	370	361
Number of electrolyser	**1**	**1**	**1**
Power Ratio (WE/OWF)	**0.89**	**0.88**	**0.86**
WE Capacity Factor	0.479	0.483	0.487
Battery Capacity (MWh)	71	65	61
Battery Power (MW)	142	130	122
Export Cable Capacity (MVA)	-	1x91.7MVA	2x290MVA
Energy transmitted to grid	-	0.3%	0.9%
LCoH2 (€/kg)	6.88	7.067	7.394
H2 Production (tons)	458372	4563332	**445929**
Energy Loss (% OWF output)	0.02%	0%	0%

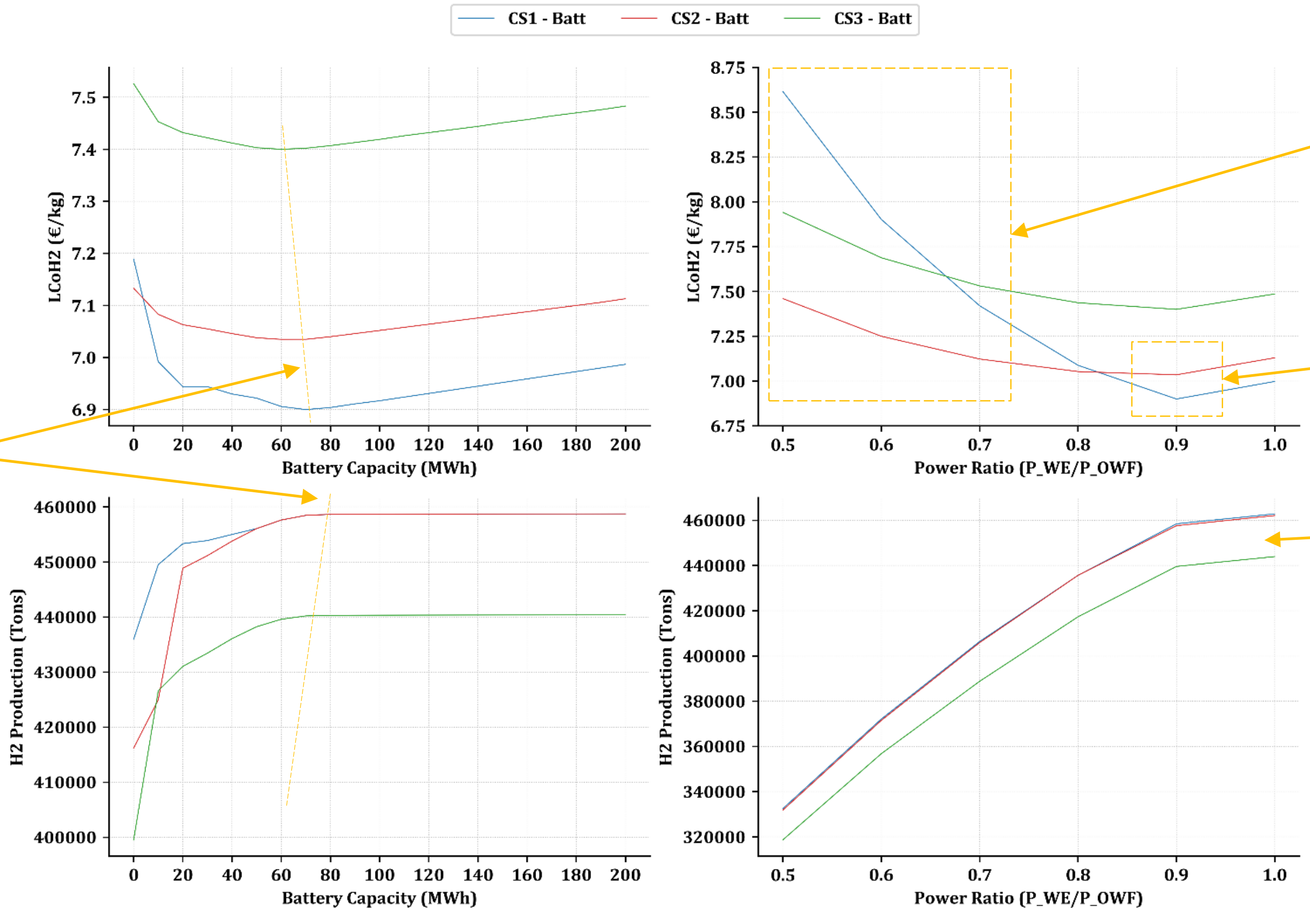
- OWF power reaches upper boundary in optimization (not constrained by demand or storage, tries to increase H_2 volume)
- Hydrogen production located offshore over-performs, but transportation costs are not included
- Alkaline technology (lower CAPEX, better efficiency) over-performs over PEM technology
- CS3 under-performs, it suffers from transmission costs and losses, however, **H_2 available onshore**
- Only one electrolyzer: battery has a cost advantage in absorbing excess energy

CS1 with transportation (vessel capacity: 20t, daily rate: 14k€, fuel cost: 0,6€/L): **7.45€/kg**



Results are only orders of magnitudes used to compare different architectures, depending on the hypothesis taken for this study.

CASE STUDIES – SENSITIVITY ANALYSIS – OWF 420MW



Battery presence offers better performances (volume, price), until optimal capacity is reached. After this point, maximum energy that can be absorbed by the system is reached: an increase in battery capacity is not necessary and increases $LCoH_2$

For the non connected case, $LCoH_2$ is more sensitive to energy losses, whereas connected case can sell excess energy to the grid, limiting $LCoH_2$ variation.

At optimal sizing in offshore production cases (CS1, CS2), CS1 is better than CS2: balance cost/gain of export cable presence and excess energy sale is not favorable.

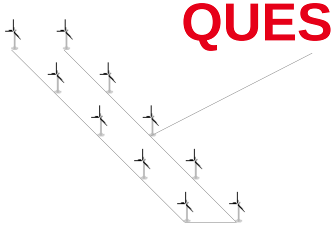
Onshore production suffers from transmission losses

- **CS1**: **Not Connected** - Offshore Wind Farm – **Offshore** Electrolysis
- **CS2**: **Connected** - Offshore Wind Farm – **Offshore** Electrolysis
- **CS3**: **Connected** - Offshore Wind Farm – **Onshore** Electrolysis

FUTURE WORK

- **Optimized power distribution** (perfect knowledge of wind speeds and electricity costs at given horizons (hours/days)): battery usage, electrolysis load, hydrogen production volume, electricity purchase costs and electricity sale revenues that finds the best trade-offs in power use
- Include electrolyzers **startup** times
- Optimal electrolyzer use and control
- Turbine **generator downsizing**: influences costs: turbines, substation and transmission

QUESTIONS ?



THANK YOU

Commissariat à l'énergie atomique et aux énergies alternatives
17 rue des Martyrs | 38054 Grenoble Cedex
www.cea-tech.fr

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