Support mechanisms for hydrogen: Interactions and distortions of different instruments

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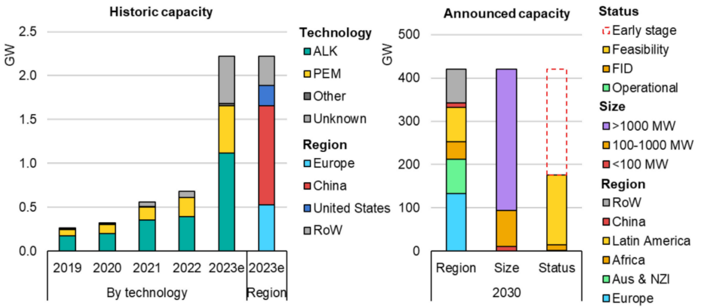
0 Outline

1 Outline

1 Where do things stand?

- Currently +95% of H_2 is produced using Steam Methane Reforming (SMR)
- Global electrolyser capacity exceeded **1 GW in 2023**
- Not cost-competitive yet

Governments wish to support renewable hydrogen production



Notes: ALK = alkaline electrolysers; FID = final investment decision and under construction; PEM = proton exchange membrane electrolysers; RoW = rest of world; Aus & NZI = Australia and New Zealand; 2023e = estimate for 2023 capacity, based on projects planned to start operations in 2023 and that have at least reached FID. “Other” technology refers to solid oxide electrolysis, anion exchange membrane electrolysis or a combination of different technologies. The unit is GW of electrical input. Only projects with a disclosed start year are included.

Source: IEA Hydrogen Projects, (Database, October 2023 release).

1 Support mechanisms for hydrogen

- The question arises how to design these support mechanisms: e.g., **trade-offs between capacity- and energy-based subsidies**
- A lot of research dedicated to RES support exists but this not directly applicable to hydrogen support.[1]
- But, electrolysers are dispatchable $\rightarrow$ higher **risk for inefficiencies**
- Policies can distort the operational decisions and investment in electrolysers

Research question

Given the different ways hydrogen production can be subsidised, what is the effect of these policies on hydrogen, carbon- and electricity markets?

[1] Ödemir, Ö, Hobbs, B. F., van Hout, M., & Koutstaal, P. R. (2020). Capacity vs energy subsidies for promoting renewable investment: Benefits and costs for the EU power market. Energy Policy, 137, 111166.

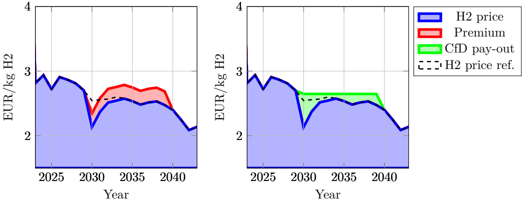
1 Overview of hydrogen support mechanisms

Name	Region	Type	Eligibility
Inflation Reduction Act	USA	Fixed premium	<4kg CO2/ kg H2
Hydrogen Business models	UK	Hydrogen CfD	Blue & green H2
H2Global	DE	Hydrogen CfD	Ammonia import, methanol or SAF
Important projects of Common interest	EU	Capacity grant	Innovative nature
Innovation Fund	EU	Capacity grant	Innovative nature
Hydrogen Bank	EU	Fixed premium	Defined in DA of RED III

- Historically more "project basis" capacity-based support
- Current trend towards energy-based support
- Organising capacity-based support through an auction seems overlooked

1 Overview of the compared mechanisms

- **Fixed premium** (EUR/MWh)
- **Contract for Difference** with yearly H_2 reference price (EUR/MWh)
- **Capacity grant** (EUR/MW)
- **Investment subsidy** (EUR%)



(b) Fixed premium

(c) H2 CfD

Variants of the mechanisms that are studied:

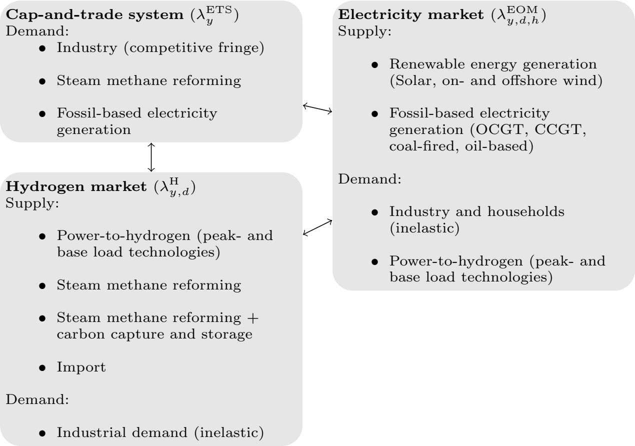
- FP where the annual production is kept constant
- FP where support is limited to x hours of full load operation

Single auction is considered in 2030, agent covered under support mechanism can install capacity only in 2030. All are calibrated to cover the same production volume 2031-2040.

2 Outline

2 Model

- We use equilibrium models to describe investment behaviour of **electricity**, **hydrogen** and **industrial agents** for 2020-2060
- MCP solved using price search algorithm (Alternating Direction Methods of Multipliers)



2 Case study

- Case study on a system based on EU: including cap-and-trade system, 45% renewable electricity ambition, 10 Mt domestic hydrogen production by 2030 ambition, etc.
- We consider a peak and base load technology
- This represents the inherent trade-off between CAPEX and OPEX in alkaline PtH technology (e.g. thickness membrane) [2]

Technology		SMR	SMR-CCS	PtH-peak	PtH-base
Investment cost $IC_t^{H_2}$	EUR/kW_e	740	1000	**1500**	**2000**
Lead time	years	3	3	3	3
Lifetime	years	25	25	20	20
Learning rate	% change YoY	-	-	2%	2%
Efficiency $\eta_t^{P \to H_2}$				**65%**	**70%**
Efficiency $\eta_t^{NG \to H_2}$		75%	62%		
Carbon Intensity $CI_t^{H_2}$	tCO_2/MWh	0.328	0.0328	0	0
Legacy capacity	GW	70	0	1	1

[2] IRENA. (2020). Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5C climate goal.

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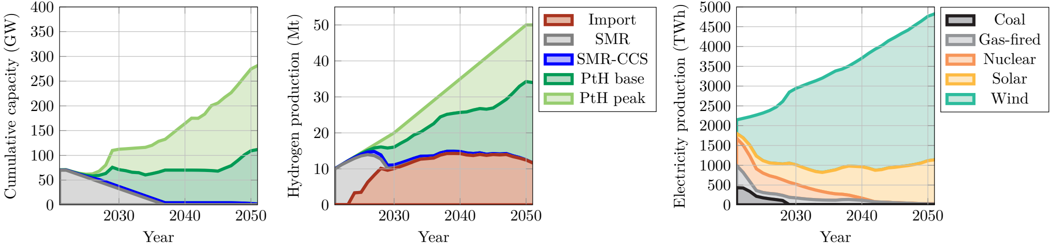
3 Outline

1. Context
2. Model
3. Results
   - No subsidy policy case
   - Influence on hydrogen sector
   - Influence on power sector
   - Changes in total system cost

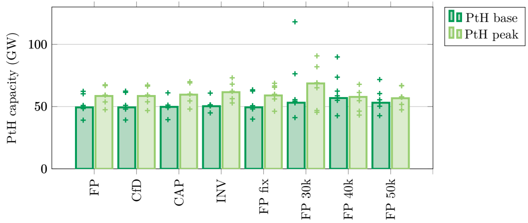
3 No subsidy policy case

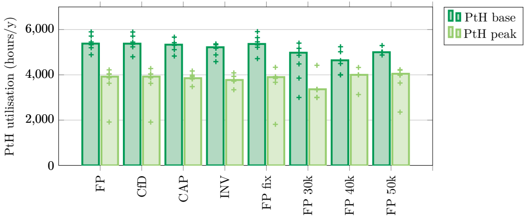


- By 2030 8.6 Mt is produced by PtH out of the 10 Mt domestic hydrogen production.
- A mix of expensive, high-efficiency and cheap, low-efficient PtH technologies arises.
- 2416 TWh of electrical power is supplied by solar and wind, and 522 TWh by non-renewable generation in 2030.
- Various sensitivities were carried out

