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Long-term optimization of hydrogen-electricity nexus

Blue, green or pink hydrogen?

Behrang Shirizadeh (Deloitte Economic Advisory - CIRED)
Philippe Quirion (CNRS – CIRED)

Motivation

- Electricity & hydrogen supply interdependent:
  - Electricity procurement = dominant part of hydrogen cost
  - Hydrogen consumption may saturate renewable energy potential
  - Hydrogen is a long-term storage option for renewable-based electricity systems
- French context
  - Zero GHG emission target by 2050 (French Energy Climate law, 2019).
  - French nuclear reactors will be all shut down by 2060 (RTE, 2021).
  - Several governmental and non-governmental organizations have recently published energy scenarios which have fueled the public debate (RTE 2021, Ademe 2022, négaWatt 2021).
  - Main differences: (1) Proportion of renewables vs. nuclear power in the electricity mix, (2) Amount of electricity consumption, (3) Amount of **Hydrogen**.
- Low-carbon hydrogen can be produced via **renewable electricity** (green hydrogen), **nuclear electricity** (pink/purple hydrogen), **reformation of methane with CCS** (blue hydrogen) and **methane pyrolysis** (turquoise hydrogen).

Questions adressed

1) What are the optimal low-carbon hydrogen production options for France?

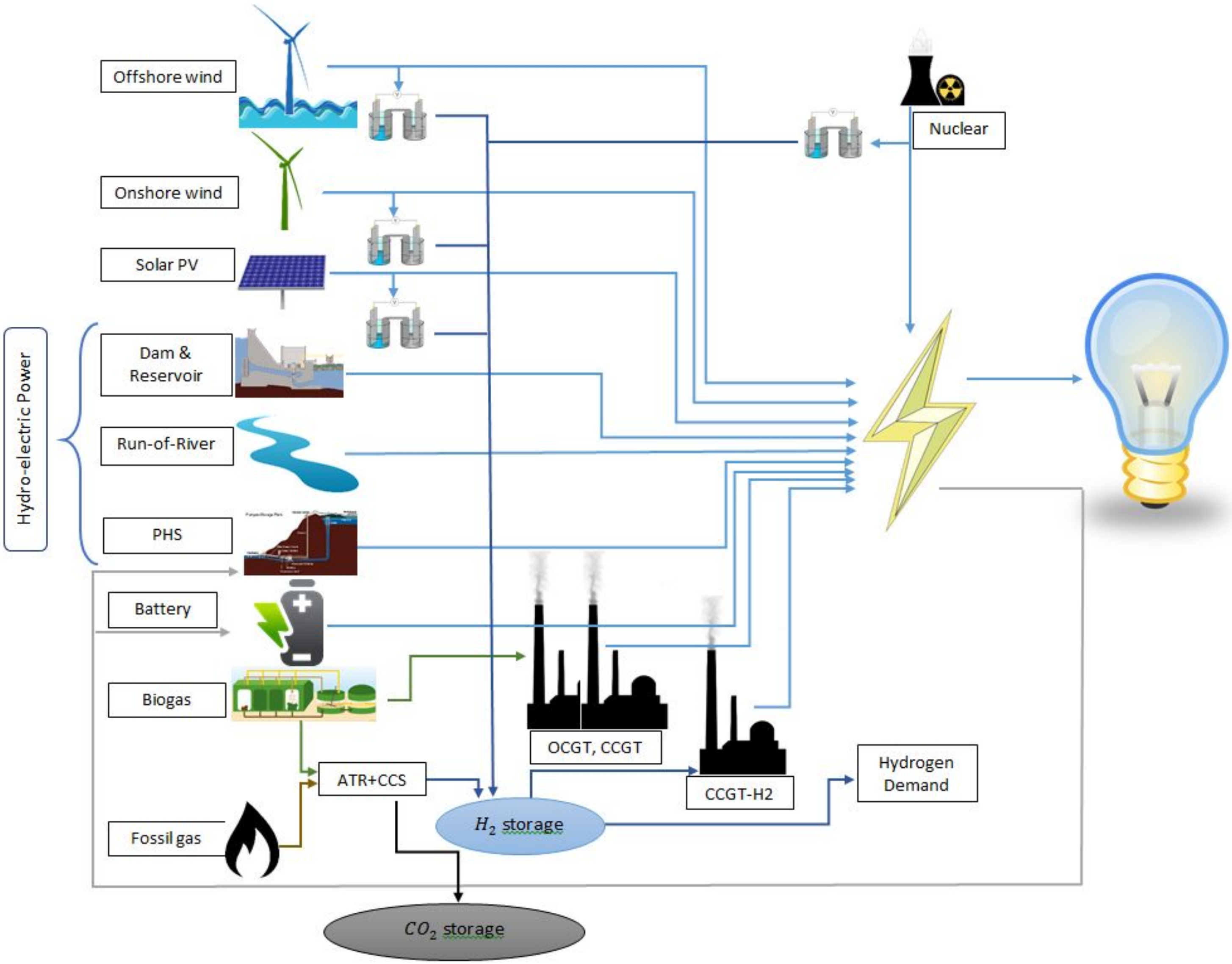
2) What is the quantity and the cost of the future low-carbon hydrogen market in France?

