WORKSHOP
THE ECONOMICS OF GAS

PARIS-DAUPHINE UNIVERSITY

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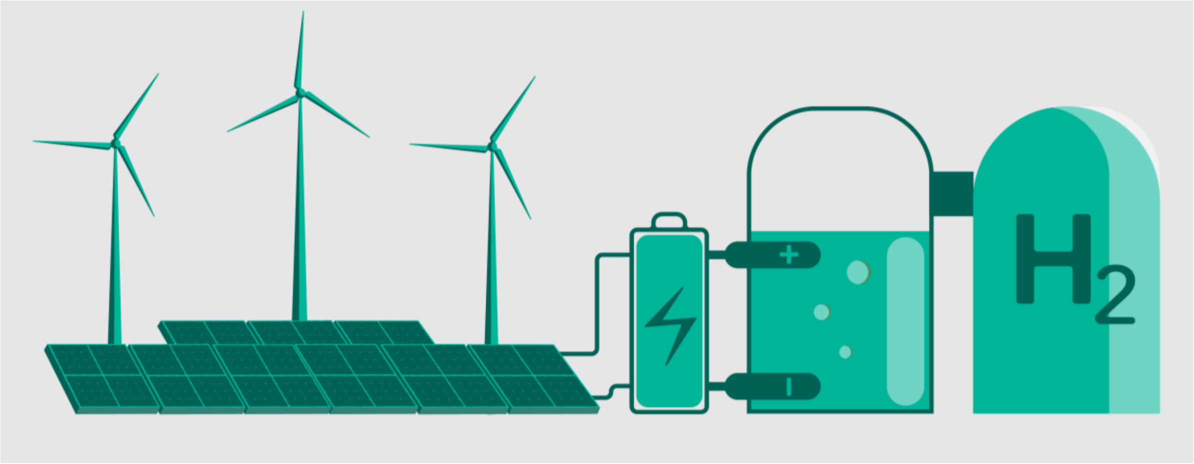
Is Power-to-Gas always beneficial? The implications of ownership structure

Camille MEGY, Olivier MASSOL



BACKGROUND - POWER-TO-GAS (PTG)

Renewable-based hydrogen could play a significant role in the energy sector’s decarbonization:

Indeed, when produced from renewable electricity, hydrogen can:

Provide flexibility to the electricity system

Replace coal, oil, natural gas, and conventional hydrogen

Contribute to the energy security by decreasing dependency on fossil fuels

BACKGROUND – PTG a as core component of the European energy & climate policy

In Europe, hydrogen is a key priority to achieve Europe’s clean energy transition.

European Hydrogen Strategy

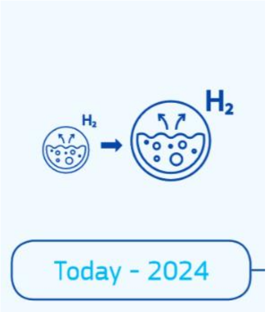
The kick-start phase
Develop pilot projects and Hydrogen Valleys

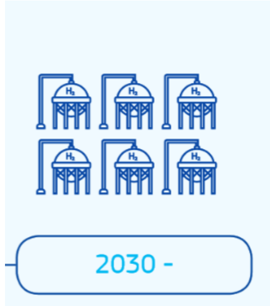
→

The ramp-up phase
Create a supporting framework to facilitate the development of the hydrogen economy

→

The market-growth phase
Obtain a market transparent and liquid





Sources: European Commission website & Hydrogen Act (Hydrogen Europe)

LITERATURE REVIEW - PTG as a sector coupling technology

Power-to-Gas:

- A growing literature in engineering
- In the economics literature, the economics of hydrogen is the subject of an increasing number of articles
- Among them, a few articles focus on PTG as a sector coupling technology
    - (Vandewalle & al, 2015)
    - (Lynch & al., 2019)
    - (Roach & Meus, 2020)
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- However, first movers in PTG are firms with a **strong oligopolistic presence** in either the power, gas, or H_2 markets (e.g., existing electricity producers, gas midstreamers, H_2 producers, independent private players…).

Can Industrial Organization considerations affect the outcomes of Power-to-Gas?

Is Power-to-Gas always beneficial?
The implication of ownership structure

This study aims at comparing the market outcomes obtained **under different asset-ownership structures** for PTG.

METHODOLOGY - Modeling the interactions between three markets

Gas Market

Electricity Market

Hydrogen Market

METHODOLOGY - Modeling the interactions between three markets

Gas Market

Gas is supplied by gas midstreamers through Long Term Contracts

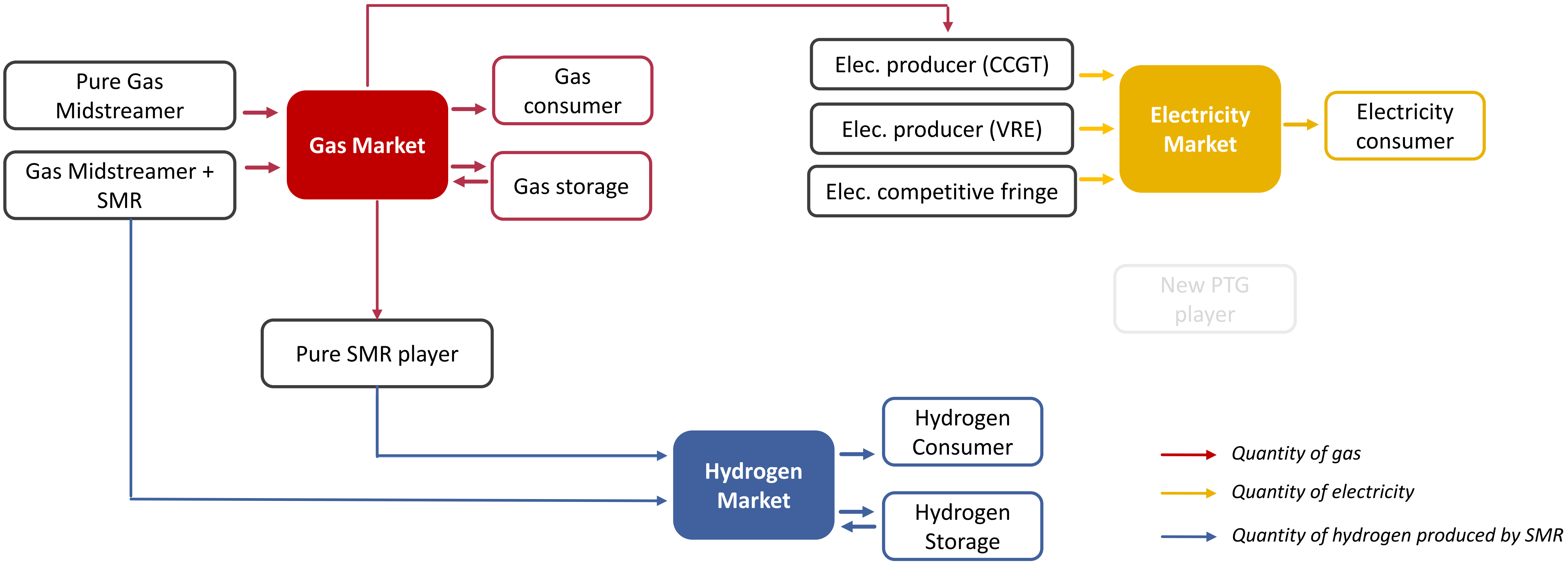
Electricity Market

Different generation technologies:
  - Combined Cycle Gas Turbine (CCGT)
  - Variable Renewable Electricity (VRE: Solar & Wind)

Hydrogen Market

Hydrogen can be produced from:
  - Electricity (Power-to-Gas – PTG)
  - Gas (Steam Methane Reforming – SMR)

METHODOLOGY - Global framework



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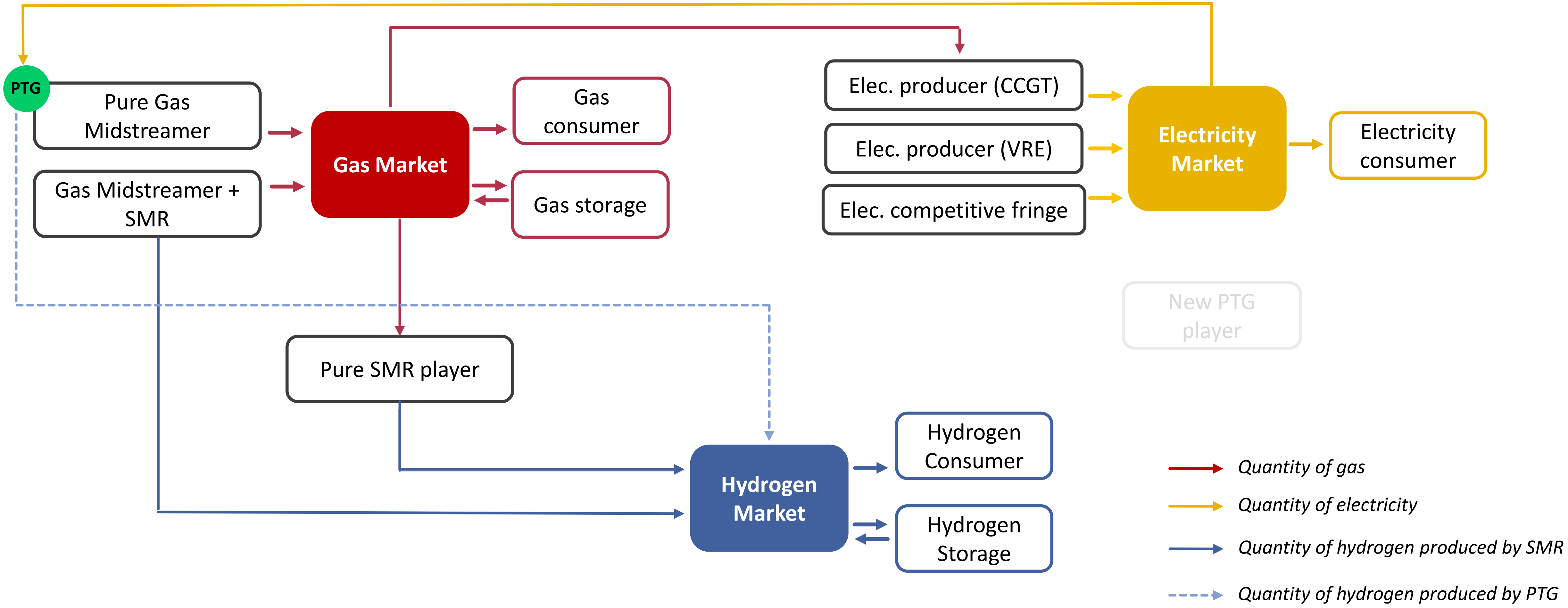

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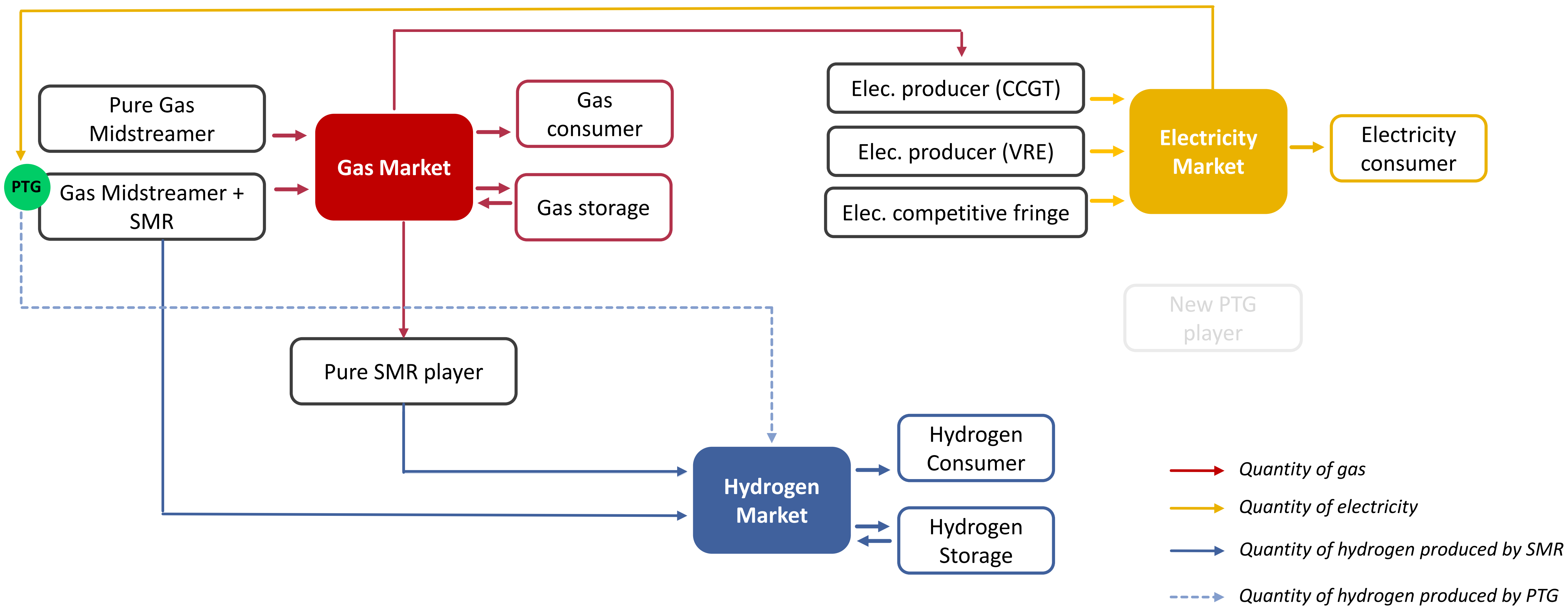

