Impact of Renewable Hydrogen on the Power System: Sector Development, Flexibility and Market Aspects

August 4 , 2025

DERlab/HyLeiT workshop #7

"Challenges of Electrolysis Systems at Relatively Weak Connection Points"

Reliable Sustainable Connected

Background, Objectives and Rationale of the Study

ENTSO-E Study on the "Impact of Renewable H2 on the power system"

Background, objectives and rationale of the study

entsoe VISION

ENTSO-E STRATEGIC ROADMAP

Previous papers:

- The role of hydrogen (2021) - link
- Study on Flexibility from P2H (2022) - link

Innovation Committee and Market Committee

Objectives	**Assessing the expected impacts of renewable H2** value chain (especially electrolysers) **on electricity systems and markets**	Proactively propose the **TSO community perspective to facilitate** an **efficient development** of the future **energy system**	Proposing forward-looking **policy & market design recommendations**, to engage with **H2 stakeholders & policymakers**
Structure	Part 1 : **Analysis of Hydrogen economy**: trends and key developments for system integration.	Part 2 : Analysis of the **systemic role of hydrogen** ecosystem and its impacts on the power system.	Part 3: Analysis of **market design and regulatory framework** for a flexible hydrogen production.

https://www.entsoe.eu/news/2025/06/18/entso-publishes-report-on-impact-of-renewable-hydrogen-on-the-power-system/

Part 1 | Analysis of H2 economy: trends and key developments for system integration.

Analysis of H2 economy: trends and key developments for system integration

Research questions

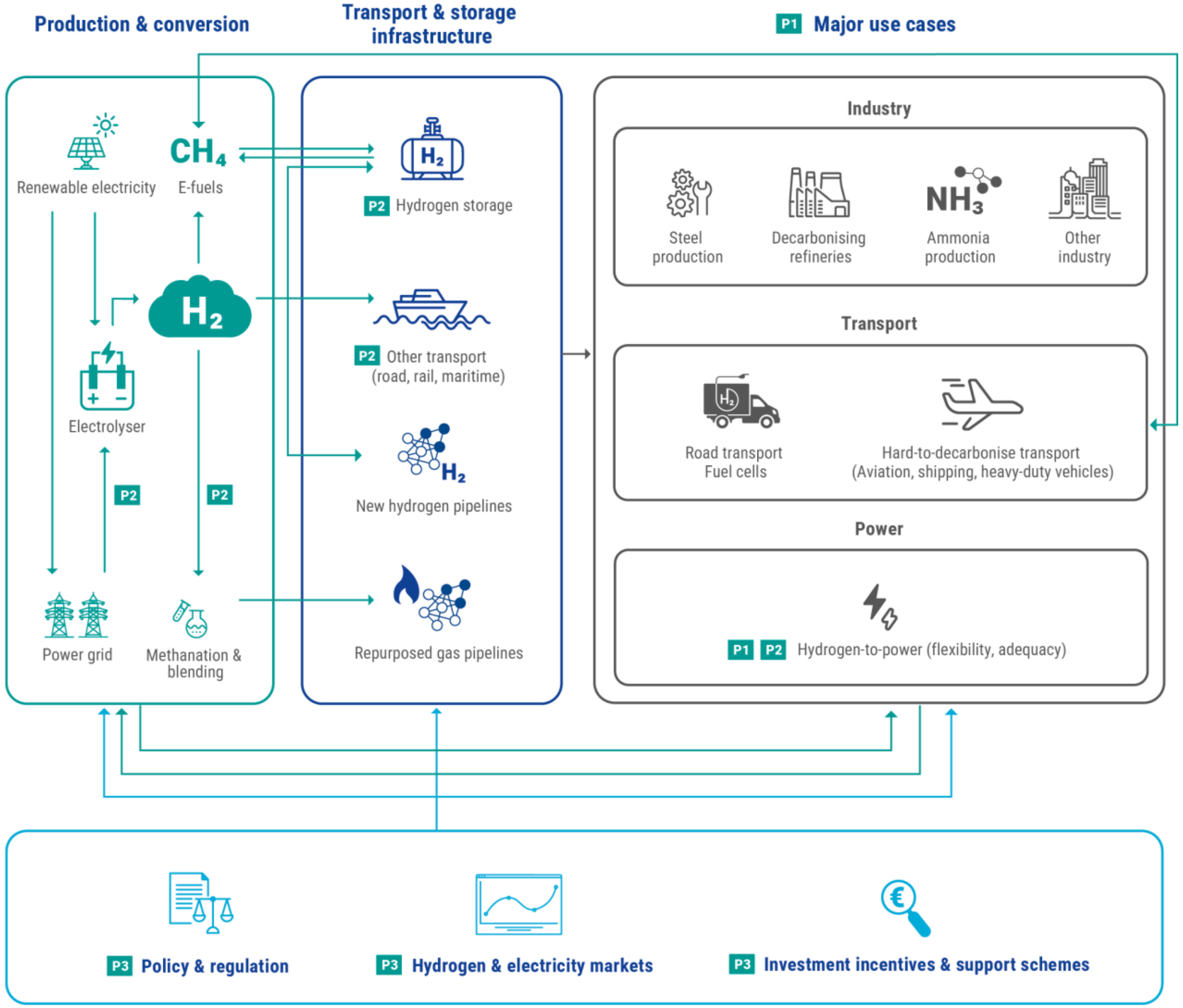
- What are the main **trends** and **developments** in the emerging H2 sector, including policy and regulation?
- What are the main future **use cases** for electrolysers and other H2-based facilities?
- What degree of electrolyser **capacity** expansion in the EU can be expected in the ramp-up and mature phases?