3) How does it impact the electricity mix?

Sensitivity analysis:

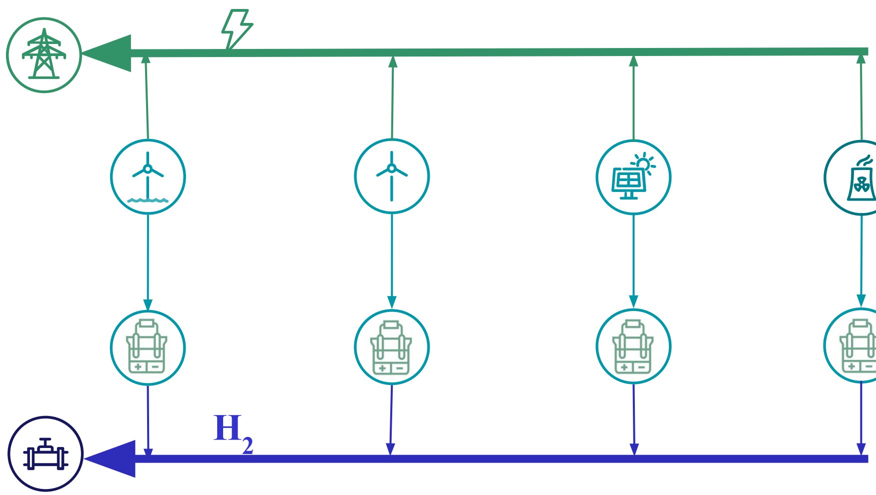
- Electrolyser cost
- Renewable potential
- Hydrogen demand
- Availability of CCS
- Cost of fossil gas

EOLES_elec_H_2



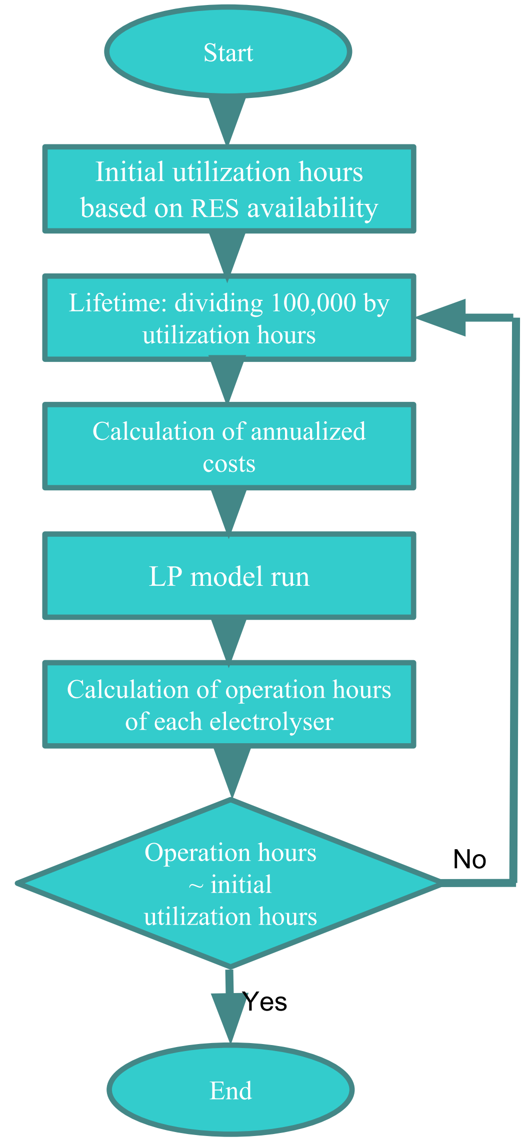
Modelling electrolysis

- Electrolysers are connected to electricity supply options.



- Electrolyser lifetime depends on the hours of utilization: 100,000-120,000 hours based on flexible or non-flexible utilization (IRENA, 2021).

- Iterative method to calculate the lifetime of electrolysers while linear programming:



APPLICATION

- Applied to continental France, for 2050.
- Historical weather data for VRE profiles; 2006 as representative weather year (previous study over 19 years: from 2000-2018; Shirizadeh et al, 2022).