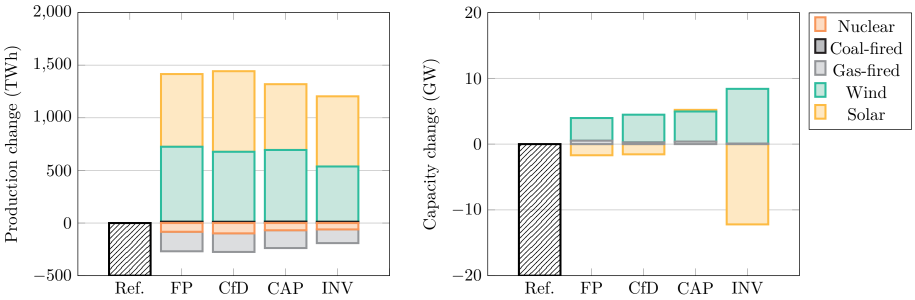
3 Influence on hydrogen sector - Technology choice

- **Both technologies are attracted** as desired by all the considered mechanisms.
- The **capacity-based instruments** (CP, INV) tend to install **more capacity** to obtain the same H2 quantity.
- **Especially INV** causes a lot of capacity investments to occur (3-9 GW)
- Mostly peak technology which indicates a **selection bias** towards the cheaper peak unit



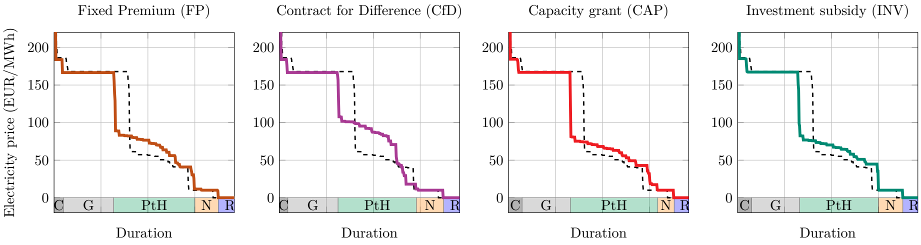


3 Influence on power sector - Decrease in curtailment



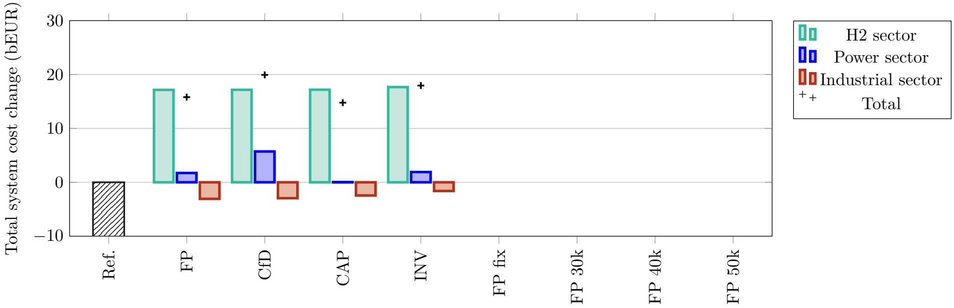
- All mechanisms decrease the production of gas-fired and nuclear generation, because of the increased attractiveness of renewables when flexible load is added to the system.
- All mechanisms increase RES production, either through additional investment or less curtailment.