Findings

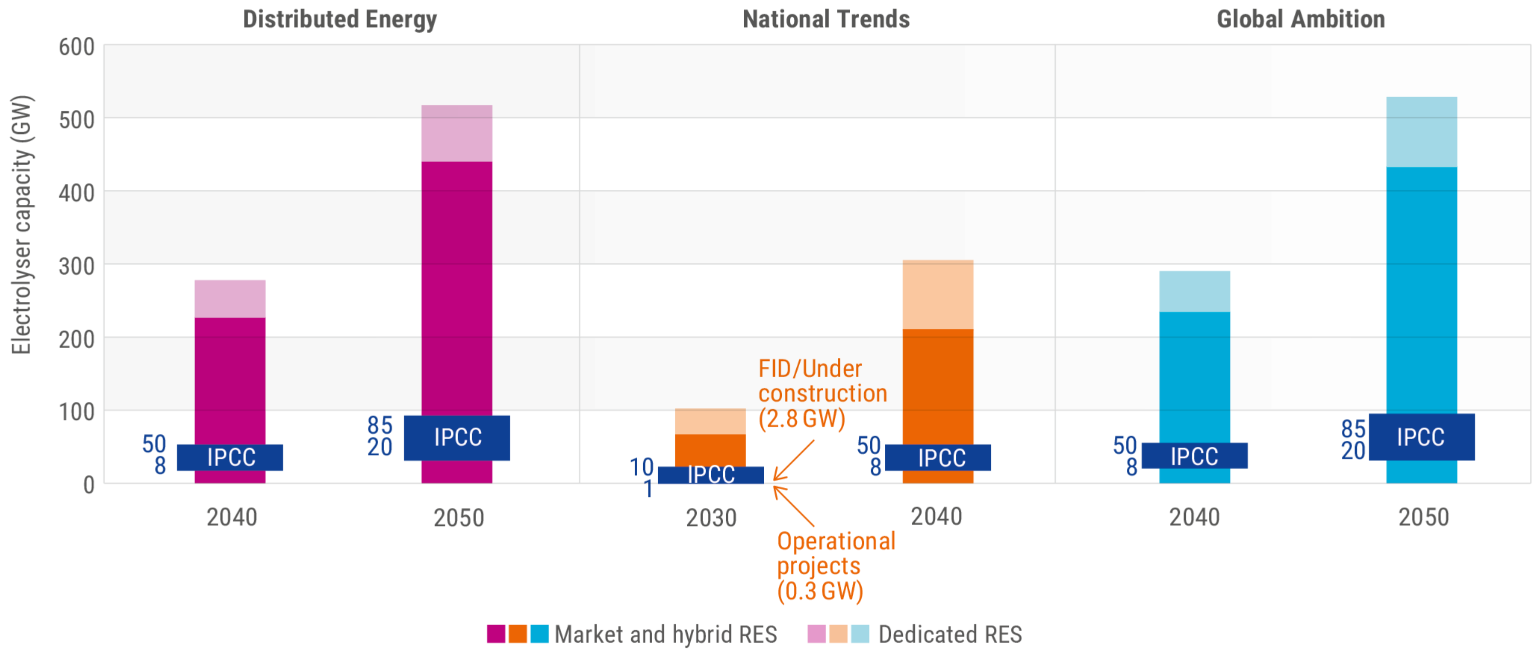
- Decarbonised **H2 demand** is the main driver for electrolysers deployment (industry, transport and e-fuels).
- EU **H2 targets** are **not presently reflected** neither **in** H2 demand nor in production.
- Renewable **LCOH** is still very high, and its **evolution** is still **uncertain**. LCOH is mainly driven by electrolsyser cost & efficiency, electricity cost and purchase profile and load factor.
- It is fundamental to develop **integration** concepts and an **effective cooperation** in hydrogen business cases since the start.

H2 ecosystem and multiple impacts on electricity system

Green H2 value chain and its integration into the power system.



Current and expected future H2 deployment in Europe

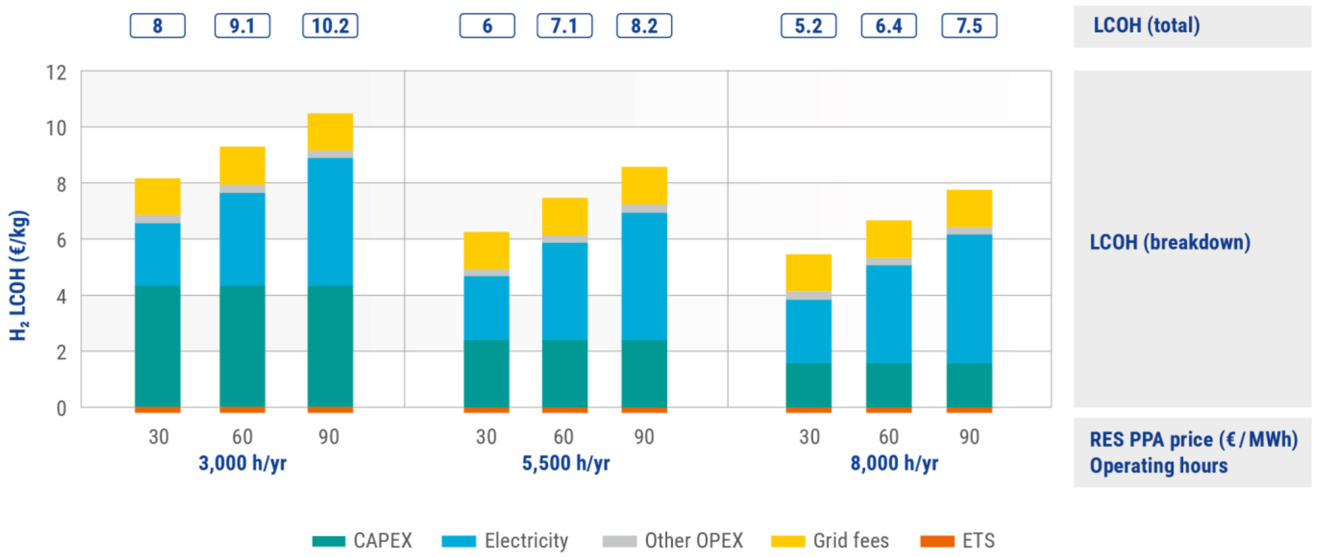


TYNDP scenarios (bars) are compared to IPCC AR6 scenarios of the 1.5 °C climate target (”IPCC” dark blue area) regarding future electrolyser capacity. The bottom-up potential (FID / under-construction and operation hydrogen projects in EU) from IEA 2024.