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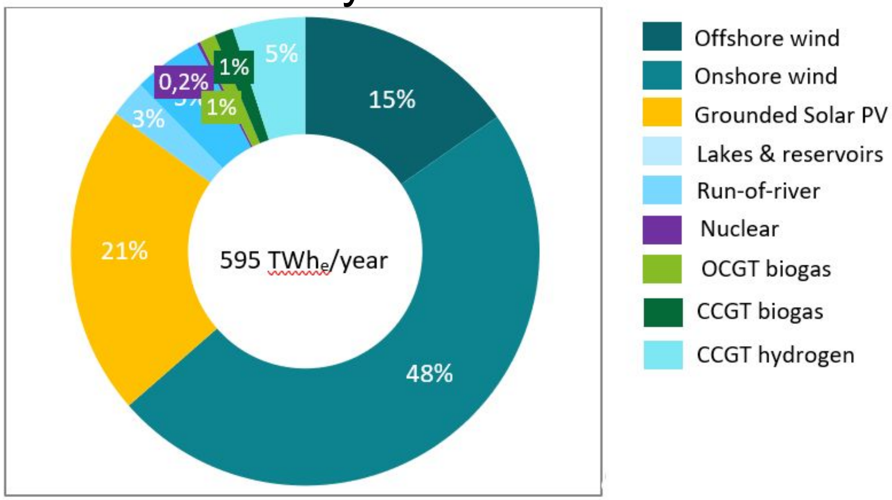
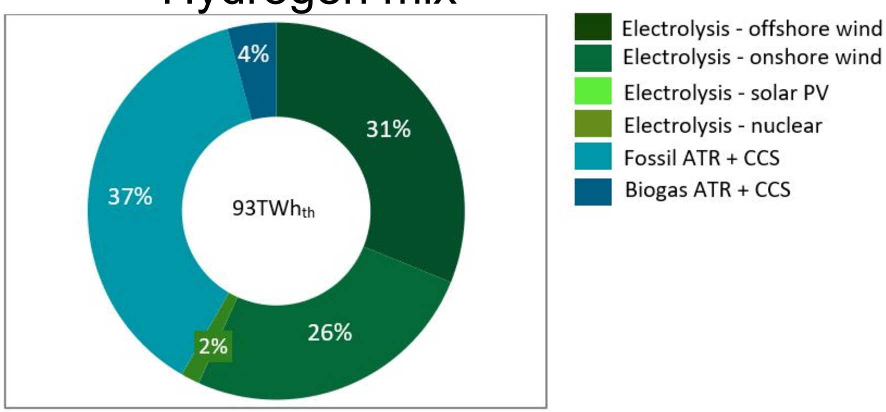
RESULTS