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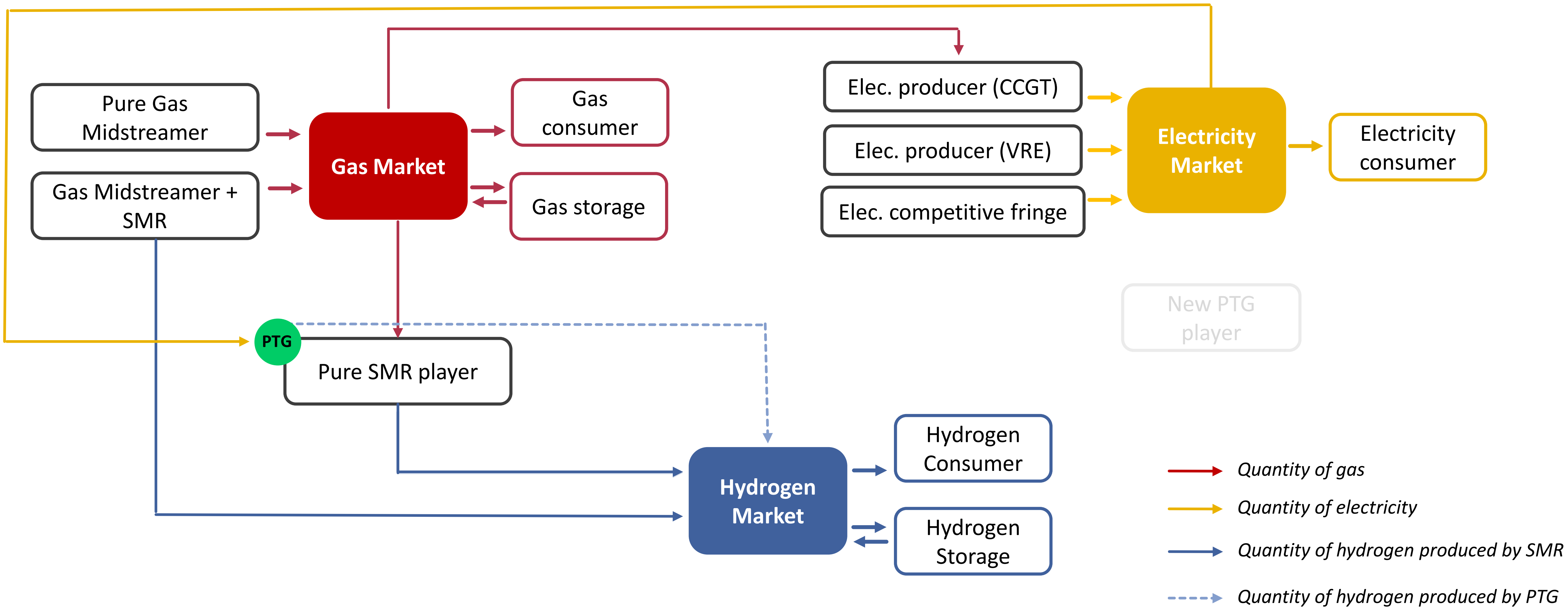

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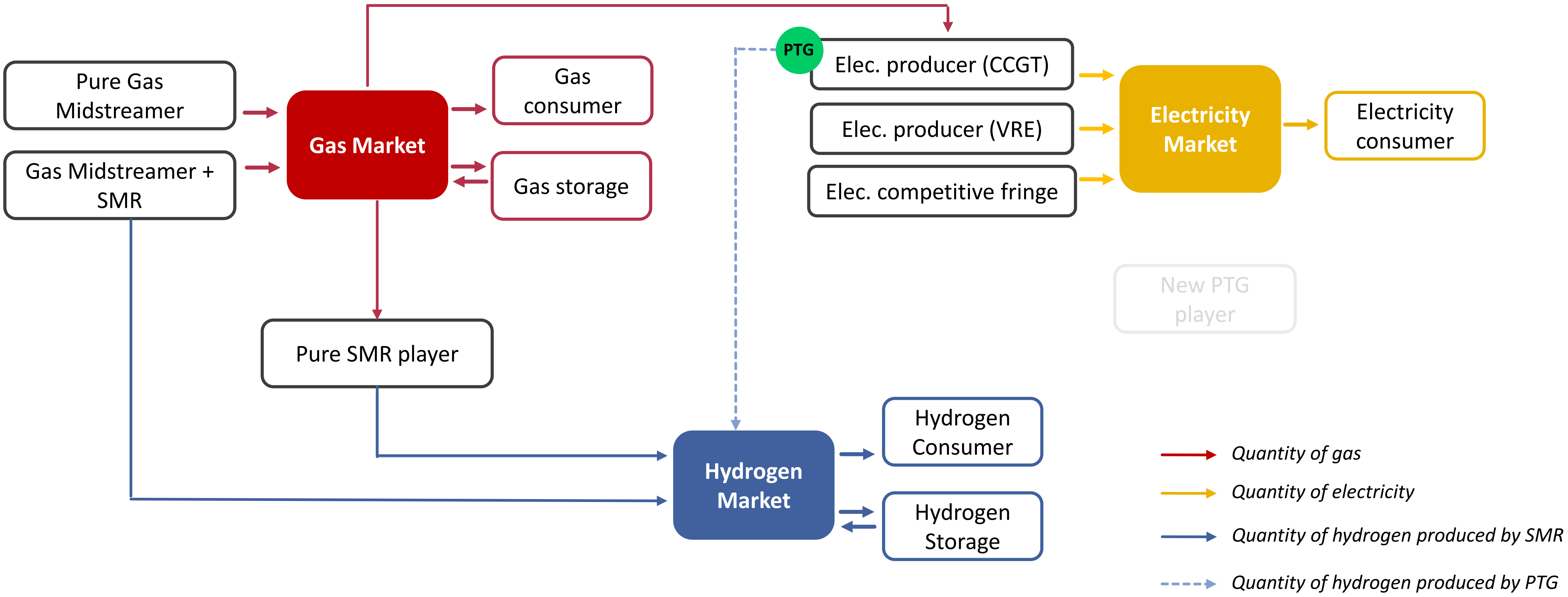

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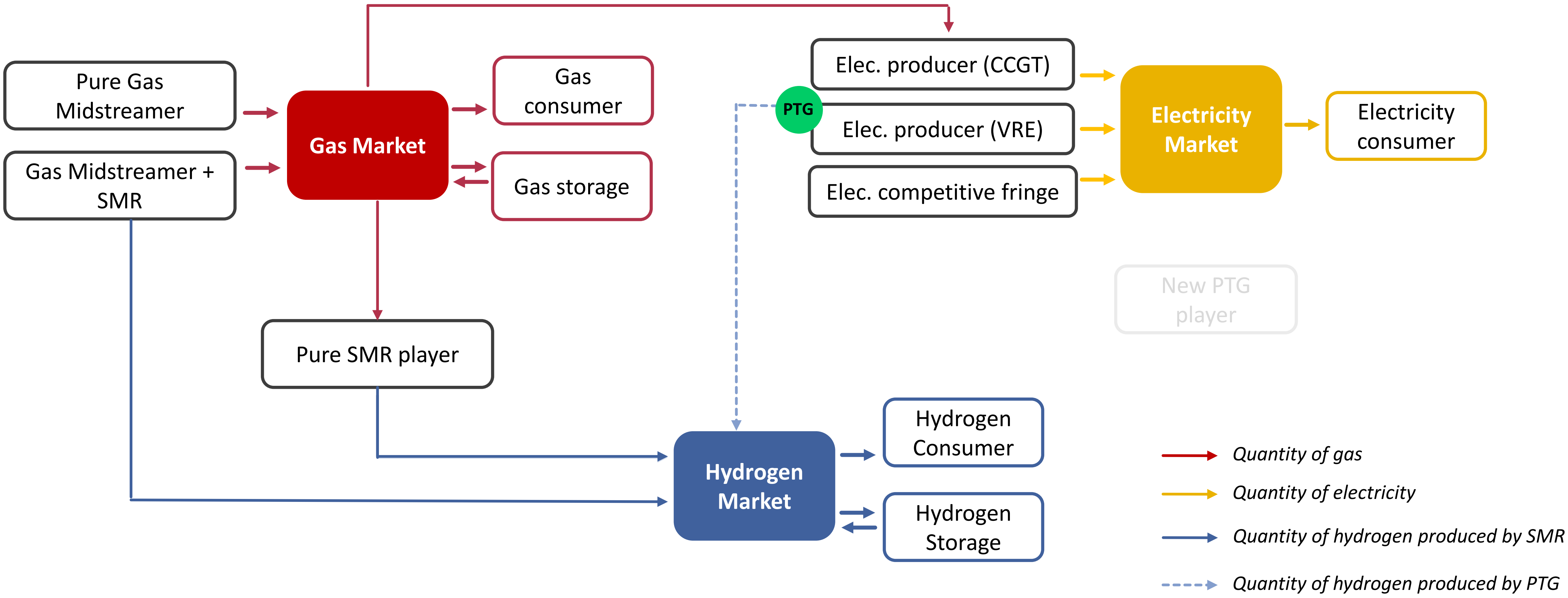

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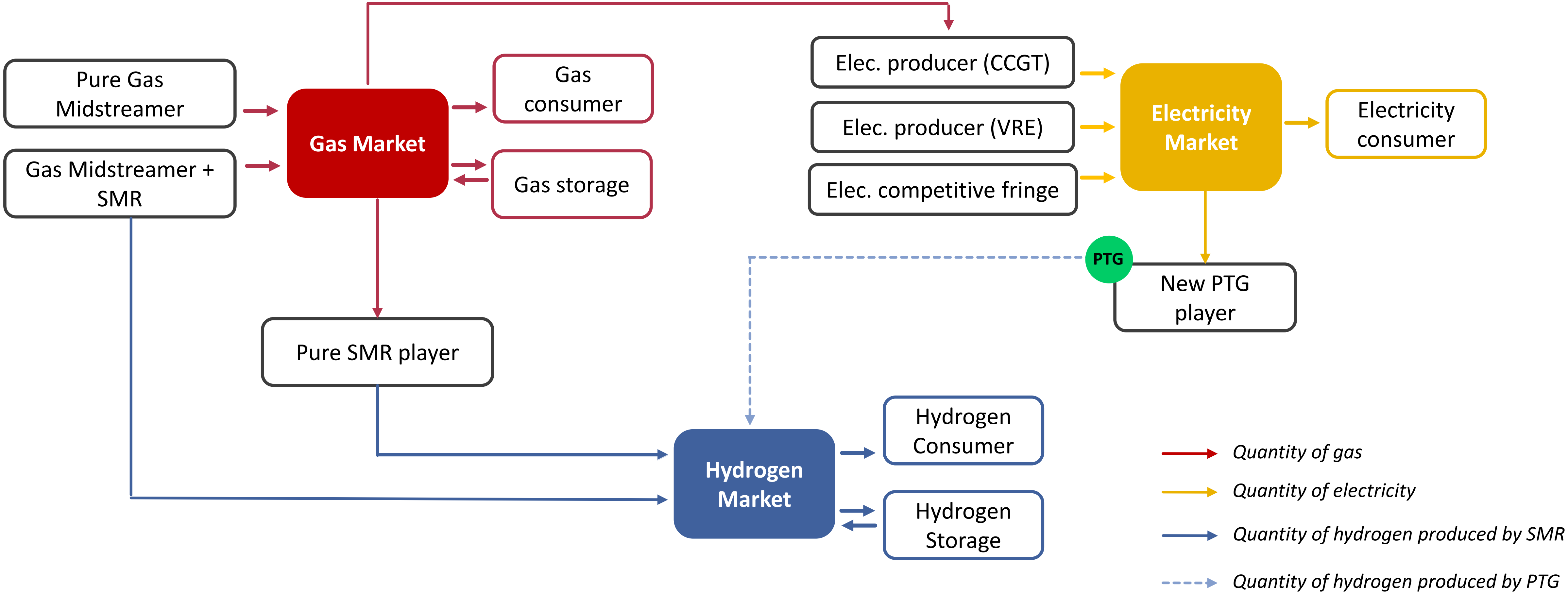


METHODOLOGY - A detailed partial equilibrium model

Deterministic Nash Cournot oligopoly model

- One-year time horizon
- Linear demand functions for Power, Gas & H_2
- Energy producers behave à la Cournot / Storage operators (gas & H_2) are price taking firms
- Short-term model – the model focuses on operations
  => Capacities are exogeneously determined.

Formulated & solved as an instance of a **Mixed Complementarity Model (MCP)**

Agents' maximization problems

Max. Profits
s.t. constraints (capacity, efficiency, ramp-up constraints...)