- Main **factors** of **electrolysers deployment**: evolution of LCOH, public support, role of imports and of blue H2, co-location of production, final demand evolution.
- Focus on short-term targets/climate neutrality leads to high electrolysers capacity (**TYNDP 2024**), while long-term climate goals highlight a lower need (**IPCC AR6 scenarios**).
- Electrolysers potential is demand driven - with a **gap** of electrolyser capacity between **top-down** and **bottom-up projections**.

Cost of green H2

- Main **drivers** of **LCOH** are CAPEX, electricity purchase costs and full load hours (FLH).
- **Electricity cost** and **FLH** are tied: using only low/zero price power also reduces the working time, business optimisation is made on a case-by-case basis.
- **Dedicated RES** option and **decoupling intake from offtake** can drive down the LCOH.
- General **decreasing trend** of LCOH from now (median **6 EUR/kg**) towards 2050 (median **3 EUR/kg**).
- **LCOH forecasts range** is largely **varying** between TYNDP 2024 scenarios (3-11 EUR/kg) and other studies (TNO study at almost 14 EUR/kg). Many policy studies consider a long-term cost down to 1-1,5 EUR/kg, but depending on several **uncertain assumptions**.



LCOH of low-temperature electrolysis depends on the prices of renewable PPAs and the number of operating hours.

Part 2 | Analysis of the systemic role of hydrogen ecosystem and its impacts on the power system.

Identification of the systemic role of the H2 ecosystem and impacts on the power system

Research questions

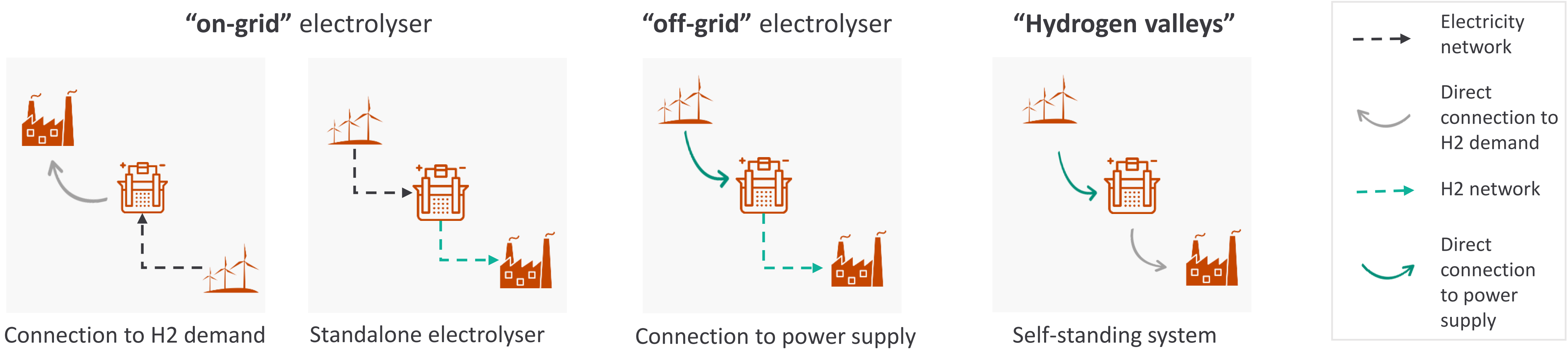
- What are main **capabilities and constraints** of electrolysers and associated effects on the power grid?
- What are the grid **connections options, operational modes and business models** (**taxonomy**) and how they impact on the power system, split into ramp-up and mature phases?
- What **flexibility potential, short and long duration,** can be expected from electrolysers based on the different taxonomy modes and on H2 infrastructures?

Findings

- **Only a fraction of H2** shall impact the power grid, excluding **imported** H2, **non-electrolyser** H2 and **off grid** electrolysers.
- If electrolysers installed capacity will increase, **it shall not be just a new connecting load, rather a new component** of the energy system.
- Today grid issues are **not enpugh in radar** of H2 developers.
- Electrolyser **flexibility** potential **depends** on technology, configurations, bat also attitude and business behaviour.
- Under a holistic perspective, regulation, market design and TSOs should **favour configurations** (including siting), most beneficial for both electricity and H2 systems.
- **H2-fuelled power plants** could play a relevant role as reserve, adequacy, long duration storage.

Electrolysers and H2 fuelled plants may become new components of the integrated energy system

Electrolysers configuration, connection type and siting impact both power grid planning and its operation.



H2-fuelled power plants (H2P):

- In near term will play a **limited** (if any) **role**. In 2050, 27-97 TWh **can be expected** (TYNDP 2024).
- **German case** – 4,4 GW out for tender for H2 hybrid plants & up to 15 GW of natural gas plants converted to H2 by 2035.