Results – central scenario

Electricity mix



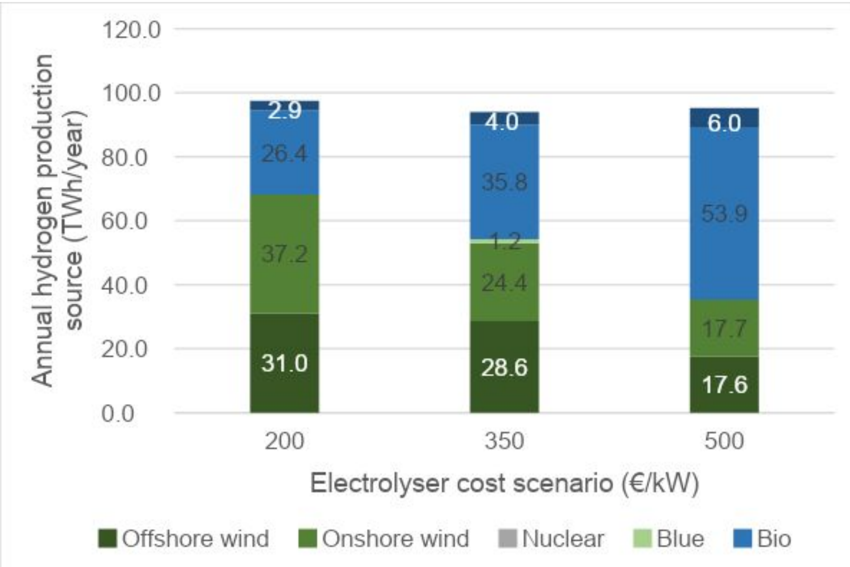
Hydrogen mix

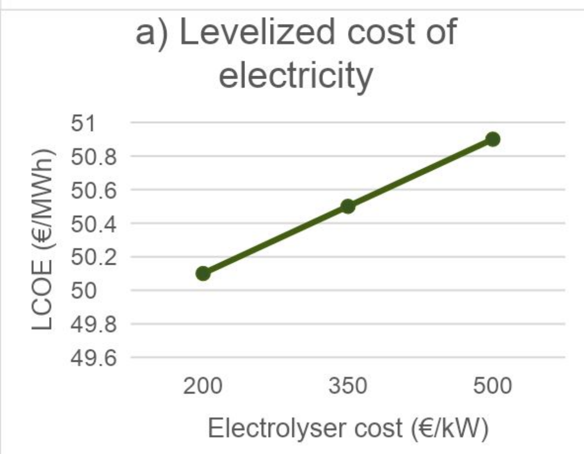


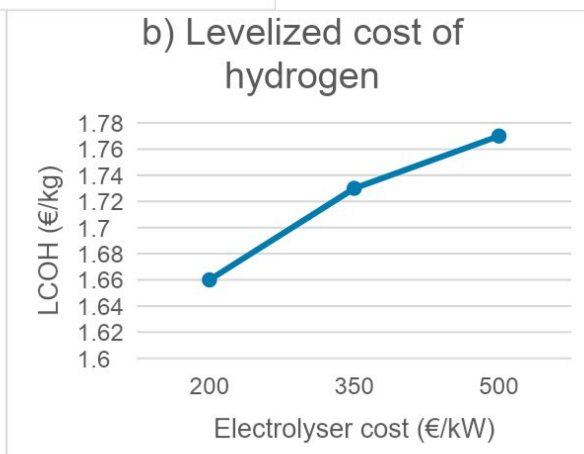
- **Electricity mix ~100% renewable**
  - **Grounded offshore wind, onshore wind, solar PV at maximum potential**
  - **No PV on rooftop, no floating offshore**
  - **5% from H_2 in CCGTs**
- **Hydrogen mix ~60% from electrolysis**
  - **Mostly wind, 2% nuclear**
  - **40% from ATR+CCS, mostly fossil gas**

System characteristic	Annualized overall system cost (bn.€)	Levelized cost of hydrogen (LCOH, €/kgH_2)	Cost per electricity consumed (€/MWh)	Storage losses (%)	Load curtailment (%)
Value	31.4	1.73	50.5	1.3	1.2

Results: Sensitivity to electrolyser cost



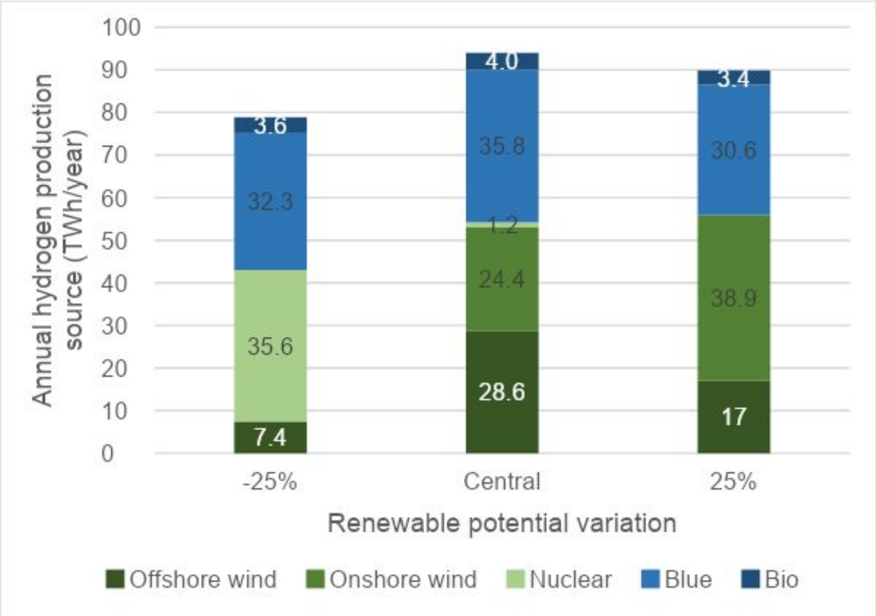




- **LCOE & LCOH rather robust**
  - **LCOE variation ~0.53% for €100/kW (28.6%) variation of electrolyser cost**
  - **LCOH variation ~2.12% for €100/kW (28.6%) variation of electrolyser cost**

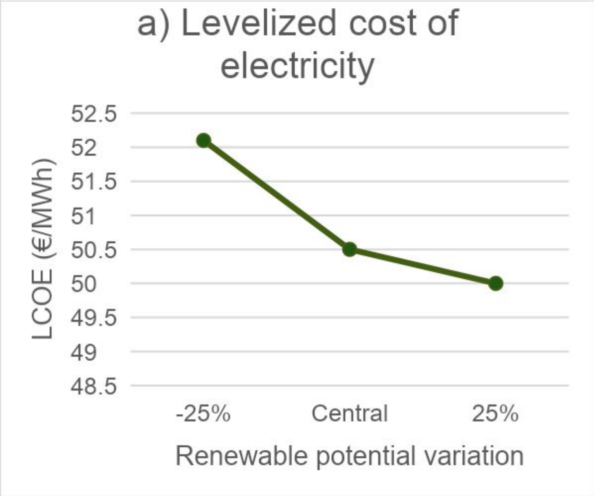
- **Hydrogen supply mix more sensitive**
  - **37% to 70% variation of electrolysis share in H_2 production**