Market Clearing condition

METHODOLOGY – The agents’ problem

1 – Power producer (eventually with PTG)

Profit on the electricity market

$$\underset{\substack{q^{E}_{p,x,d,h},\, q^{E,up}_{p,CCGT,d,h},\\ q^{H}_{p,PTG,d,h}}}{\text{maximize}} \quad \sum_{d,h} w_d.w_h. \boxed{\Big[\sum_{x\in\mathcal{X}} \left(q^{E}_{p,x,d,h}.\pi^{E}_{d,h} - q^{E}_{p,x,d,h}.C^{E}_{p,x,d} \right) - q^{E,up}_{p,CCGT,d,h}.C^{E,up}_{CCGT,d}} \tag{1a}$$

$$\boxed{+\, q^{H}_{p,PTG,d,h}.\left(\pi^{H}_{d} - \frac{1}{\gamma_{PTG}}.\pi^{E}_{d,h} \right) \Big]} \tag{1b}$$

Profit on the hydrogen market (if PTG included)

subject to

Capacity constraints

$$q^{E}_{p,VRE,d,h} = K^{E}_{p,VRE}.AVA^{E}_{p,d,h} \qquad \forall d,h, \quad (\lambda^{E,1}_{p,d,h}), \tag{1c}$$

$$q^{E}_{p,CCGT,d,h} \leq K^{E}_{p,CCGT} \qquad \forall d,h, \quad (\lambda^{E,2}_{p,d,h}), \tag{1d}$$

$$q^{H}_{p,PTG,d,h} \leq K^{H}_{p,PTG} \qquad \forall d,h, \quad (\lambda^{E,3}_{p,d,h}), \tag{1e}$$

Ramp up constraint

$$w_h.q^{E}_{p,CCGT,d,h} \leq w_{h-1}.q^{E}_{p,CCGT,d,h-1} + w_h.q^{E,up}_{p,CCGT,d,h} \forall d,h, \quad (\lambda^{E,4}_{p,d,h}), \tag{1f}$$

$$0 \leq q^{E}_{p,x,d,h}, \quad 0 \leq q^{E,up}_{p,CCGT,d,h}, \quad 0 \leq q^{H}_{p,PTG,d,h} \qquad \forall d,h,x \tag{1g}$$

METHODOLOGY – The agents’ problem

2 – Gas midstreamer (eventually with PTG)

Profit on the gas market

$$\underset{\substack{q^G_{p,d}, q^H_{p,SMR,d},\\ q^H_{p,PTG,d,h}}}{\text{maximize}} \quad \sum_d \boxed{w_d.\left[q^G_{p,d}.\pi^G_d - q^G_{p,d}.\left(C^G_{inter} + C^G_{slope}.q^G_{p,d}\right)\right]} \tag{4a}$$

Profit on the hydrogen market

$$+ \sum_d w_d.\left[q^H_{p,SMR,d}.\left(\pi^H_d - \frac{1}{\gamma_{SMR}}.(\pi^G_d + C_{CCS})\right)\right] \tag{4b}$$

$$+ \sum_{d,h} w_d.w_h.\left[q^H_{p,PTG,d,h}.\left(\pi^H_d - \frac{1}{\gamma_{PTG}}.\pi^{E}_{d,h}{}^{*}\right)\right] \tag{4c}$$

subject to

Capacity constraints

$$q^H_{p,SMR,d} \leq K^H_{p,SMR} \qquad \forall d \qquad (\lambda^{G,1}_{p,d}), \tag{4d}$$

$$q^H_{p,PTG,d,h} \leq K^H_{p,PTG} \qquad \forall d,h \qquad (\lambda^{G,2}_{p,d,h}), \tag{4e}$$

$$0 \leq q^G_{p,d}, \quad 0 \leq q^H_{p,SMR,d}, \quad 0 \leq q^H_{p,PTG,d,h} \qquad \forall d,h \tag{4f}$$

** Signals an exogeneous price variable*

METHODOLOGY – The agents’ problem

3 – H2 producer (eventually with PTG)

Profit on the hydrogen market

$$\underset{\substack{q^H_{p,SMR,d},\\ q^H_{p,PTG,d,h}}}{\text{maximize}} \quad \boxed{\begin{aligned} &\sum_{d\in\mathcal{D}} w_d . \left[q^H_{p,SMR,d} . \left(\pi^H_d - \frac{1}{\gamma_{SMR}} . (\pi^{G}_d{}^{*} + C_{CCS}) \right) \right] && \text{(8a)} \\ &+ \sum_{d\in\mathcal{D}, h\in\mathcal{H}} w_d . w_h . \left[q^H_{p,PTG,d,h} . \left(\pi^H_d - \frac{1}{\gamma_{PTG}} . \pi^{E}_{d,h}{}^{*} \right) \right] && \text{(8b)} \end{aligned}}$$

subject to

$$\text{Capacity constraints} \left\{ \begin{aligned} & q^H_{p,SMR,d} \leq K^H_{p,SMR} && \forall d \quad (\lambda^{H,1}_{p,d}), && \text{(8c)} \\ & q^H_{p,PTG,d,h} \leq K^H_{p,PTG} && \forall d,h \quad (\lambda^{H,2}_{p,d,h}), && \text{(8d)} \end{aligned} \right.$$

$$0 \leq q^H_{p,SMR,d}, \quad 0 \leq q^H_{p,PTG,d,h} \qquad \forall d,h \qquad \text{(8e)}$$

* *Signals an exogeneous price variable*

METHODOLOGY – The agents' problem

4- Gas or H2 storage operator

Storage injection cost

$$\underset{\substack{u^G_{stor,d}, r^G_{in,d},\\ r^G_{out,d}}}{\text{maximize}} \quad \sum_{d\in\mathcal{D}} w_d.\left[r^G_{out,d}.\pi^{G\,*}_d - r^G_{in,d}.\left(\pi^{G\,*}_d + C^G_{in}\right)\right] \tag{5a}$$

subject to

Capacity constraints

$$r^G_{in,d} \leq T^G_{in}.K^G_{stor} \qquad \forall d \quad (\lambda^{G,1}_{stor,d}), \tag{5b}$$

$$r^G_{out,d} \leq T^G_{out}.K^G_{stor} \qquad \forall d \quad (\lambda^{G,2}_{stor,d}), \tag{5c}$$

$$u^G_{stor,d} \leq K^G_{stor} \qquad \forall d \quad (\lambda^{G,3}_{stor,d}), \tag{5d}$$

Storage state equation

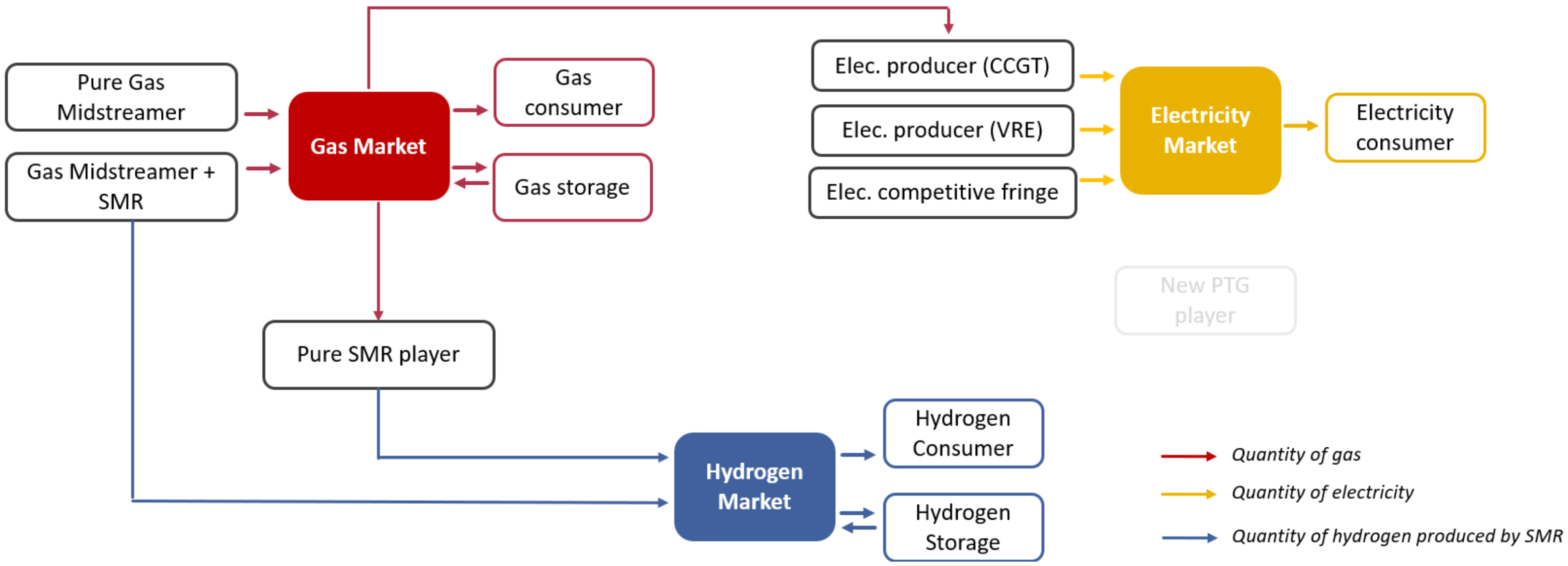
$$u^G_{stor,d} = u^G_{stor,d-1} + w_d.\left(r^G_{in,d} - r^G_{out,d}\right) \qquad \forall d \quad (\lambda^{G,4}_{stor,d}), \tag{5e}$$

$$0 \leq r^G_{in,d}, \quad 0 \leq r^G_{out,d}, \quad 0 \leq u^G_{stor,d} \qquad \forall d \tag{5f}$$

** Signals an exogeneous price variable*

METHODOLOGY

We solve a **linear complementarity problem** to obtain a **Nash equilibrium of the three markets**.



CASE STUDY - DATA

- We calibrate the model to represent the **Dutch energy system**
- Capacities are based on **EU projections for the year 2030**
- Power & gas demand parameters and RES generation variability are based on historical patterns
- The calibration of H_2 demand is based on GIE projections

CASE STUDY – 7 *Ceteris Paribus* scenarios

Baseline scenario : No PTG is developed.

Six scenarios with various asset ownership structures for PTG.

Scenario	**Business model posited for the PtG operator**	
No PtG	Baseline Scenario	Without PtG
H-New Prod	Independent firm	PtG as a pure player
H- SMR	Multi-market firm	SMR-based producer with PtG conversion
G- Gas		Gas midstreamer with PtG conversion
G- Gas+SMR		Gas midstreamer with both SMR and PtG conversion
E- CCGT		Thermal generator with PtG conversion
E- VRE		VRE generator with PtG conversion

CASE STUDY - Objectives

Objectives

1. See whether PTG operation depends on market structure,
2. Analyze the observed market outcomes and the allocation of net social welfare in power, gas, and H2 markets,
3. Study the contribution of PTG in reducing CO_2 emissions.

MAIN RESULTS

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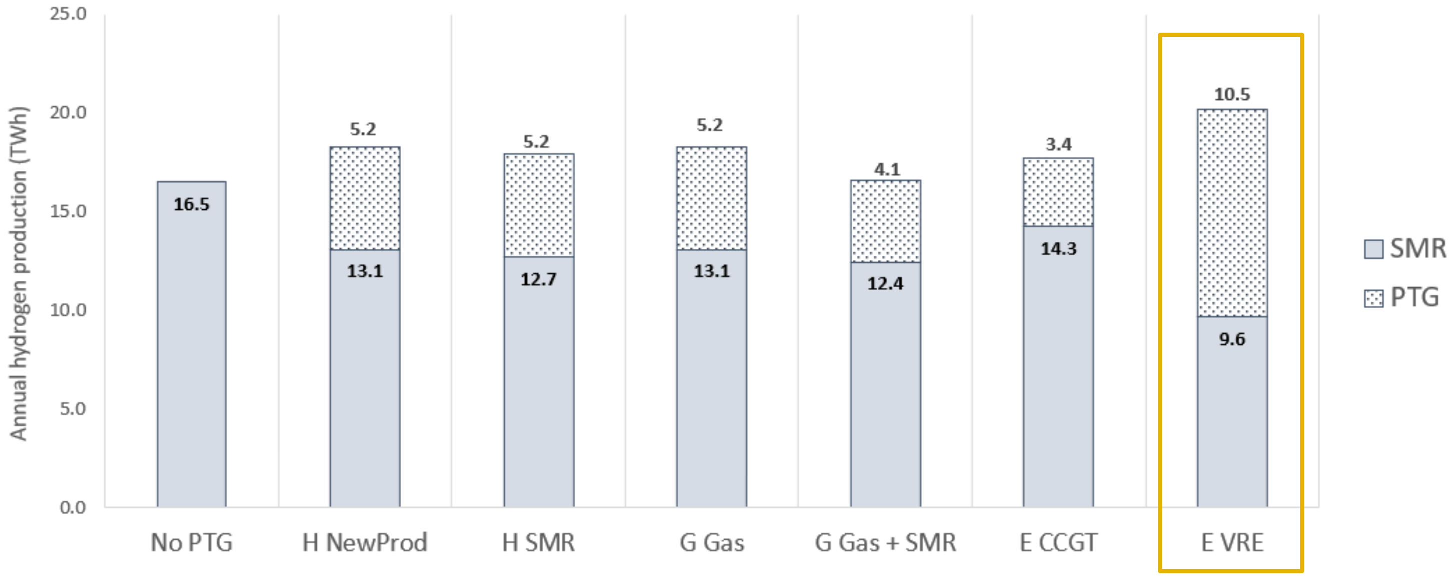
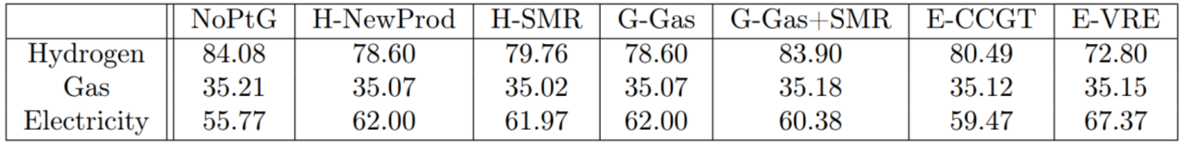
1. The ownership structure retained for PtG has a significant impact of its operations.