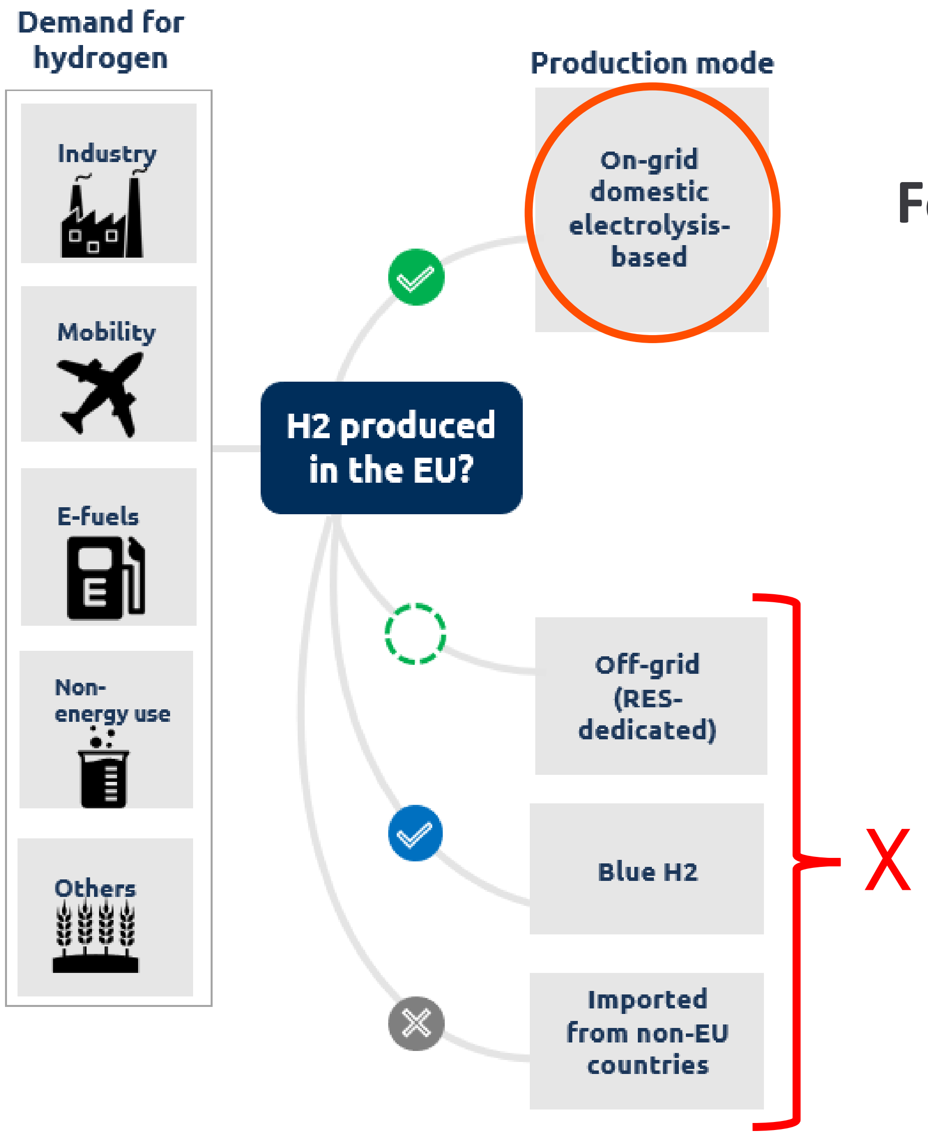
Electrolysers system support capabilities

Flexible operation of electrolysers is possible, providing several system services, especially if this is included in their functional specification design.

		FCR	aFRR	mFRR	RR	Voltage control	Congestion management
Alkaline (AEC) Mature, scalable, cheap	Today	Yes with limits	Yes with limits	Yes	Yes	For voltage control, electrolysers can provide reactive power if they are equipped with self-commutated rectifiers	Yes
	2030	Yes with limits	Yes with limits	Yes	Yes		Yes
Proton Membrane Exchange (PEM) Compact, efficient, good dynamics	Today	Yes with limits	Yes	Yes	Yes		Yes
	2030	Yes with limits	Yes	Yes	Yes		Yes
Solid Oxide (SOEC) Low maturity but promising technology, reversible operation	Today	No	No	No	No		No
	2030	Uncertainty about flexibility					