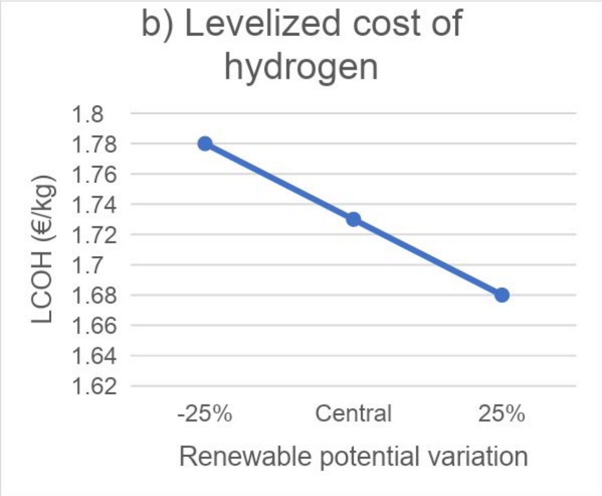
Results: Sensitivity to Renewable potential



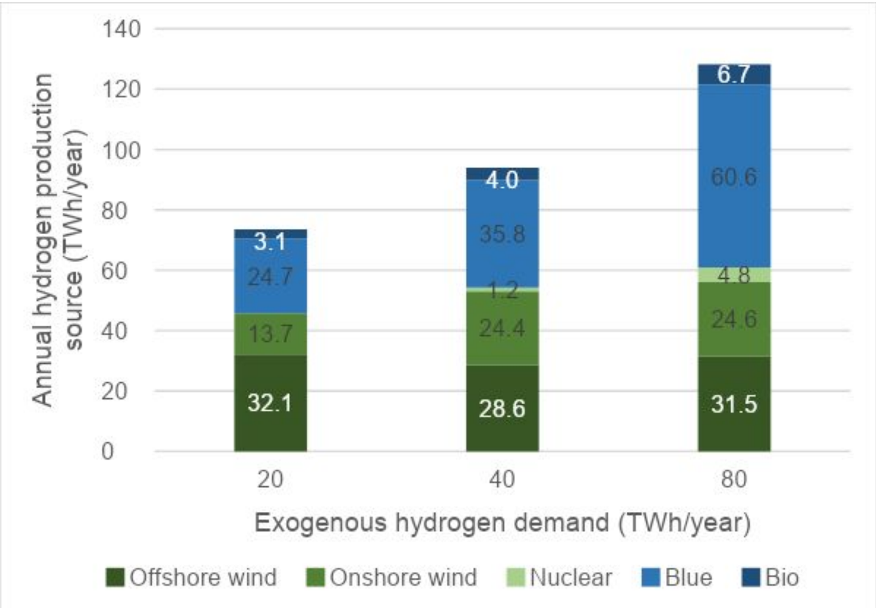
- **Nuclear significant only if renewable potential is low**
  - 45.2% for low RES potential
  - 0 for high RES potential

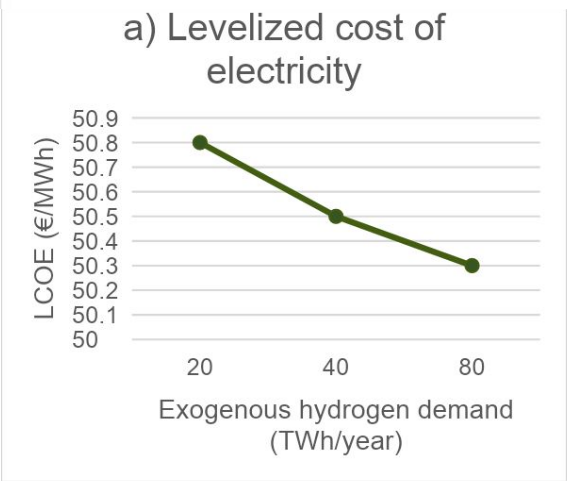
- **LCOE and LCOH are more sensitive to renewable potential than to the other variants**
  - 2,1% variation of LCOE over 25% of variation of renewable potential
  - 2,9% variation of LCOH over 25% of variation of renewable potential