PTG OPERATION



Annual hydrogen production per scenario when P_{CO2} *=30€/* t_{CO2} *(TWh)*



	NoPtG	H-NewProd	H-SMR	G-Gas	G-Gas+SMR	E-CCGT	E-VRE
Hydrogen	84.08	78.60	79.76	78.60	83.90	80.49	72.80
Gas	35.21	35.07	35.02	35.07	35.18	35.12	35.15
Electricity	55.77	62.00	61.97	62.00	60.38	59.47	67.37

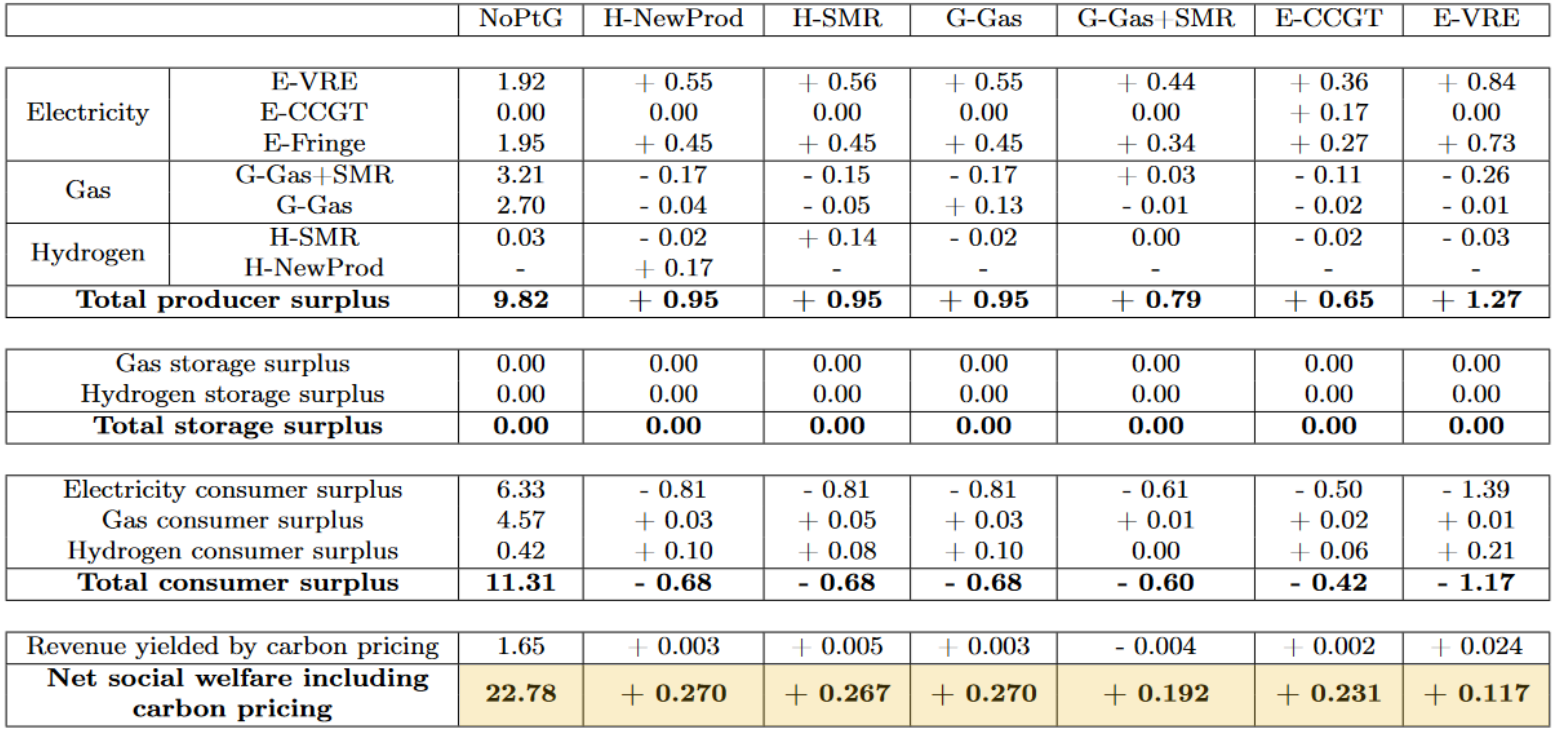
Comparison of the average power, gas and hydrogen prices (€/MWh)

MAIN RESULTS

1. The ownership structure retained for PtG has a significant impact of its operations.

2. The change in short-term welfare associated with the addition of PTG is positive.
However, its distribution is unequal.

SOCIAL IMPACTS



		NoPtG	H-NewProd	H-SMR	G-Gas	G-Gas+SMR	E-CCGT	E-VRE
Electricity	E-VRE	1.92	+ 0.55	+ 0.56	+ 0.55	+ 0.44	+ 0.36	+ 0.84
	E-CCGT	0.00	0.00	0.00	0.00	0.00	+ 0.17	0.00
	E-Fringe	1.95	+ 0.45	+ 0.45	+ 0.45	+ 0.34	+ 0.27	+ 0.73
Gas	G-Gas+SMR	3.21	- 0.17	- 0.15	- 0.17	+ 0.03	- 0.11	- 0.26
	G-Gas	2.70	- 0.04	- 0.05	+ 0.13	- 0.01	- 0.02	- 0.01
Hydrogen	H-SMR	0.03	- 0.02	+ 0.14	- 0.02	0.00	- 0.02	- 0.03
	H-NewProd	-	+ 0.17	-	-	-	-	-
Total producer surplus		**9.82**	**+ 0.95**	**+ 0.95**	**+ 0.95**	**+ 0.79**	**+ 0.65**	**+ 1.27**
Gas storage surplus		0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydrogen storage surplus		0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total storage surplus		**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Electricity consumer surplus		6.33	- 0.81	- 0.81	- 0.81	- 0.61	- 0.50	- 1.39
Gas consumer surplus		4.57	+ 0.03	+ 0.05	+ 0.03	+ 0.01	+ 0.02	+ 0.01
Hydrogen consumer surplus		0.42	+ 0.10	+ 0.08	+ 0.10	0.00	+ 0.06	+ 0.21
Total consumer surplus		**11.31**	**- 0.68**	**- 0.68**	**- 0.68**	**- 0.60**	**- 0.42**	**- 1.17**
Revenue yielded by carbon pricing		1.65	+ 0.003	+ 0.005	+ 0.003	- 0.004	+ 0.002	+ 0.024
Net social welfare including carbon pricing		**22.78**	**+ 0.270**	**+ 0.267**	**+ 0.270**	**+ 0.192**	**+ 0.231**	**+ 0.117**

Annual surpluses obtained under the baseline scenario and the changes observed under the alternative scenarios when P_{CO2} =30€/ t_{CO2} (Bn €)

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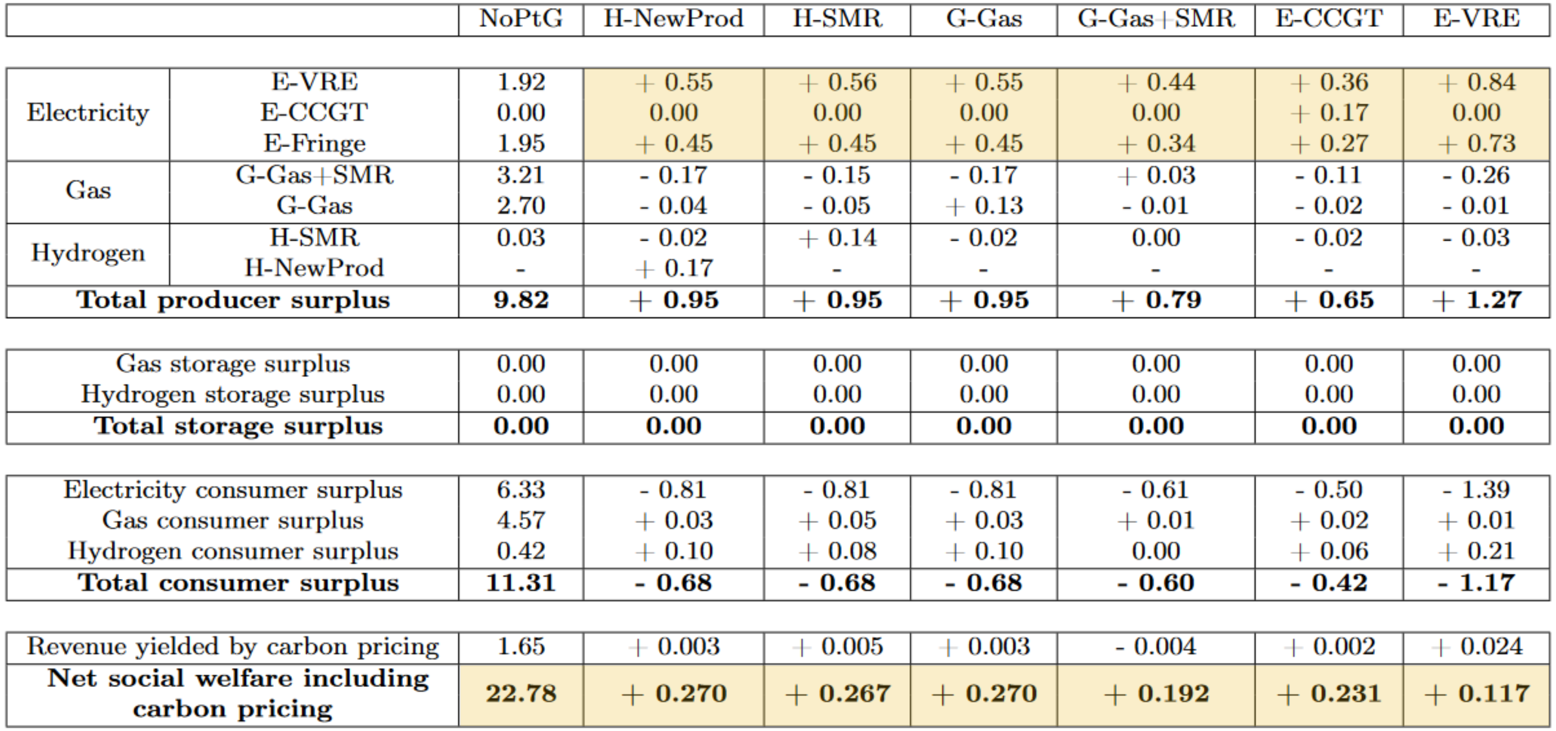