3 Influence on power sector - Operational decisions



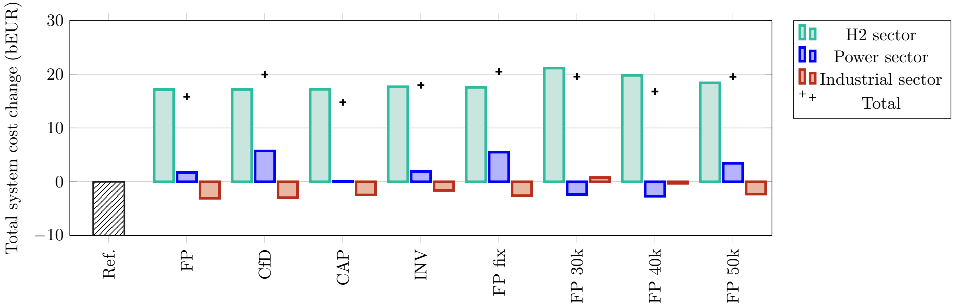
- ▶ Capacity-based mechanisms do not change electricity prices that much
- ▶ Energy-based instruments increase electricity prices when H2 production is price setting

3 Capacity support reduces cost increase in the power sector



- Additional cost increase primarily in H2 sector, but also an effect on the power sector
- Capacity-based instruments cause less costs in the power sector
- Subsidising decarbonisation decreases carbon prices and abatement cost of industry

3 CAP performs best according to total system cost



- Sensitivities confirm trends in central reference scenario
- CAP performs best according to total system cost for all sensitivities (besides ‘expensive base’)

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4 Conclusion

- This model captures the **interactions** between **hydrogen** and **electricity** markets.
- The research compared capacity-based subsidy mechanisms with two energy-based mechanisms: a fixed-premium (FP) and a hydrogen contract for difference (CfD).
- The choice of mechanism influences the **renewable capacity** and **displacement of gas-fired generation** in the power sector.
- Capacity-based instruments tend to have a technology selection bias. Energy-based instruments distort electricity markets.
- The CAP performs best followed by the FP, according to total system cost.

Thank you!

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5 Outline

5 Electricity agents

- Energy only market with economic dispatch of conventional $g^{\text{C}}_{y,d,h,p}$ and renewable generation assets $g^{\text{R}}_{y,d,h,r}$
- Possibility to invest in new conventional $cp^{\text{C}}_{y,r}$ and renewable generation capacity $cp^{\text{R}}_{y,r}$, to meet growing electricity demand

Fossil-based generation:

$$\text{Max.} \quad \sum_{y \in \mathcal{Y}} A_y \cdot \sum_{h \in \mathcal{H}} (\lambda^{\text{EOM}}_{y,d,h} - VC_p) \cdot g^{\text{C}}_{y,d,h,p} - IC^{\text{C}}_p \cdot cp^{\text{C}}_{y,r} - \lambda^{\text{ETS}}_y \cdot b^{\text{C}}_{y,p} \tag{1}$$

Renewable generation:

$$\text{Max.} \quad \sum_{y \in \mathcal{Y}} A_y \cdot \sum_{h \in \mathcal{H}} \lambda^{\text{EOM}}_{y,d,h} \cdot g^{\text{R}}_{y,d,h,r} + \lambda^{\text{REC}}_y \cdot g^{\text{R,NB}}_{y,r} - IC^{\text{R}}_r \cdot cp^{\text{R}}_{y,r} \tag{2}$$

Note that constraints are omitted here

5 Power-to-hydrogen

- The power-to-hydrogen actors (peak- and base-load, $\forall q \in \mathcal{Q}$) aim to optimize their generation $g^{\mathrm{H}}_{y,d,h,q}$ and capacity $cp^{\mathrm{H}}_{y,q}$ to maximize their profit $P(g^{\mathrm{H}}_{y,d,h,q},\ cp^{\mathrm{H}}_{y,q})$

$$P(g^{\mathrm{H}}_{y,d,h,q},\ cp^{\mathrm{H}}_{y,q}) = \sum_{y\in\mathcal{Y}} A_y \sum_{h\in\mathcal{H}} (\lambda^{\mathrm{H}}_{y,d} - \lambda^{\mathrm{EOM}}_{y,d,h}/\eta^{P\rightarrow H_2}_t) \cdot g^{\mathrm{H}}_{y,d,h,q} - IC^{\mathrm{H}}_q \cdot cp^{\mathrm{H}}_{y,q} \quad (3)$$