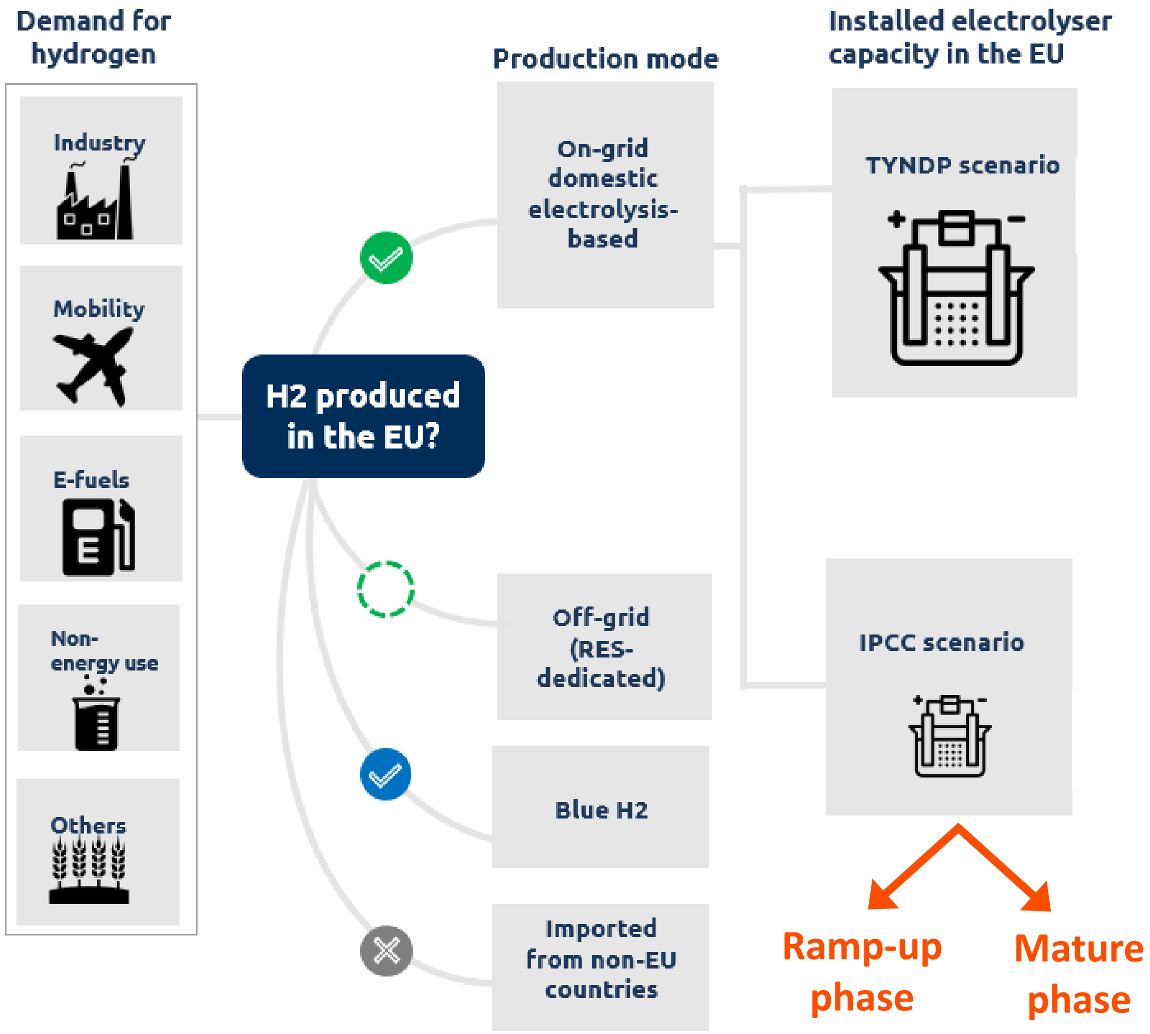
Excerpt from ENTSO-E Study on Flexibility from P2H (2022) - link

Structure of the analysis: production mode



Focus only on **supply modalities impacting the grid**

Structure of the analysis: scenarios and target years



2 **Scenarios** - wide range to account for high uncertainties:

- Upper bound of **TYNDP 2024** scenarios
- **IPCC** scenarios

2 **Target years**:

- **Ramp-up phase (2030)**: some carbon intensive industrial processes, typically in H2 valleys
- **Mature phase (2050)**: H2 demand extending to other uses