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	E-Fringe	1.95	+ 0.45	+ 0.45	+ 0.45	+ 0.34	+ 0.27	+ 0.73
Gas	G-Gas+SMR	3.21	- 0.17	- 0.15	- 0.17	+ 0.03	- 0.11	- 0.26
	G-Gas	2.70	- 0.04	- 0.05	+ 0.13	- 0.01	- 0.02	- 0.01
Hydrogen	H-SMR	0.03	- 0.02	+ 0.14	- 0.02	0.00	- 0.02	- 0.03
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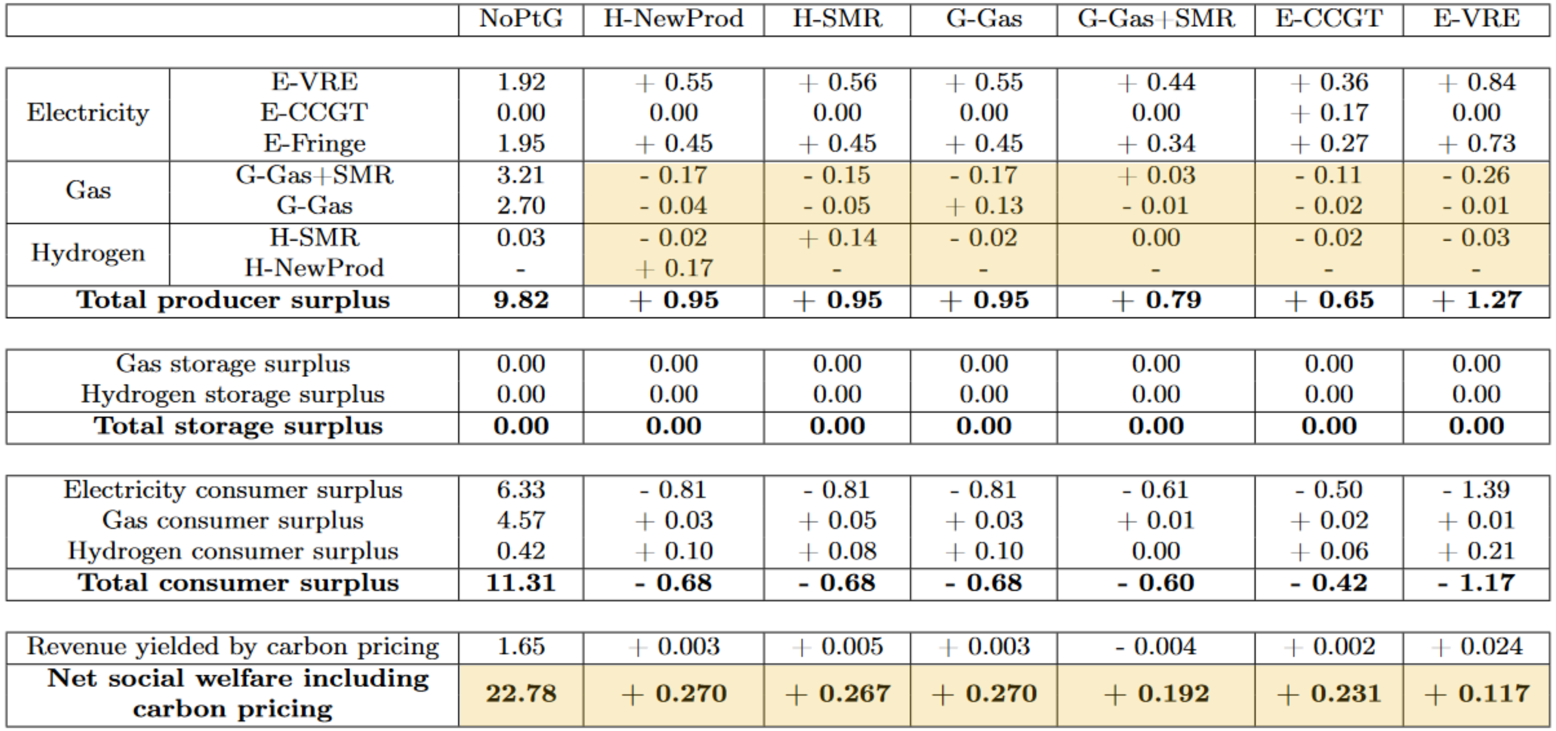

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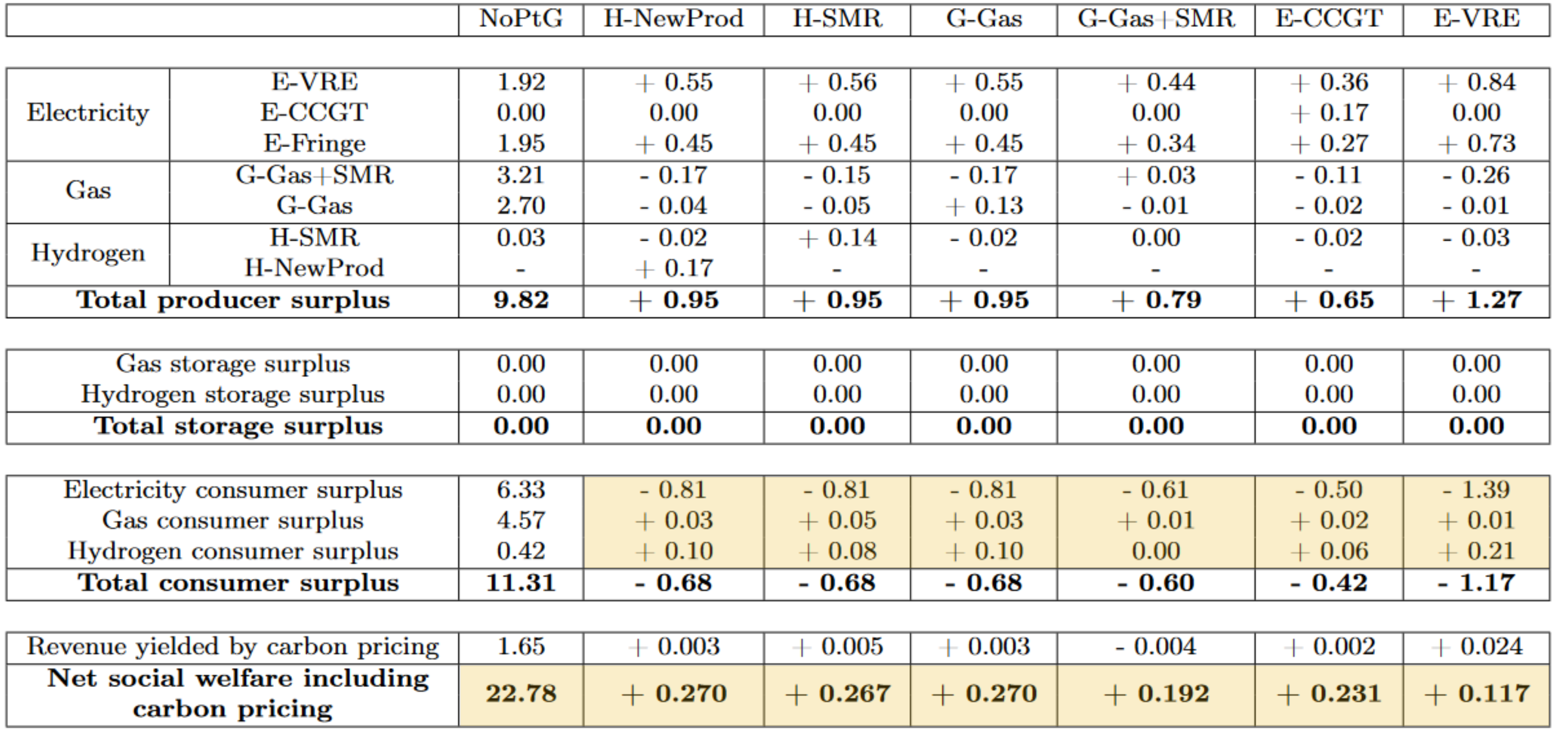


		NoPtG	H-NewProd	H-SMR	G-Gas	G-Gas+SMR	E-CCGT	E-VRE
Electricity	E-VRE	1.92	+ 0.55	+ 0.56	+ 0.55	+ 0.44	+ 0.36	+ 0.84
	E-CCGT	0.00	0.00	0.00	0.00	0.00	+ 0.17	0.00
	E-Fringe	1.95	+ 0.45	+ 0.45	+ 0.45	+ 0.34	+ 0.27	+ 0.73
Gas	G-Gas+SMR	3.21	- 0.17	- 0.15	- 0.17	+ 0.03	- 0.11	- 0.26
	G-Gas	2.70	- 0.04	- 0.05	+ 0.13	- 0.01	- 0.02	- 0.01
Hydrogen	H-SMR	0.03	- 0.02	+ 0.14	- 0.02	0.00	- 0.02	- 0.03
	H-NewProd	-	+ 0.17	-	-	-	-	-
Total producer surplus		**9.82**	**+ 0.95**	**+ 0.95**	**+ 0.95**	**+ 0.79**	**+ 0.65**	**+ 1.27**
Gas storage surplus		0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydrogen storage surplus		0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total storage surplus		**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Electricity consumer surplus		6.33	- 0.81	- 0.81	- 0.81	- 0.61	- 0.50	- 1.39
Gas consumer surplus		4.57	+ 0.03	+ 0.05	+ 0.03	+ 0.01	+ 0.02	+ 0.01
Hydrogen consumer surplus		0.42	+ 0.10	+ 0.08	+ 0.10	0.00	+ 0.06	+ 0.21
Total consumer surplus		**11.31**	**- 0.68**	**- 0.68**	**- 0.68**	**- 0.60**	**- 0.42**	**- 1.17**
Revenue yielded by carbon pricing		1.65	+ 0.003	+ 0.005	+ 0.003	- 0.004	+ 0.002	+ 0.024
Net social welfare including carbon pricing		**22.78**	**+ 0.270**	**+ 0.267**	**+ 0.270**	**+ 0.192**	**+ 0.231**	**+ 0.117**

Annual surpluses obtained under the baseline scenario and the changes observed under the alternative scenarios when P_{CO2} =30€/ t_{CO2} (Bn €)

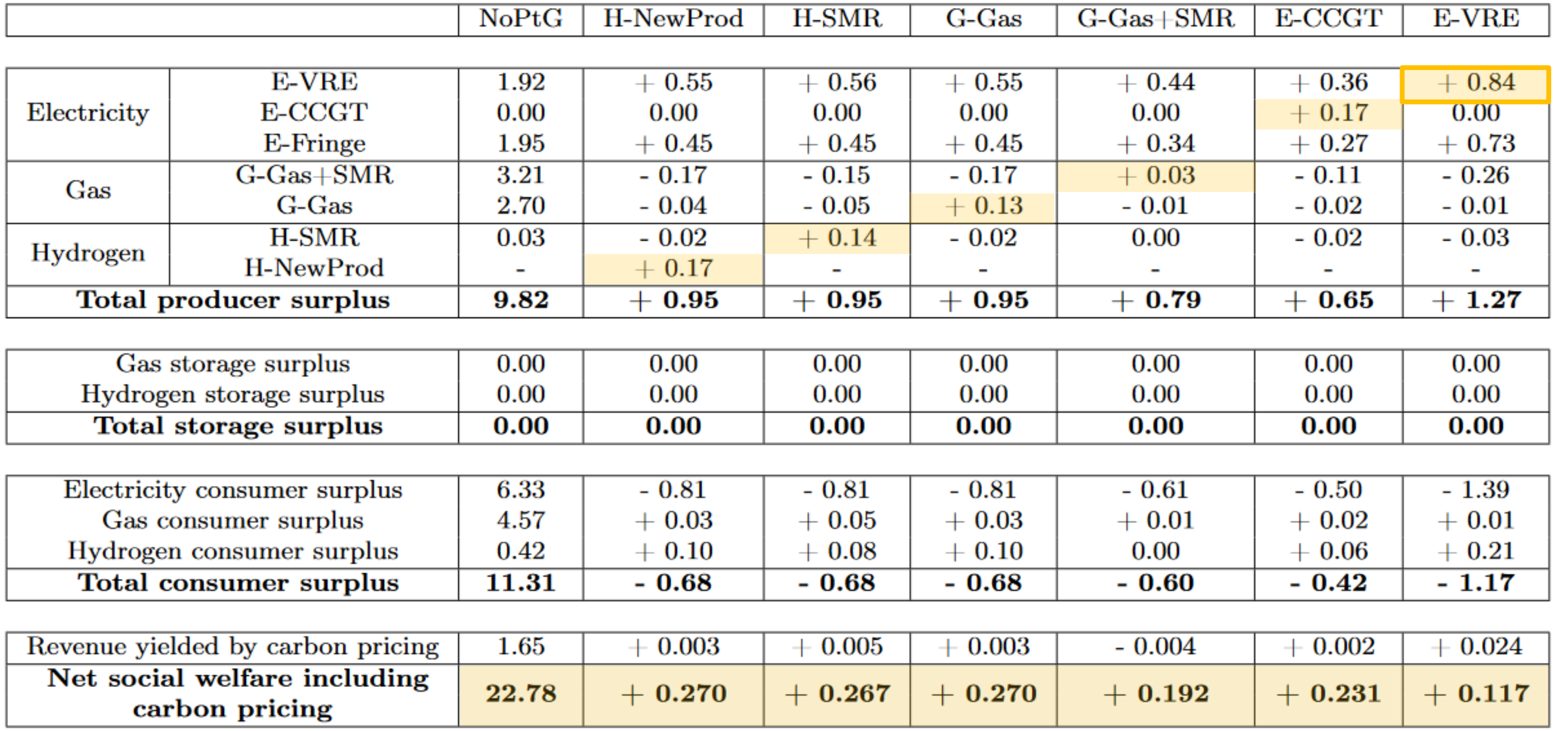
MAIN RESULTS

1. The ownership structure retained for PtG has a significant impact of its operations.

2. The change in short-term welfare associated with the addition of PTG is <u>positive.</u>
However, its distribution is <u>unequal</u>.