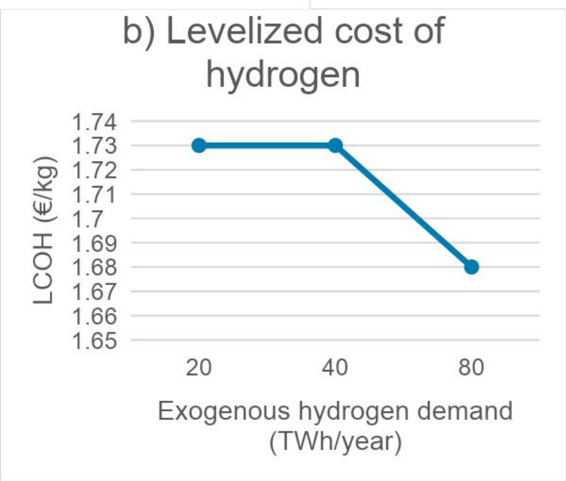




Results: Sensitivity to hydrogen demand

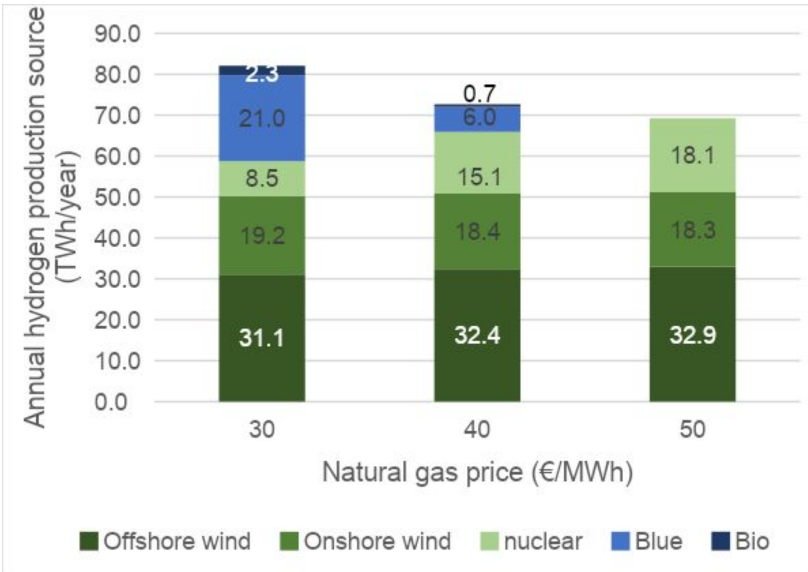




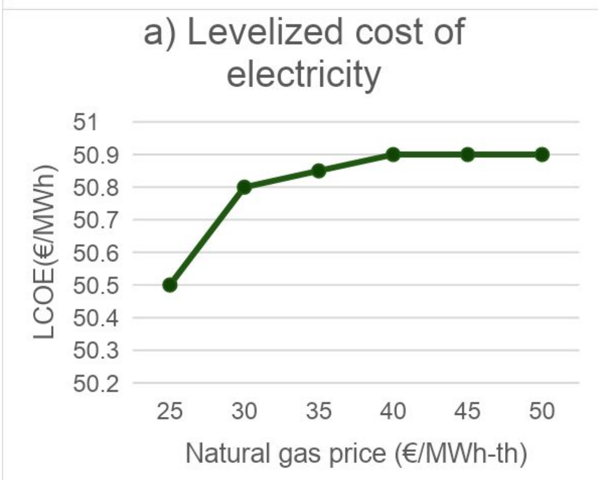


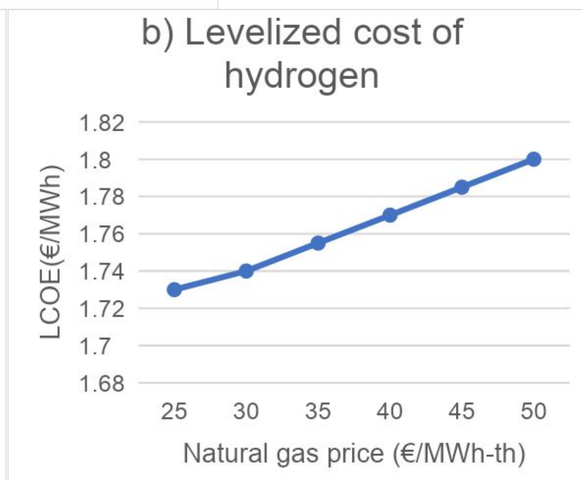
- **LCOE & LCOH decrease with hydrogen demand!**
  - Higher H2 demand higher electrolyser capacity energy storage
- **% of blue hydrogen increases with hydrogen demand**
  - Potential constraints become more binding

Results: Sensitivity to natural gas price



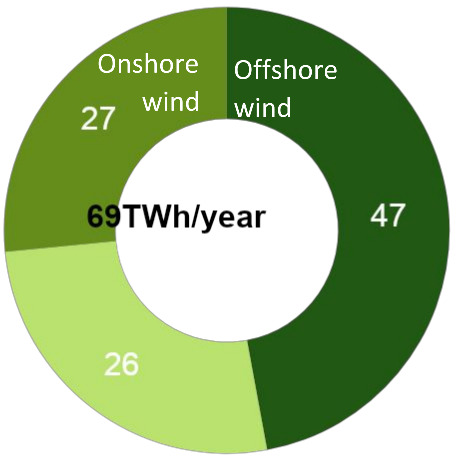
- **Central scenario: fossil gas at €25/MWh**
- **No blue hydrogen if gas price reaches €50/MWh**
- **LCOH up by only 4% for doubling of fossil gas price**





Results: Exclusion of blue hydrogen

System characteristic	Annualized overall system cost (bn€)	Levelized cost of hydrogen (LCOH, €/kgH_2)	Cost per electricity consumed (€/MWh)	Storage losses (%)	Load curtailment (%)
Value	31.7	1.80	50.9	1.3	1.1
Difference from central scenario	+0.96%	+4.05%	+0,79%	0	-8.33%



CCS faces challenges what if no blue hydrogen?