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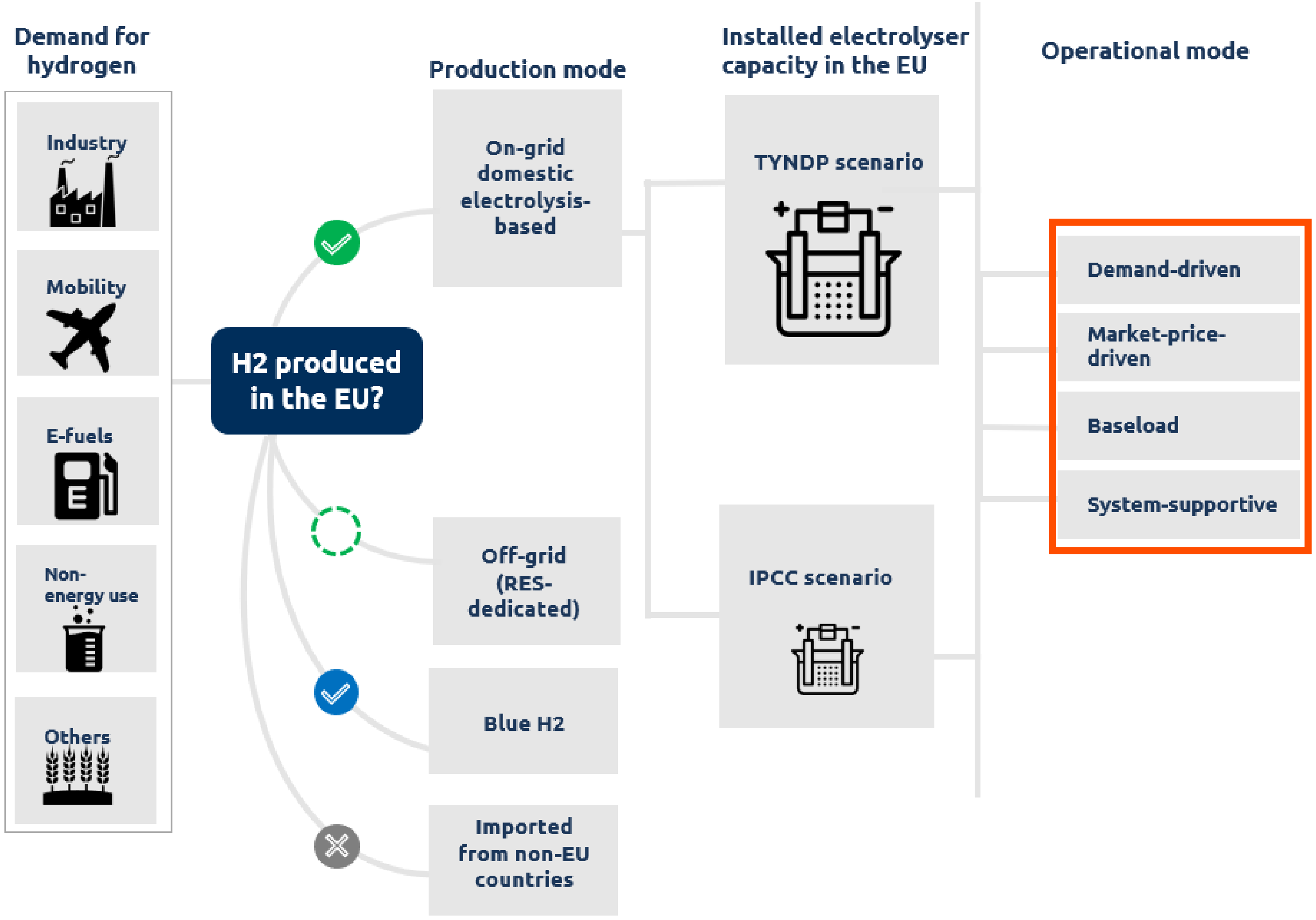
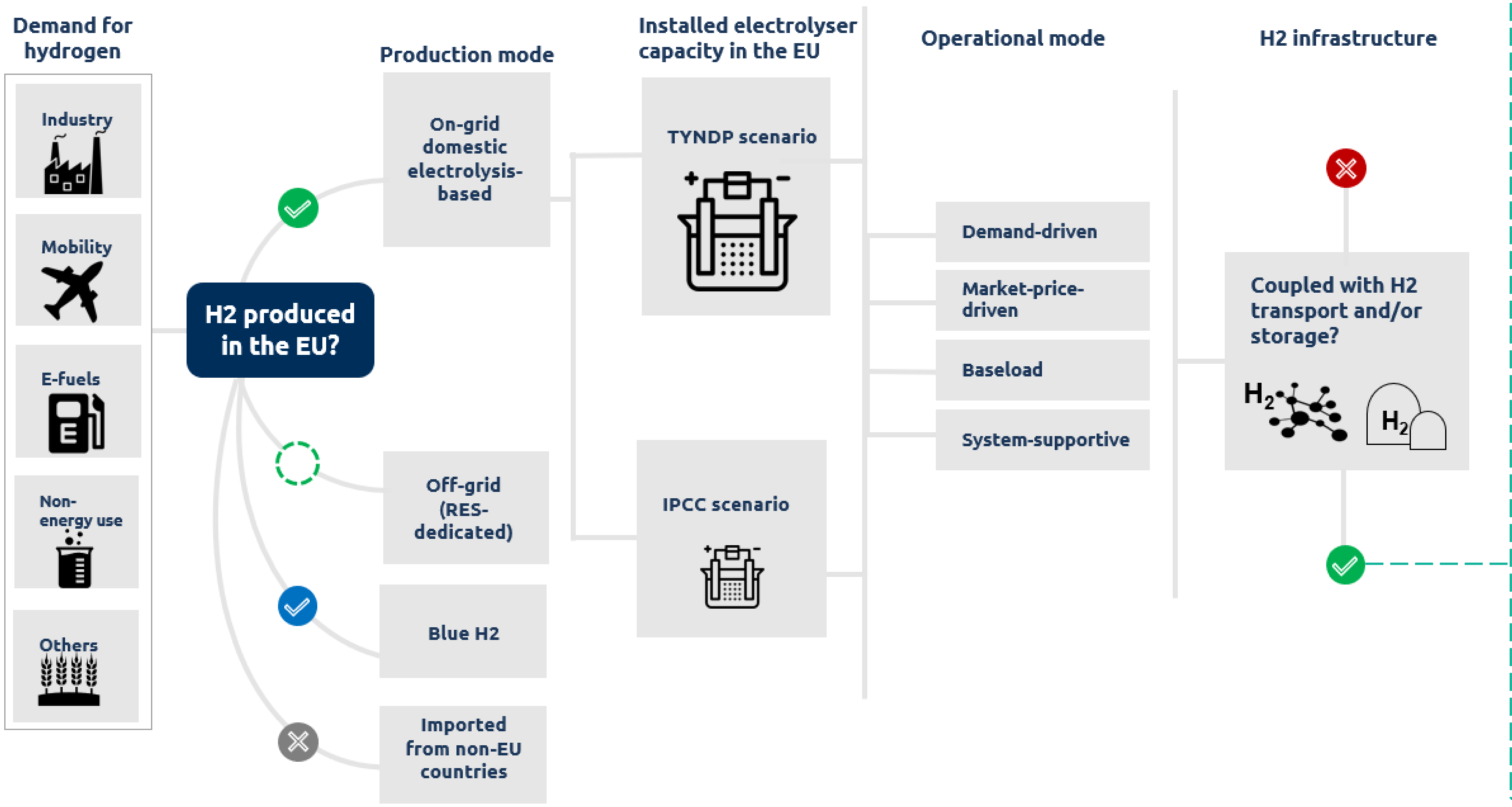
Structure of the analysis: operational mode



Modes as paradigmatic cases of load profile from the grid (in reality combinations will be probable):

- **Demand-driven**: follows H2 contracted off-take
- **Market price-driven**: follows lowest electricity prices to minimise OPEX cost in LCOH
- **Baseload**: maximises capacity factor to minimise CAPEX cost in LCOH
- **System-supportive**: considers in their business plan also selling system services

Structure of the analysis: H2 infrastructure



H2 infrastructures make it possible to **decouple**:

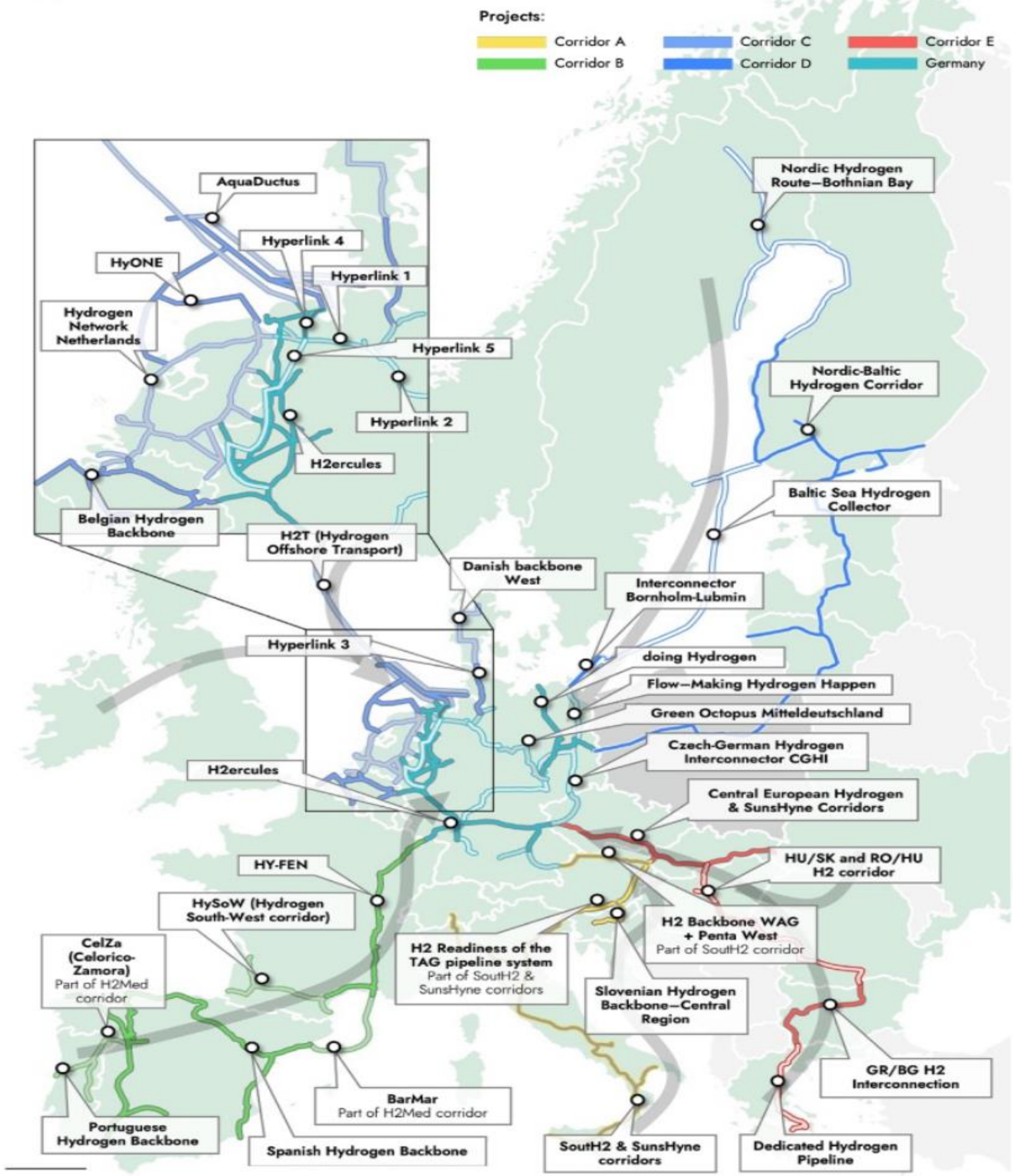
- Power load profile from H2 production
- H2 production from H2 consumption

Creating possibility to **modulate electrolyser operation**, i.e. flexibility.

As well as allowing a liquid market (commodity)

H2 infrastructures are necessary for integration with the power system

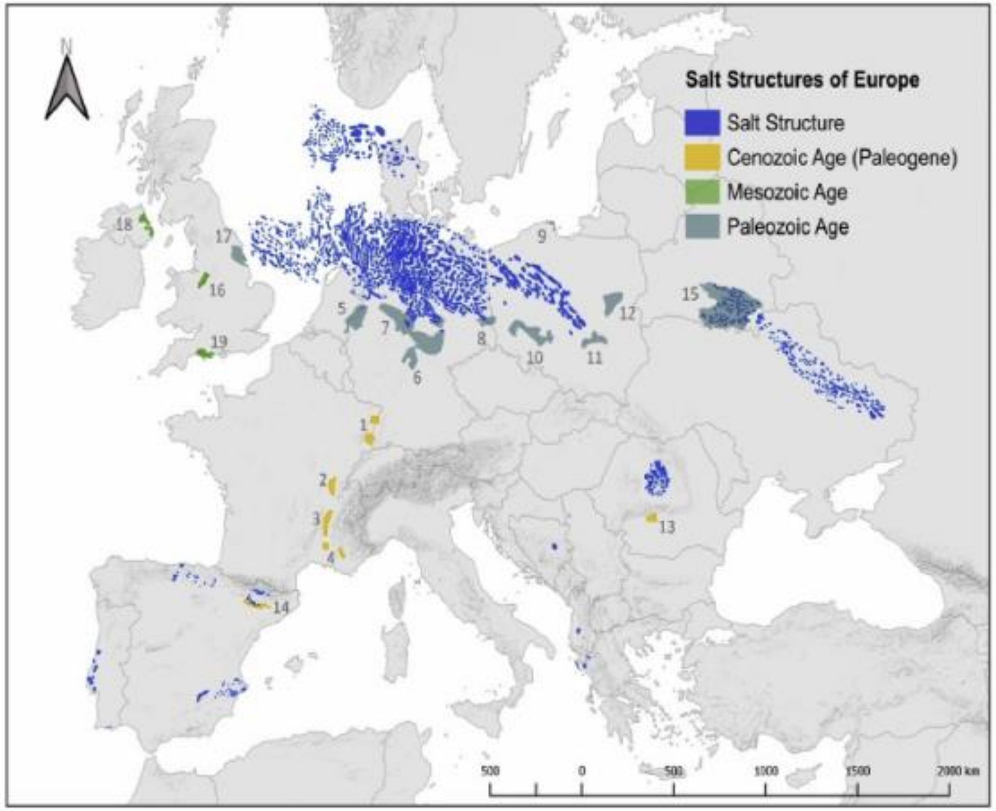
- The H2 and Gas Markets Decarbonisation Package establishes a **European Network of Network Operators for H2 (ENNOH)** with whom ENTSO-E and ENTSO-G **are mandated to cooperate**
- The EHB initiative (European H2 Backbone) made a master plan with a progressive repurposing & construction of 28,000 km in 2030 (75% repurposed) and 75,000 km in 2050 (mostly new lines)
- Repurposed gas pipelines have the lowest costs of around 100-200 EUR/MW/km. But there are potential risks and challenges, such as different ranges of operating pressures which translate into lower intrinsic storage potential
- **Coordinated infrastructure planning and investment framework consistency is necessary across the whole gas-hydrogen-electricity system of systems**