3. PtG investment cost is too high to make PtG a welfare-enhancing technology in the long term.

SOCIAL IMPACTS



		NoPtG	H-NewProd	H-SMR	G-Gas	G-Gas+SMR	E-CCGT	E-VRE
Electricity	E-VRE	1.92	+ 0.55	+ 0.56	+ 0.55	+ 0.44	+ 0.36	+ 0.84
	E-CCGT	0.00	0.00	0.00	0.00	0.00	+ 0.17	0.00
	E-Fringe	1.95	+ 0.45	+ 0.45	+ 0.45	+ 0.34	+ 0.27	+ 0.73
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Hydrogen	H-SMR	0.03	- 0.02	+ 0.14	- 0.02	0.00	- 0.02	- 0.03
	H-NewProd	-	+ 0.17	-	-	-	-	-
Total producer surplus		**9.82**	**+ 0.95**	**+ 0.95**	**+ 0.95**	**+ 0.79**	**+ 0.65**	**+ 1.27**
Gas storage surplus		0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydrogen storage surplus		0.00	0.00	0.00	0.00	0.00	0.00	0.00
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Annual surpluses obtained under the baseline scenario and the changes observed under the alternative scenarios when P_{CO2} =30€/ t_{CO2} (Bn €)

PtG annual equivalent cost of capital: €0.71 billion

MAIN RESULTS

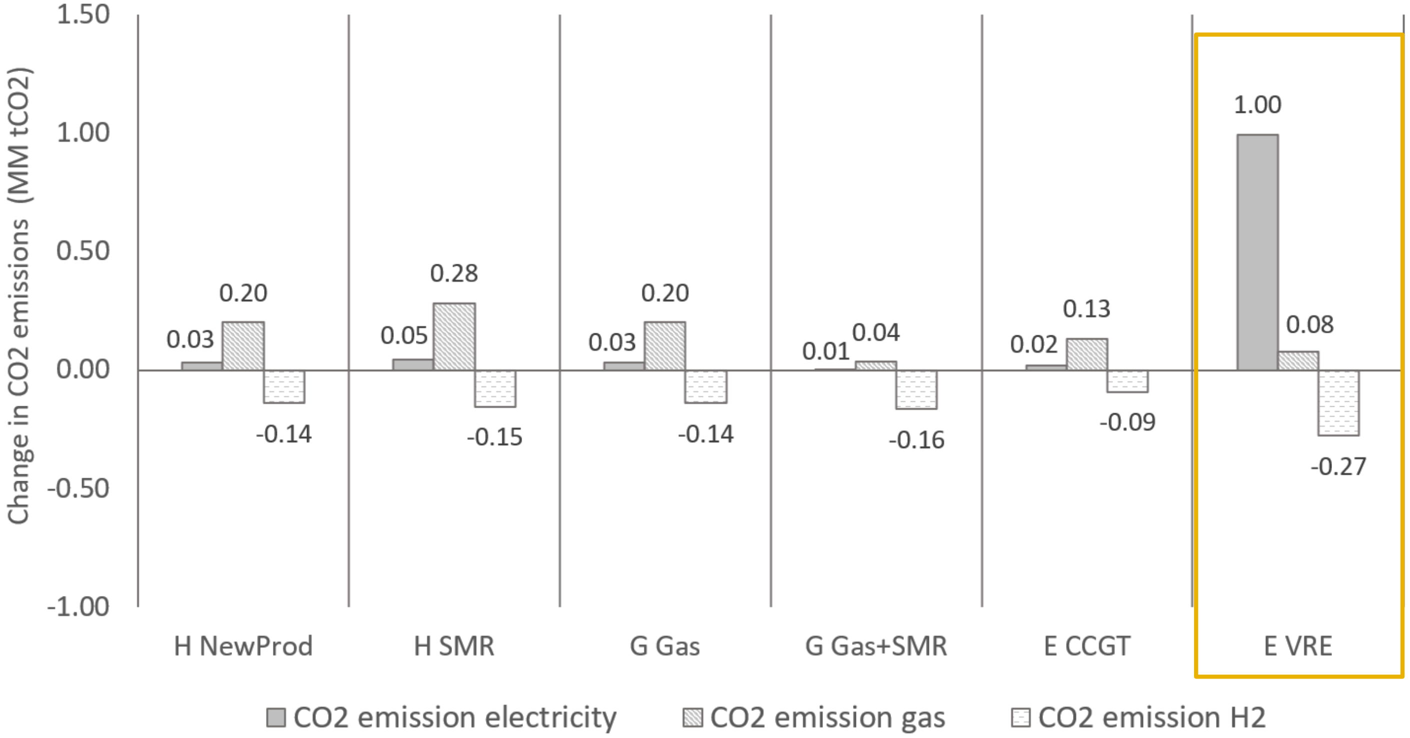
1. The ownership structure retained for PtG has a significant impact of its operations.

2. The change in short-term welfare associated with the addition of PTG is <u>positive.</u>
However, its distribution is <u>unequal</u>.

3. PtG investment cost is too high to make PtG a welfare-enhancing technology in the long term.

4. PtG could indirectly lead to a high increase in carbon-based electricity generation

ENVIRONMENTAL IMPACTS



Change in CO2 emissions by sector compared to the No PTG case when PCO2 =30€/ tCO2

CONCLUSION

In an imperfectly competitive electricity, gas and hydrogen system:

- The **operation and profitability of PtG differ** depending on the **profile of its owner**.
- The operation of PtG can **increase the total social welfare** but **change its distribution**.
- The ownership organization that provides the PtG owner with **the largest individual gain** is also **the least desirable from a social and environmental perspective**.

CONTACT

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Thanks for your attention!

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APPENDICES

- Appendices – Background – technology at its early stage
- Appendices – Data
    - Electricity market
    - Gas market
    - H2 market
- Appendices – Preliminary results
    - Production / Demand
    - Emission costs

BACKGROUND - POWER-TO-GAS
A TECHNOLOGY AT ITS EARLY STAGE

There are still challenges associated with the widespread adoption of PtG technologies

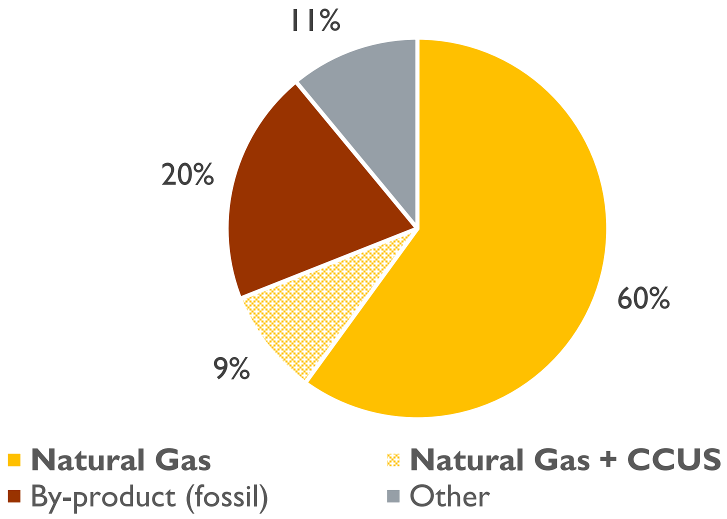
- Lack of Maturity
- Strong need for renewable electricity
- Political and regulation uncertainty
- Change in the industrial organisation

BACKGROUND - POWER-TO-GAS

A TECHNOLOGY THAT IS PART OF THE EUROPEAN ENERGY CLIMATE POLICY

Producing decarbonized hydrogen requires strong changes and adaptations of current production sources

European Regional supply of pure hydrogen (2019)



Future European Regional supply of pure hydrogen ?

Production of low carbon hydrogen in the short and medium term:

Retrofitting of existing hydrogen production facilities/steam methane reformers (SMRs) with CCS

&

Production of renewable hydrogen : **Power-to-Gas**

Production of green hydrogen from renewable electricity by electrolysis of water

Sources: IEA – Hydrogen in North-Western Europe, a Vision towards 2030

REPRESENTATIVE DAYS

8 representative days (2 per season, 1 weekday and 1 weekend day), and 5 representative hours per day.

Seasons :

- Summer: May -> August (weight: 123)
- Autumn: September, October (weight: 61)
- Winter: November -> February (weight: 120)
- Spring: March, April (weight: 61)

Day	Description
1	Summer - Week
2	Summer – Weekend
3	Autumn – Week
4	Autumn – Weekend

Day	Description
5	Winter – Week
6	Winter – Weekend
7	Spring – Week
8	Spring – Weekend

Time steps per day:

- 2h – 7h AM (weight: 5)
- 7h – 12h AM (weight: 5)
- 12h AM – 5h PM (weight: 5)
- 5h – 10h PM (weight: 5)
- 10h PM – 2h AM (weight: 4)

Hours	Description
1	10h PM – 2h AM
2	2h – 7h AM
3	7h – 12h AM
4	12h AM – 5h PM
5	5h – 10h PM

For each period, the data found for the year is averaged

DATA – ELECTRICITY MARKET

Technology costs:

- Operational cost
- Ramp up cost
- Fuel cost (when exogenous)
- Conversion efficiency
- CO2 Emission rate
- CO2 price

Producer portfolio

- Global installed capacity
- Maximum generation capacity for each producer

Technology features:

- Availability factor for conventional energy generation
- Availability factor for renewable energy generation

Demand function:

- Intercept and slope of linear inverse demand function

DATA – ELECTRICITY MARKET
GENERATION CAPACITY

References:

- *Capacity by generation source: EU Reference Scenario 2020: Energy, Transport and GHG Emissions : Trends to 2050 (PRIMES assumptions)*
- *Maximum generation capacity per producer: personal preference*

Capacity by generation source

	GW	%
VRE (solar, wind)	53	82%
CCGT (Gas)	12	18%
TOTAL (GW)	65	100%

Maximum generation capacity per producer

	VRE	CCGT
E_VRE	50% **26 GW**	0%
E_CCGT	0%	50% **6 GW**
E_Fringe	50% **27 GW**	50% **6 GW**

DATA – ELECTRICITY MARKET
GENERATION COST

References:

- *Operational, Fuel cost:, and conversion efficiency: EU Reference Scenario 2020: Energy, Transport and GHG Emissions :Trends to 2050 (PRIMES assumptions)*
- *CO2 emission rate and ramp-up cost: (Virasjoki & al, 2016)*
- *CO2 Price: IAE projected cost of generating energy 2020 (lien)*

Technology	Operational cost in 2030 (€/MWh)	Ramp up cost (€/MWh)	Fuel cost (€/MWh)	Conversion efficiency (%)	CO2 emission rate (tCO2/MWh)
Gas (CCGT)	2.3	5,8	Endogenous to the model	0,58	0,37
VRE	0	0	0	1	0

CO2 price:

- The EGC includes a harmonized **carbon price of USD 30 per tone of CO2**
- The Fit for 55 package will lead to a rise in CO2 prices to **EUR 90 by 2030**

DATA – ELECTRICITY MARKET

AVAILABILITY FACTOR

References:

- *Conventional technologies: IAE projected cost of generating energy 2020 (lien)*
- Variable renewable technologies: https://data.open-power-system-data.org/ninja_pv_wind_profiles/

Technology	Capacity Factor
Gas (CCGT)	85%
VRE	Variable (ref : 2019)

DATA – ELECTRICITY MARKET

DEMAND FUNCTION

References:

- Demand Data: ENTSOE Transparency Platform: electricity consumption data hour by hour or 15min by 15min, and by country
- Price : Eco2Mix RTE website: electricity price by hour and by country
- Elasticity : same reference as in (Li & Mulder, 2021): Labandeira X, Labeaga JM, Lopez-Otero X. A meta-analysis on the price elasticity of energy demand. Energy policy

Electricity price elasticity = -0,3

Demand function coefficient $\mathrm{a_{d,h}}$ and $\mathrm{b_{d,h}}$:

Demand function:$\forall\ d, h \quad D_{d,h}^{elec} = \mathrm{a_{d,h}^{\mathit{elec}}} - \mathrm{b_{d,h}^{\mathit{elec}}} * \mathrm{P_{d,h}^{elec}}$

With $\mathrm{a}_{\mathrm{d,h},c}^{elec} = (1-\varepsilon) * D_{d,h,c}^{elec}$ and $\mathrm{b_{d,h,c}^{\mathit{elec}}} = -\varepsilon * \frac{D_{d,h,c}^{elec}}{P_{d,h,c}^{elec}}$

DATA – GAS MARKET

Long term contract:

- Procurement cost function coefficients

Storage:

- Working gas capacity
- Maximum storage withdrawal rate
- Storage injection cost

Demand function:

- Intercept and slope of linear inverse demand function

DATA – GAS MARKET
LONG TERM CONTRACT

References:

Same reference as in (Roach &Meeus, 2021): *Del Valle & al, A fundamental analysis on the implementation and development of virtual natural gas hub.*

$$c_m(Q^{gaz}) = c_{intercept} + c_{slope} * Q^{gaz}$$

$\boldsymbol{c_{intercept}}$	15 €/MWh
$\boldsymbol{c_{slope}}$	0,000002 €/MWh²

DATA – GAS MARKET

STORAGE

References:

- *Working Gas Capacity & Storage Withdrawal Rate : Picturing the value of underground gas storage to the European hydrogen system – Gas Infrastructure Europe (lien) – Appendix Natural Gas Statistics (p.52)*
- *- Storage injection cost: PRIMES Study*

	Working Gas capacity (TWh)	Storage withdrawal rate (% of working gas capacity)	Storage injection cost (€/MWh)
Underground Gas Storage	144	0.02	0,7

DATA – GAS MARKET
DEMAND FUNCTION

References:

- Demand: ENTSOG Transparency Platform: daily gas consumption data
- Prix : Pink Sheet World Bank: price marker for the European price ~ German price
- Elasticity : same reference as in (Li & Mulder, 2021): Labandeira X, Labeaga JM, Lopez-Otero X. A meta-analysis on the price elasticity of energy demand. Energy policy

Gas price elasticity = -0,3

Demand function coefficient $\mathrm{a}_{\mathrm{d}}^{gas}$ **and** $\mathrm{b}_{\mathrm{d}}^{gas}$ **:**