- Overall system cost increase ~1%
- LCOH increase ~4%
- LCOE increase ~0.8%
- Load curtailment decreases by 8%
- Nuclear generation increases from 2% to 26% of H_2 generation

Conclusion

- ✔ The cost-optimal, zero-emission electricity production mix is almost fully renewable in our central scenario.
- ✔ The share of electrolysis vs. methane reforming is sensitive to the cost of electrolysers, with the former providing around 60% of hydrogen production in the central scenario, in which electrolysers cost around €350/kW_e (€467/kW_{H2}).
- ✔ Nuclear has a significant role only if the wind & solar potential limits their deployment (lower VRE potential or higher hydrogen demand than in our central scenario) requiring more electricity for electrolysis.
- ✔ Electrolyser cost is less important for the overall system cost than the amount of hydrogen demand, natural gas price and the renewable potential.
- ✔ Eliminating blue hydrogen from hydrogen supply options increases the overall system cost only by less than 1%.
- ✔ A doubling of fossil gas price (€25 □ €50/MWh) eliminates blue hydrogen.

Discussion points

- As the share of renewables increase, the utilization rate of electrolyzers decreases, but LCOH as well (in line with Stöckl et al, 2021, Caglayan et al, 2021, etc.), thanks to high frequency of cheap electricity periods in a highly renewable power system.

- RTE finds an LCOH of €3.6/kg$_{H2}$, while we find <€2/kg$_{H2}$ (in-line with Agora Energiewende, 2021, IRENA, 2020, IEA, 2021, etc.). The difference comes from how electricity price is accounted for (annual average price vs. hourly market price).

- Acceptability issues (social and political) for renewables, while they are crucial for the cost-optimality.

- Higher hydrogen demand has ambiguous effect on renewables:
  - Higher electrolyser capacity □ cheaper long-term storage
  - Renewable potential limits become more binding

- Lately observed natural gas prices (€200/MWh$_{th}$) won't result in cost-optimal production of blue hydrogen. For €50/MWh$_{th}$ of natural gas price, there is no blue hydrogen (with less than 1% of increase in the overall cost of the hydrogen-electricity system.

Limits & Future Research

I. **No spatial optimisation, France is considered as a single node with copper plate assumption.**

II. **Greenfield optimisation considering an end-point and not a dynamic trajectory.**

III. **Inelastic electricity demand.**

IV. **Limited endogeneity of hydrogen demand.**

V. **Limited represntation of off-grid hydrogen production.**

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Merci!

bshirizadeh@deloitte.fr

@bshirizadeh

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APPENDICES

Appendix 1. Calculation of LCOE and LCOH

Calculation of Levelized cost of hydrogen

$$LCOH\left(\frac{€}{kWh_{th}}\right) = \frac{\left[\boxed{\sum_{H_2} Q_{H_2} \times \left(Annuity_{H_2} + fO\&M_{H_2}\right)} + \boxed{\sum_{H_2,h} E_{H_2,h} \times vO\&M_{H_2}} + \boxed{\sum_{H_2 \in electrolysis,h} \frac{E_{H_2,h} \times Price_h^{electricity}}{\eta_{electrolysis}}} + \boxed{Q_{salt\ cavern}^{en} \times}\right.}{\sum_{H_2,h} E_{H_2,h}}$$

Electrolyser fixed and variable costs

Hydrogen transport cost

Electricity cost

Storage cost cost

Calculation of system-wide levelized cost of electricity

$$LCOE_{system} = \frac{COST^{total} - \left(LCOH \times \sum_h demand_h^{H_2,exogenous}\right)}{\sum_h demand_h^{electricity}}$$

Appendix 3. Main characteristics

Scenario	**Annualised overall system cost (bn. €)**	**LCOH (€/tonne of H_2)**	**LCOE(€/MWh)**	**Storage losses (%)**	**Load curtailmen t (%)**
Central	31.4	1.73	50.5	1.3	1.2
Low-high electrolyser cost	31-31.6	1.66-1.77	50.1-50.9	1.2-1.3	0.7-2.1
High-low wind and PV potential	31-32.4	1.68-1.78	50-52.1	1.28-1.02	0.15-0.09
Low-high hydrogen demand	30.5-33.2	1.73-1.68	50.8-50.3	1.3-1.3	0.11-0.07
Blue hydrogen not allowed	31.7	1.80	50.9	1.3	0.11