$$s.t. \quad \forall y \in \mathcal{Y}, \forall d \in \mathcal{D}, \forall h \in \mathcal{H}, \forall q \in \mathcal{Q} : g^{\mathrm{H}}_{y,d,h,q} \leq \sum_{y\in\mathcal{Y}} cp^{\mathrm{H}}_{y^*,q} + \overline{cp^{\mathrm{H}}_{y,q}} \quad (4)$$

$$\forall y \in \mathcal{Y}^0, \forall q \in \mathcal{Q} : cp^{\mathrm{H}}_{y,q} \leq \Delta^{max.}_q \cdot (\sum_{y\in\mathcal{Y}} cp^{\mathrm{H}}_{y^*,q} + \overline{cp^{\mathrm{H}}_{y,q}}) \quad (5)$$

$$\forall y \in \mathcal{Y}, \forall d \in \mathcal{D}, \forall h \in \mathcal{H}, \forall q \in \mathcal{Q} : g^{\mathrm{H}}_{y,d,h,q},\ cp^{\mathrm{H}}_{y,q} \geq 0 \quad (6)$$

The profit $P(g^{\mathrm{H}}_{y,d,h,q},\ cp^{\mathrm{H}}_{y,q})$ will in what follows be augmented with income through various subsidy mechanisms.

5 Energy-based support instruments

10-year fixed premium: [EUR/MWh]
Participants offer an annual generation of electrolytic hydrogen [TWh/y], which they must keep for 10 years.

$$\underset{g^{\mathrm{H}}_{y,d,h,q},\ cp^{\mathrm{H,T}}_{q},\ g^{\mathrm{H,FP}}_{y,q}}{\mathrm{Max.}} P(g^{\mathrm{H}}_{y,d,h,q},\ cp^{\mathrm{H}}_{y,q}) + \sum_{\forall y \in \mathcal{Y}_T} A_y \cdot \lambda^{\mathrm{FP}} \cdot g^{\mathrm{H,FP}}_{y,q} \tag{7}$$

Subject to (4)-(6) and:

$$\forall y \in \mathcal{Y}_T, \forall q \in \mathcal{Q} : g^{\mathrm{H,FP}}_{y,q} \leq \sum_{d \in \mathcal{D}} W_d \sum_{h \in \mathcal{H}} g^{\mathrm{H}}_{y,d,h,q} \tag{8}$$

$$\forall y \in \mathcal{Y}_T, \forall q \in \mathcal{Q} : g^{\mathrm{H,FP}}_{y,q} \geq 0 \tag{9}$$

5 Energy-based support instruments (2)

10-year hydrogen CfD: [EUR/MWh]
Operators receive compensation according to the difference between a fixed strike price and the average yearly hydrogen price

- Agents receive a fixed strike price for 10 years and is determined through an auction
- Agents keep their market revenues from selling hydrogen (daily clearing) but pay-back a yearly average hydrogen price

$$\underset{g^{\mathrm{H}}_{y,d,h,q},\ cp^{\mathrm{H,T}}_{q},\ g^{\mathrm{H,CfD}}_{y,q}}{\mathrm{Max.}} P(g^{\mathrm{H}}_{y,d,h,q},\ cp^{\mathrm{H}}_{y,q}) + \sum_{\forall y \in \mathcal{Y}_T} A_y \cdot (\lambda^{\mathrm{CfD}} - \lambda^{\mathrm{H},ref}_{y}) \cdot g^{\mathrm{H,CfD}}_{y,q} \tag{10}$$

Subject to (4-6) and:

$$\forall y \in \mathcal{Y}_T, \forall q \in \mathcal{Q} : g^{\mathrm{H,CfD}}_{y,q} \leq \sum_{d \in \mathcal{D}} W_d \sum_{h \in \mathcal{H}} g^{\mathrm{H}}_{y,d,h,q} \tag{11}$$

$$\forall y \in \mathcal{Y}_T, \forall q \in \mathcal{Q} : g^{\mathrm{H,CfD}}_{y,q} \geq 0 \tag{12}$$