Demand function: $\forall\, d, \quad D_{d}^{gas} = \mathrm{a}_{\mathrm{d}}^{gas} - \mathrm{b}_{\mathrm{d}}^{gas} * \mathrm{P}_{\mathrm{d}}^{\mathrm{gas}}$

With $\mathrm{a}_{\mathrm{d},c}^{gas} = (1-\varepsilon) * D_{d,c}^{gas}$ and $\mathrm{b}_{\mathrm{d,c}}^{gas} = -\varepsilon * \frac{D_{d,c}^{gas}}{P_{d,c}^{gas}}$

DATA – H2 MARKET

SMR & PTG:

- Operational cost
- Conversion efficiency
- Generation capacity

Storage:

- Working gas capacity
- Maximum storage withdrawal rate
- Storage injection cost

Demand function:

- Intercept and slope of linear inverse demand function

DATA – H2 MARKET
GENERATION CAPACITY & GENERATION COST

References:

- *Electrolysers capacity: Dutch National Climate agreement*
- *SMR capacity: personal choice*
- *Conversion efficiency: PRIMES study assumptions & (Li & Mulder,2021)*
- *CCS cost: (Li & Mulder,2021)*

	Capacity (GW)	Efficiency
Electrolyser	4	0,7
SMR	10	0,6

- PTG generation cost: Electricity price
- SMR generation cost: Gas price and CO2 capture and storage (CCS) cost:
  SMR cost: $\gamma \ * \ (\lambda * c_{carbon\ price} + (1-\lambda) * c_{CCS})$
  With γ carbon emission of burned gas, et λ fraction of carbon being emitted in SMR

	γ (t CO2/MWh)	λ	c_{CCS} (€/t CO2)
SMR	0,2	0,2	50

DATA – H2 MARKET

STORAGE

References:

- *Working Gas Capacity: Picturing the value of underground gas storage to the European hydrogen system – Gas Infrastructure Europe (lien)) – (p.38)*
- *Storage Withdrawal Rate: personal assumption considering Picturing the value of underground gas storage to the European hydrogen system – Gas Infrastructure Europe (lien)) – (p.38)*
- *Storage injection cost: PRIMES Study*

	Working Gas capacity (TWh)	Storage withdrawal rate (% of working gas capacity)	Storage injection cost (€/MWh)
H2 Storage	6	0,12	0,7

DATA – H2 MARKET
DEMAND FUNCTION

References:

- *Demand: Etude Picturing the value of underground gas storage to the European hydrogen system – Gas Infrastructure Europe (lien) (p.38)*
- *H2 price and elasticity: (Li & Mulder, 2021)*

Demand	Daily demand	Price	Elasticity
4,42 Mt H2/year	403,2 GWh/day	45 €/MWh	-0,5

Demand function coefficient $\mathrm{a_d}$ **and** $\mathrm{b_d}$ **:** $D_d^{H2} = \mathrm{a}_\mathrm{d}^{H2} - \mathrm{b}_\mathrm{d}^{H2} * \mathrm{P}_\mathrm{d}^{H2}$

- $\mathrm{a}_\mathrm{d}^{H2} = (1-\varepsilon) * D_d^{H2} = 604{,}8\ \mathrm{GWh}$
- $\mathrm{b}_\mathrm{d}^{H2} = -\varepsilon\ * \frac{D_\mathrm{d}^{H2}}{P_d^{H2}} = 4480\ \mathrm{MWh/€}$

METHODOLOGY

EQUATIONS – ELECTRICITY MARKET

Electricity Producer : Optimization problem – Profit Maximization

$$\underset{\substack{q^E_{p,x,d,h}, q^{E,up}_{p,CCGT,d,h},\\ q^H_{p,PTG,d,h}}}{\text{maximize}} \quad \sum_{d,h} w_d.w_h.\Bigg[\sum_{x\in\mathcal{X}}\Big(q^E_{p,x,d,h}.\pi^E_{d,h} - q^E_{p,x,d,h}.C^E_{p,x,d}\Big) - q^{E,up}_{p,CCGT,d,h}.C^{E,up}_{CCGT,d} \tag{1a}$$

$$+ q^H_{p,PTG,d,h}.\Big(\pi^H_d - \frac{1}{\gamma_{PTG}}.\pi^E_{d,h}\Big)\Bigg] \tag{1b}$$

subject to

$$q^E_{p,VRE,d,h} = K^E_{p,VRE}.AVA^E_{p,d,h} \qquad \forall d,h, \quad (\lambda^{E,1}_{p,d,h}), \tag{1c}$$

$$q^E_{p,CCGT,d,h} \leq K^E_{p,CCGT} \qquad \forall d,h, \quad (\lambda^{E,2}_{p,d,h}), \tag{1d}$$

$$q^H_{p,PTG,d,h} \leq K^H_{p,PTG} \qquad \forall d,h, \quad (\lambda^{E,3}_{p,d,h}), \tag{1e}$$

$$w_h.q^E_{p,CCGT,d,h} \leq w_{h-1}.q^E_{p,CCGT,d,h-1} + w_h.q^{E,up}_{p,CCGT,d,h} \forall d,h, \quad (\lambda^{E,4}_{p,d,h}), \tag{1f}$$

$$0 \leq q^E_{p,x,d,h}, \quad 0 \leq q^{E,up}_{p,CCGT,d,h}, \quad 0 \leq q^H_{p,PTG,d,h} \qquad \forall d,h,x \tag{1g}$$

METHODOLOGY

EQUATIONS – ELECTRICITY MARKET

Electricity Market Clearing Constraint

$$\forall d, h, \quad D^E_{d,h} = a^E_{d,h} - b^E_{d,h} . {\pi^E_{d,h}}^* \qquad a^E_{d,h} > 0, b^E_{d,h} > 0 \tag{2}$$

$$\forall d, h, \quad 0 \leq \sum_{p,x} q^E_{p,x,d,h} - \left(D^E_{d,h} + \sum_{p} \frac{1}{\gamma_{PTG}} . q^H_{p,PTG,d,h} \right) \perp {\pi^E_{d,h}}^* \geq 0 \tag{3}$$

METHODOLOGY

EQUATIONS – GAS MARKET

Gas Midstreamers : Optimization problem – Profit Maximization

$$\underset{\substack{q^G_{p,d}, q^H_{p,SMR,d},\\ q^H_{p,PTG,d,h}}}{\text{maximize}} \quad \sum_d w_d.\left[q^G_{p,d}.\pi^G_d - q^G_{p,d}.\left(C^G_{inter} + C^G_{slope}.q^G_{p,d}\right)\right] \tag{4a}$$

$$+\sum_d w_d.\left[q^H_{p,SMR,d}.\left(\pi^H_d - \frac{1}{\gamma_{SMR}}.(\pi^G_d + C_{CCS})\right)\right] \tag{4b}$$

$$+\sum_{d,h} w_d.w_h.\left[q^H_{p,PTG,d,h}.\left(\pi^H_d - \frac{1}{\gamma_{PTG}}.\pi^E_{d,h}{}^*\right)\right] \tag{4c}$$

subject to

$$q^H_{p,SMR,d} \leq K^H_{p,SMR} \qquad \forall d \quad (\lambda^{G,1}_{p,d}), \tag{4d}$$

$$q^H_{p,PTG,d,h} \leq K^H_{p,PTG} \qquad \forall d,h \quad (\lambda^{G,2}_{p,d,h}), \tag{4e}$$

$$0 \leq q^G_{p,d}, \quad 0 \leq q^H_{p,SMR,d}, \quad 0 \leq q^H_{p,PTG,d,h} \qquad \forall d,h \tag{4f}$$

METHODOLOGY

EQUATIONS – GAS MARKET

Gas Storage : Optimization problem – Profit Maximization

$$\underset{\substack{u^G_{stor,d}, r^G_{in,d},\\ r^G_{out,d}}}{\text{maximize}} \quad \sum_{d \in \mathcal{D}} w_d . \left[r^G_{out,d} . {\pi^G_d}^* - r^G_{in,d} . \left({\pi^G_d}^* + C^G_{in} \right) \right] \tag{5a}$$

subject to

$$r^G_{in,d} \leq T^G_{in} . K^G_{stor} \qquad \forall d \quad (\lambda^{G,1}_{stor,d}), \tag{5b}$$

$$r^G_{out,d} \leq T^G_{out} . K^G_{stor} \qquad \forall d \quad (\lambda^{G,2}_{stor,d}), \tag{5c}$$

$$u^G_{stor,d} \leq K^G_{stor} \qquad \forall d \quad (\lambda^{G,3}_{stor,d}), \tag{5d}$$

$$u^G_{stor,d} = u^G_{stor,d-1} + w_d . \left(r^G_{in,d} - r^G_{out,d} \right) \qquad \forall d \quad (\lambda^{G,4}_{stor,d}), \tag{5e}$$

$$0 \leq r^G_{in,d}, \quad 0 \leq r^G_{out,d}, \quad 0 \leq u^G_{stor,d} \qquad \forall d \tag{5f}$$

METHODOLOGY

EQUATIONS – GAS MARKET

Gas Market Clearing Constraint

$$\forall d, \quad D_d^G = a_d^G - b_d^G . {\pi_d^G}^* \qquad a_d^G > 0, b_d^G > 0 \qquad (6)$$

$$\forall d, \quad 0 \leq \sum_p q_{p,d}^G - \left(D_d^G + \sum_p \frac{q^H_{p,SMR,d}}{\gamma_{SMR}} + \sum_p \sum_{h \in \mathcal{H}} \frac{q^E_{p,CCGT,d,h}}{\gamma_{CCGT}}\right) + \left(r^G_{out,d} - r^G_{in,d}\right) \perp {\pi_d^G}^* \geq 0 \quad (7)$$

METHODOLOGY

EQUATIONS – H2 MARKET

H2 Producer : Optimization problem – Profit Maximization

$$\underset{\substack{q^H_{p,SMR,d},\\ q^H_{p,PTG,d,h}}}{\text{maximize}} \quad \sum_{d\in\mathcal{D}} w_d.\left[q^H_{p,SMR,d}.\left(\pi^H_d - \frac{1}{\gamma_{SMR}}.(\pi^{G\ *}_d + C_{CCS})\right)\right] \tag{8a}$$

$$+ \sum_{d\in\mathcal{D},h\in\mathcal{H}} w_d.w_h.\left[q^H_{p,PTG,d,h}.\left(\pi^H_d - \frac{1}{\gamma_{PTG}}.\pi^{E\ *}_{d,h}\right)\right] \tag{8b}$$

subject to

$$q^H_{p,SMR,d} \leq K^H_{p,SMR} \qquad \forall d \qquad (\lambda^{H,1}_{p,d}), \tag{8c}$$

$$q^H_{p,PTG,d,h} \leq K^H_{p,PTG} \qquad \forall d,h \qquad (\lambda^{H,2}_{p,d,h}), \tag{8d}$$

$$0 \leq q^H_{p,SMR,d}, \quad 0 \leq q^H_{p,PTG,d,h} \qquad \forall d,h \tag{8e}$$

METHODOLOGY
EQUATIONS – H2 MARKET

H2 Storage : Optimization problem – Profit Maximization

$$\underset{\substack{u^H_{stor,d}, r^H_{in,d},\\ r^H_{out,d}}}{\text{maximize}} \quad \sum_{d \in \mathcal{D}} w_d . \left[r^H_{out,d} . \pi^{H\,*}_d - r^H_{in,d} \left(\pi^{H\,*}_d + C^H_{in} \right) \right] \tag{9a}$$

subject to

$$r^H_{in,d} \leq T^H_{in} . K^H_{stor} \qquad \forall d \quad (\lambda^{H,1}_{stor,d}), \tag{9b}$$

$$r^H_{out,d} \leq T^H_{out} . K^H_{stor} \qquad \forall d \quad (\lambda^{H,2}_{stor,d}), \tag{9c}$$

$$u^H_{stor,d} \leq K^H_{stor} \qquad \forall d \quad (\lambda^{H,3}_{stor,d}), \tag{9d}$$

$$u^H_{stor,d} = u^H_{stor,d-1} + w_d . \left(r^H_{in,d} - r^H_{out,d} \right) \qquad \forall d \quad (\lambda^{H,4}_{stor,d}), \tag{9e}$$

$$0 \leq r^H_{in,d}, \quad 0 \leq r^H_{out,d}, \quad 0 \leq u^H_{stor,d} \qquad \forall d \tag{9f}$$

METHODOLOGY

EQUATIONS – H2 MARKET

H2 Market Clearing Constraint

$$\forall d, \quad D_d^H = a_d^H - b_d^H . {\pi_d^H}^* \qquad a_d^H > 0, b_d^H > 0 \tag{10}$$

$$\forall d, \quad 0 \leq \sum_p \left(q^H_{p,SMR,d} + \sum_{h \in \mathcal{H}} w_h . q^H_{p,PTG,d,h} \right) - D_d^H + \left(r^H_{out,d} - r^H_{in,d} \right) \perp {\pi_d^H}^* \geq 0 \tag{11}$$

METHODOLOGY

MARKET POWER REPRESENTATION

Price in the agent's optimization problem : $\pi = (1-\delta).\underset{\text{Market clearing price}}{\underset{\downarrow}{\pi^*}} + \delta.\underset{\text{Inverse demand function}}{\underset{\searrow}{\Pi(.)}}$

The parameter δ denotes the player's degree of market power.