Appendix 4. Installed capacities

Scenario	**Nuclear**	**OCGT**	**CCGT**	**CCGT-H_2**	**Battery 1h**	**Battery 4h**	**Electrolysis from offshore wind**	**Electrolysis from onshore wind**	**Electrolysis from nuclear**	**Fossil gas, ATR+CCS**	**Biogas, ATR+CCS**
Central	0.4	26	6.6	12.7	4.8	19.9	8.9	6	0.3	12.6	1.5
Low-high electrolyser cost	0-0	26.3-26.3	6.9-6.1	13.2-13	6.3-4.1	17.8-21	11.3-5.7	10.8-3.1	0-0	11.4-14.4	1.3-1.6
High-low wind and PV potential	0-12.2	27.1-19.8	5.8-8.5	12.0-9.5	6.7-10	17.7-9.5	4.7-2.6	9.9-0	0-9.2	11.8-10.8	1.2-1.6
Low-high hydrogen demand	0-1.2	25.7-26.4	7.1-6.2	13.3-11.9	5.9-5	18.4-19.7	8.9-9.4	3.5-6.9	0-0.9	10.8-16.2	1.3-1.9
Blue hydrogen not allowed	4.5	23.9	8.7	8.6	4.8	19.9	9.1	5	3.4	0	0

Appendix 5. Annual electricity production

Scenario	Floating offshore wind	Fixed offshore wind	Onshore wind	Ground-based PV	Run-of-river hydro	Dam-based hydro	Nuclear	OCGT	CCGT	CCGT-H_2	Battery 1h	Battery 4h
Central	0	91	287.4	127.6	28.5	15.3	1.4	6.5	7.8	29.8	2.3	21.3
Central (%)	0%	14%	44%	21%	5%	2%	0%	1%	1%	5%	0%	3%
Low-high electrolyser cost	0-0	91.9-92	279-294.3	130.7-125.3	28.5-28.5	15.3-15.3	0-0	6.2-7.1	8.3-7	31.8-31.1	2.6-2.1	19.9-23.4
High-low wind and PV potential	0-31	43.3-84.8	334.9-234.9	124.5-96.0	28.5-28.5	15.3-15.3	0-59.2	7-4.6	7-10.6	27.8-21.8	3.4-4.7	19.9-11.1
Low-high hydrogen demand	0-0	84.7-88.2	290.8-280.8	122.8-129.5	28.5-28.5	15.3-15.3	0-4.4	6.1-7	8.4-7.2	31.6-27.1	2.8-2.5	20.4-21.9
Blue hydrogen not allowed	0	84.7	287.7	126.2	28.5	15.3	15.1	5.1	9.8	15.8	2.5	21.8

Appendix 6. Hydrogen production mix

Scenario	**Fossil gas, ATR+CCS**	**Biogas, ATR+CCS**	**Electrolysis from offshore wind**	**Electrolysis from onshore wind**	**Electrolysis from PV**	**Electrolysis from nuclear**	**Share of electrolysis in H_2 generation**
Central	35	3.9	29.1	23.9	0	1.5	58%
Low-high electrolyser cost	26.5-54.1	2.9-6	31.7-22.2	36.2-12.9	0-0	0-0	70%-37%
High-low wind and PV potential	30.6-32.3	3.4-3.6	17-7.4	38.9-0	0-0	0-35.6	62%-54%
Low-high hydrogen demand	24.7-60.6	3.1-6.7	32.1-31.5	13.7-24.6	0-0	0-4.8	60%-48%
Blue hydrogen not allowed	0	0	32.5	18.2	0	18.3	100%

Appendix 7. EOLES family of models

- EOLES is a family of linear optimization models that minimize simultaneously cost of investment and dispatch of the energy system, assuring hourly supply demand equilibrium.
- Therefore, EOLES is an energy market model, based on merit-order supply choice and marginal pricing of the energy, with many technical details to ensure technical coherence.
- Several journal publications using EOLES (alongside with many conferences)

- Shirizadeh, B. & Quirion, P. (2022). The importance of renewable gas in reaching carbon-neutrality: Insights from and energy system optimization model. *Energy*.
- Shirizadeh, B., Perrier, Q., & Quirion. P. (2022). How sensitive are fully renewable power systems to the cost uncertainty? *The Energy Journal*. Vol. 43, No. 1.
- Shirizadeh, B. & Quirion, P. (2022). Do multi-sector energy system optimization models need hourly temporal resolution? *Applied Energy*. 305C 117951.
- Shirizadeh, B., & Quirion, P. (2021). Low-carbon options for the French power sector; what role for renewables, nuclear power and carbon capture and storage. *Energy Economics*. 105004.
- De Guibert, P., Shirizadeh, B., & Quirion, P. (2020). Variable time-step: a way to improve computational tractability for energy system models with long-term storage. *Energy*. 119024.
- Shirizadeh, B. & Quirion, P. (expected 2022). Long-term optimization of hydrogen-electricity nexus for France. *In progress*.