5 Capacity-based support instruments

Capacity grant: [EUR/MW]
The support level λ^{CG} is determined through an auction that ensures that a hydrogen production target HT_y is produced through PtH, similar to the previous mechanisms, but the renumeration is based on its capacity investment $cp_q^{\mathrm{H,T}}$.

$$\underset{g^{\mathrm{H}}_{y,d,h,q},\ cp_q^{\mathrm{H,T}},\ g_{y,q}^{\mathrm{H,CG}}}{\mathrm{Max.}} P(g^{\mathrm{H}}_{y,d,h,q},\ cp^{\mathrm{H}}_{y,q}) + A_y \cdot \lambda^{\mathrm{CG}} \cdot cp_q^{\mathrm{H,T}} \tag{13}$$

Subject to (4)-(6) and:

$$\forall y \in \mathcal{Y}_T, \forall q \in \mathcal{Q} : g_{y,q}^{\mathrm{H,CG}} \leq \sum_{d \in \mathcal{D}} W_d \sum_{h \in \mathcal{H}} g^{\mathrm{H}}_{y,d,h,q} \tag{14}$$

$$\forall y \in \mathcal{Y}_T, \forall q \in \mathcal{Q} : g_{y,q}^{\mathrm{H,CG}} \geq 0 \tag{15}$$

5 Capacity-based support instruments (2)

Investment subsidy mechanism: [EUR/EUR]
the subsidy is a percentage of the investment cost IC_q^{H} and is determined in an auction system that ensures a hydrogen production target HT_y is reached.

$$\underset{g^{\mathrm{H}}_{y,d,h,q},\ cp^{\mathrm{H,T}}_{q},\ g^{\mathrm{H,INV}}_{y,q}}{\mathrm{Max.}} P(g^{\mathrm{H}}_{y,d,h,q},\ cp^{\mathrm{H}}_{y,q}) + A_y \cdot \lambda^{\mathrm{INV}} \cdot IC^{\mathrm{H}}_{q} \cdot cp^{\mathrm{H,T}}_{q} \tag{16}$$

Subject to (4)-(6) and:

$$\forall y \in \mathcal{Y}_T, \forall q \in \mathcal{Q} : g^{\mathrm{H,INV}}_{y,q} \leq \sum_{d \in \mathcal{D}} W_d \sum_{h \in \mathcal{H}} g^{\mathrm{H}}_{y,d,h,q} \tag{17}$$

$$\forall y \in \mathcal{Y}_T, \forall q \in \mathcal{Q} : g^{\mathrm{H,INV}}_{y,q} \geq 0 \tag{18}$$

5 Market coupling constraints

- Energy- and capacity-based mechanisms are calibrated to yield the same amount of electrolytic hydrogen production HT_{y^*}
- The equilibrium price of the contracts are determined through one of the following market coupling constraints (MCC).
- Which make sure that a user defined amount of hydrogen Depending on the considered mechanism the corresponding MCC is enforced out of Eq. (19)-(20).

$$\sum_{q \in \mathcal{Q}} \sum_{\forall y \in \mathcal{Y}_T} g^{\mathrm{H,FP}}_{y,q} = HT_{y^*} \qquad \sum_{q \in \mathcal{Q}} \sum_{\forall y \in \mathcal{Y}_T} g^{\mathrm{H,CfD}}_{y,q} = HT_{y^*} \tag{19}$$

$$\sum_{q \in \mathcal{Q}} \sum_{\forall y \in \mathcal{Y}_T} g^{\mathrm{H,CG}}_{y,q} = HT_{y^*} \qquad \sum_{q \in \mathcal{Q}} \sum_{\forall y \in \mathcal{Y}_T} g^{\mathrm{H,INV}}_{y,q} = HT_{y^*} \tag{20}$$