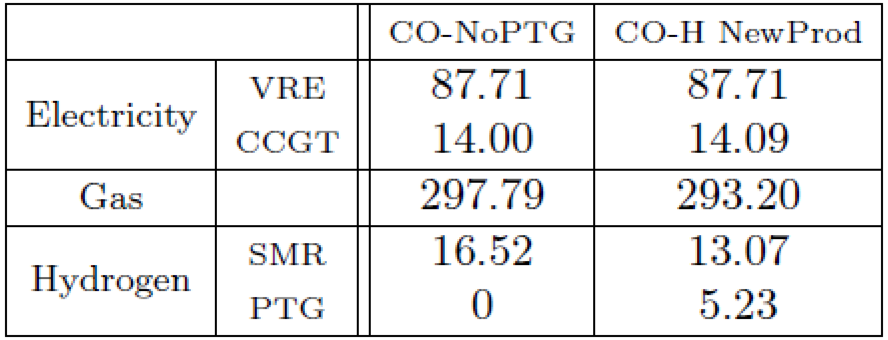
$\delta = 0 \ \rightarrow \ \pi = \pi^*$: The agent bases its operations on the market clearing price

$\delta = 1 \ \rightarrow \ \pi = \Pi(.)$: The agent knows the inverse demand function and adapt its production accordingly, thus influencing the market price

PRELIMINARY RESULTS

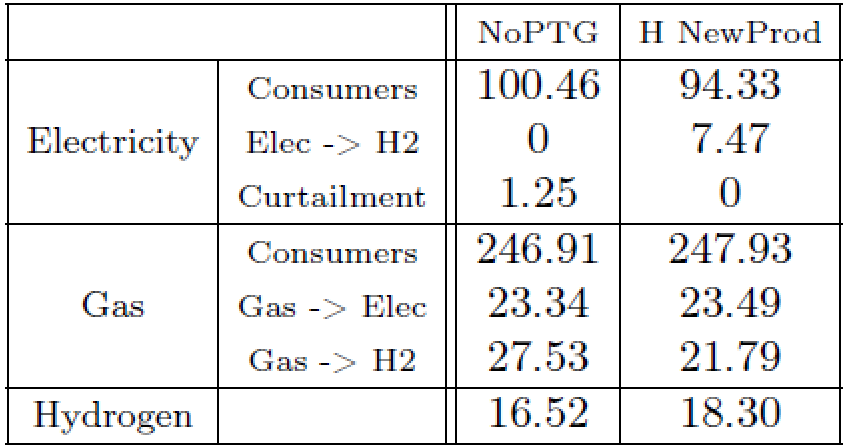
IMPACT OF PTG ON PRODUCTION AND DEMAND

(a) Comparison of annual production by sector



		CO-NoPTG	CO-H NewProd
Electricity	VRE	87.71	87.71
	CCGT	14.00	14.09
Gas		297.79	293.20
Hydrogen	SMR	16.52	13.07
	PTG	0	5.23

(b) Comparison of annual demand by sector



		NoPTG	H NewProd
Electricity	Consumers	100.46	94.33
	Elec -> H2	0	7.47
	Curtailment	1.25	0
Gas	Consumers	246.91	247.93
	Gas -> Elec	23.34	23.49
	Gas -> H2	27.53	21.79
Hydrogen		16.52	18.30

PRELIMINARY RESULTS

MARKET SHARES IN THE HYDROGEN MARKET

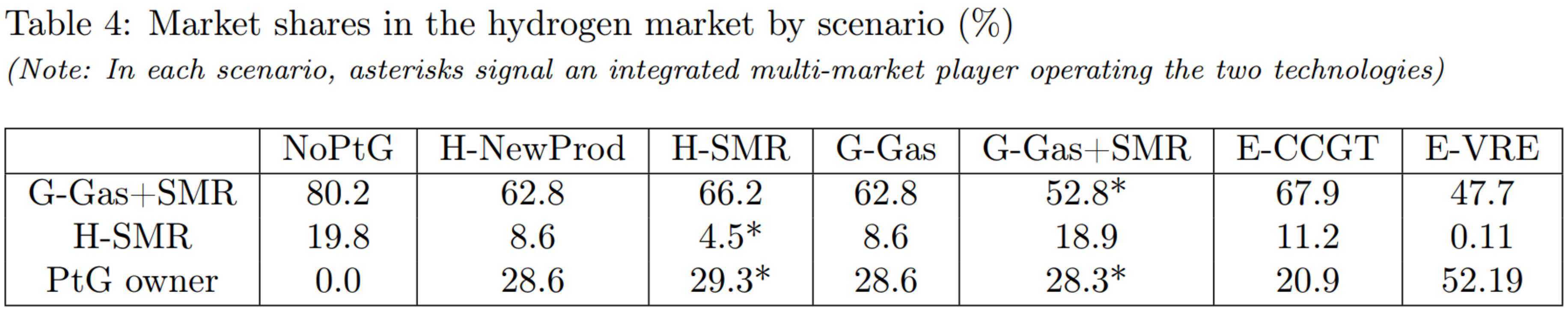


Table 4: Market shares in the hydrogen market by scenario (%)

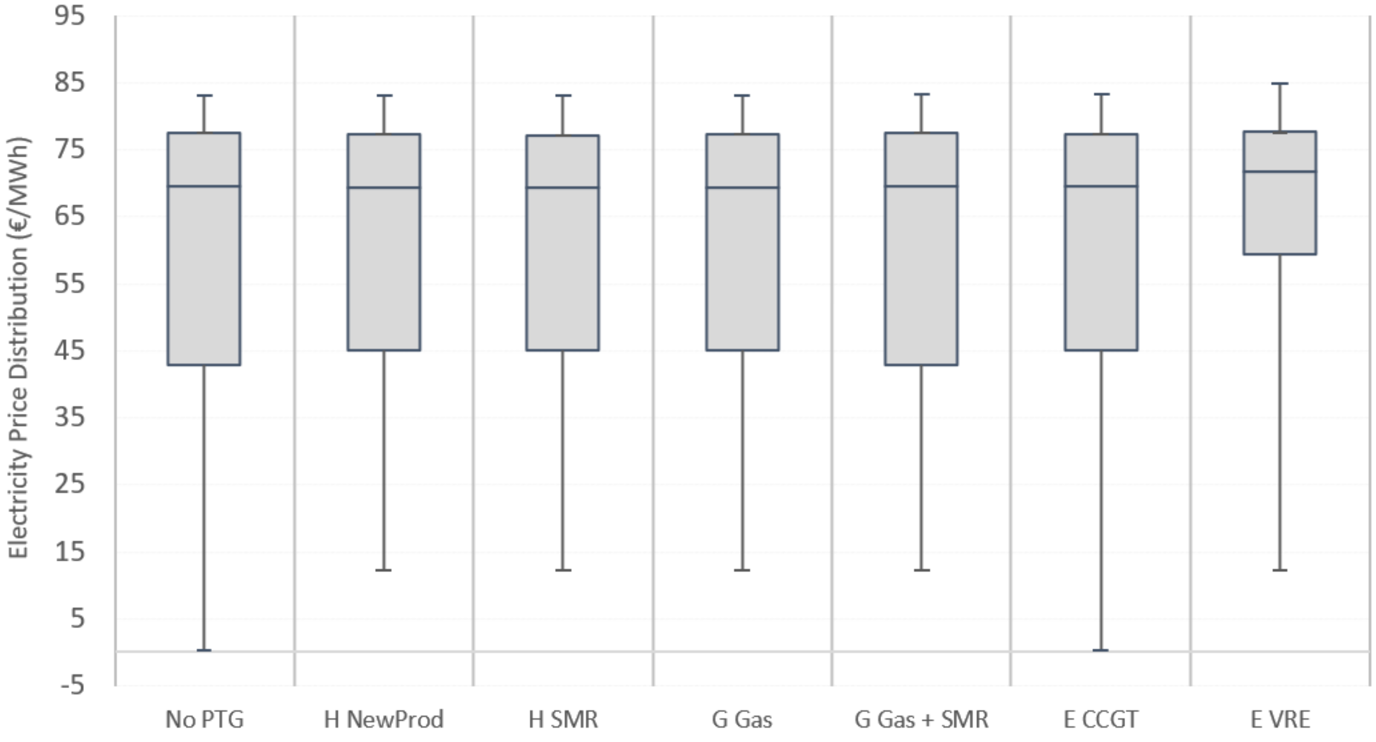
(Note: In each scenario, asterisks signal an integrated multi-market player operating the two technologies)

	NoPtG	H-NewProd	H-SMR	G-Gas	G-Gas+SMR	E-CCGT	E-VRE
G-Gas+SMR	80.2	62.8	66.2	62.8	52.8*	67.9	47.7
H-SMR	19.8	8.6	4.5*	8.6	18.9	11.2	0.11
PtG owner	0.0	28.6	29.3*	28.6	28.3*	20.9	52.19

- In all scenarios, the supply of SMR-based hydrogen is dominated by the vertically integrated firm G-Gas+SMR.

- In all scenarios except “E-VRE,” G-Gas+SMR’s strategic advantage is powerful enough to dominate the entire hydrogen market.

RESULTS – PTG AS A PROVIDER OF FLEXIBILITY



Electricity price distribution (€/MWh)

- PTG consumes electricity generated from renewable sources, increasing electricity prices when they are low.
- **It increases off-peak prices**, resulting in a lower volatility of electricity prices.
- **PTG eliminates periods of surplus electricity**: except for the "E CCGT" case, the cases with PTG no longer have zero price occurrences, which occur when part of the electricity produced is spilled.

PRELIMINARY RESULTS
PROFIT GAINED FROM PTG OWNERSHIP

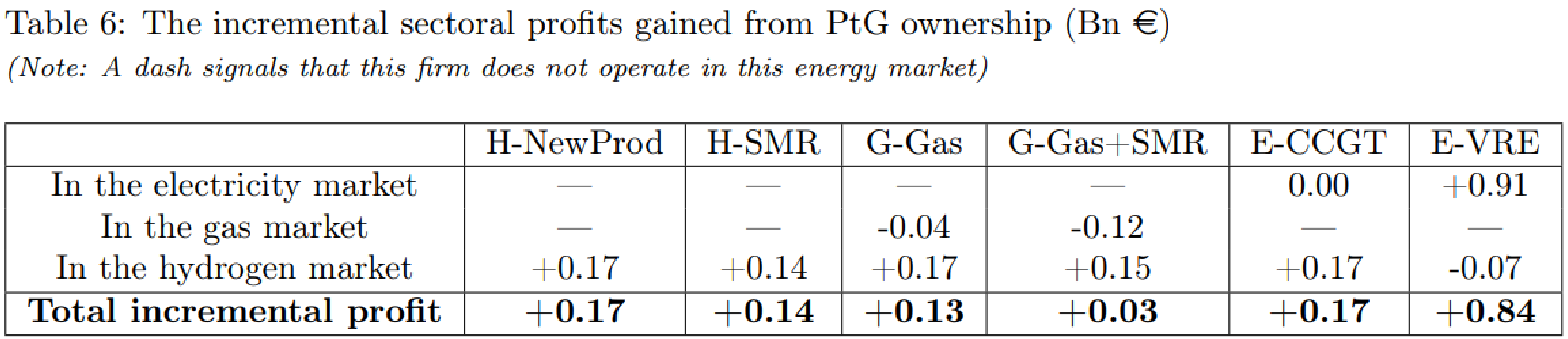


Table 6: The incremental sectoral profits gained from PtG ownership (Bn €)

(Note: A dash signals that this firm does not operate in this energy market)

	H-NewProd	H-SMR	G-Gas	G-Gas+SMR	E-CCGT	E-VRE
In the electricity market	—	—	—	—	0.00	+0.91
In the gas market	—	—	-0.04	-0.12	—	—
In the hydrogen market	+0.17	+0.14	+0.17	+0.15	+0.17	-0.07
Total incremental profit	**+0.17**	**+0.14**	**+0.13**	**+0.03**	**+0.17**	**+0.84**

- G-Gas+SMR obtains the smallest total incremental gain in profit and that gain is tiny.

  -> G-Gas + SMR may not be ideally positioned to develop PtG.

- The largest gain is that of E-VRE

  -> VRE producers may value PtG operations more than a pure player

- E-VRE strategically operates its electrolyzer at a loss, but that loss is more than compensated by the extra profits earned in the power market.

  -> an integrated management of its PtG operations must be preferred to a segmented approach whereby PtG is operated as a separate profit center

PRELIMINARY RESULTS

PTG CAPITAL RECOVERY FACTOR AND WELFARE

Comparison between overall welfare impact of PTG and the capital recovery factor of PTG (CRF):

$$CRF = \frac{i * (1 + i)^n}{(1 + i)^n - 1}$$

With i discount rate and n the expected lifetime of the investment in years (Li & Mulder, 2021).

With n = 25 years, i = 5%, and an investment cost of EUR 1 million/MWh, we get a yearly capital cost of PTG equals to EUR **0,71 billion**.

- **The yearly capital cost of PTG is higher than the overall welfare obtained by adding PTG to the system (negative long-term welfare).**
- **If we look at the additional profit obtained by the actors owning the PTG, only the E_VRE could have a personal incentive in investing in the PTG. For the others, the short-term welfare is insufficient to offset the investment cost of the PTG.**