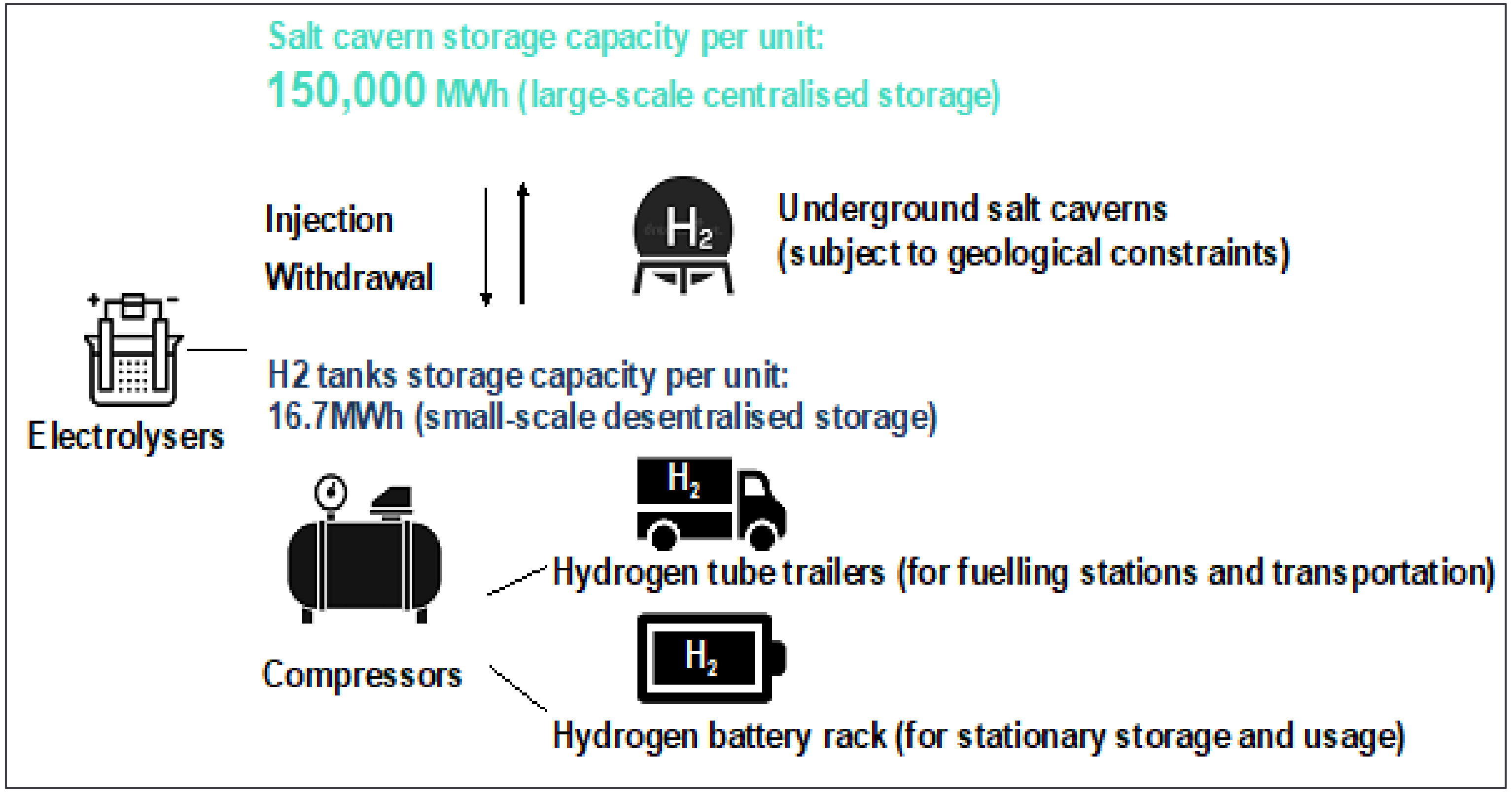


H2 infrastructures: underground storage and pressurised tanks

- **Salt caverns**: large-volume and long-term storage with low environmental impact, and relatively low investment costs
- **Depleted oil and gas fields**: high storage capacity existing infrastructure; less flexible cycles
- **Saline aquifers**: high storage capacity, but with a risk of gas leakage

- **Underground storage** is mainly for seasonal storage at integrated energy system level
- **H2 tanks** are necessary for operational and commercial reasons; expensive due to advanced materials and safety systems
- **H2 network** has intrinsic storage capacity thanks to variable pressure





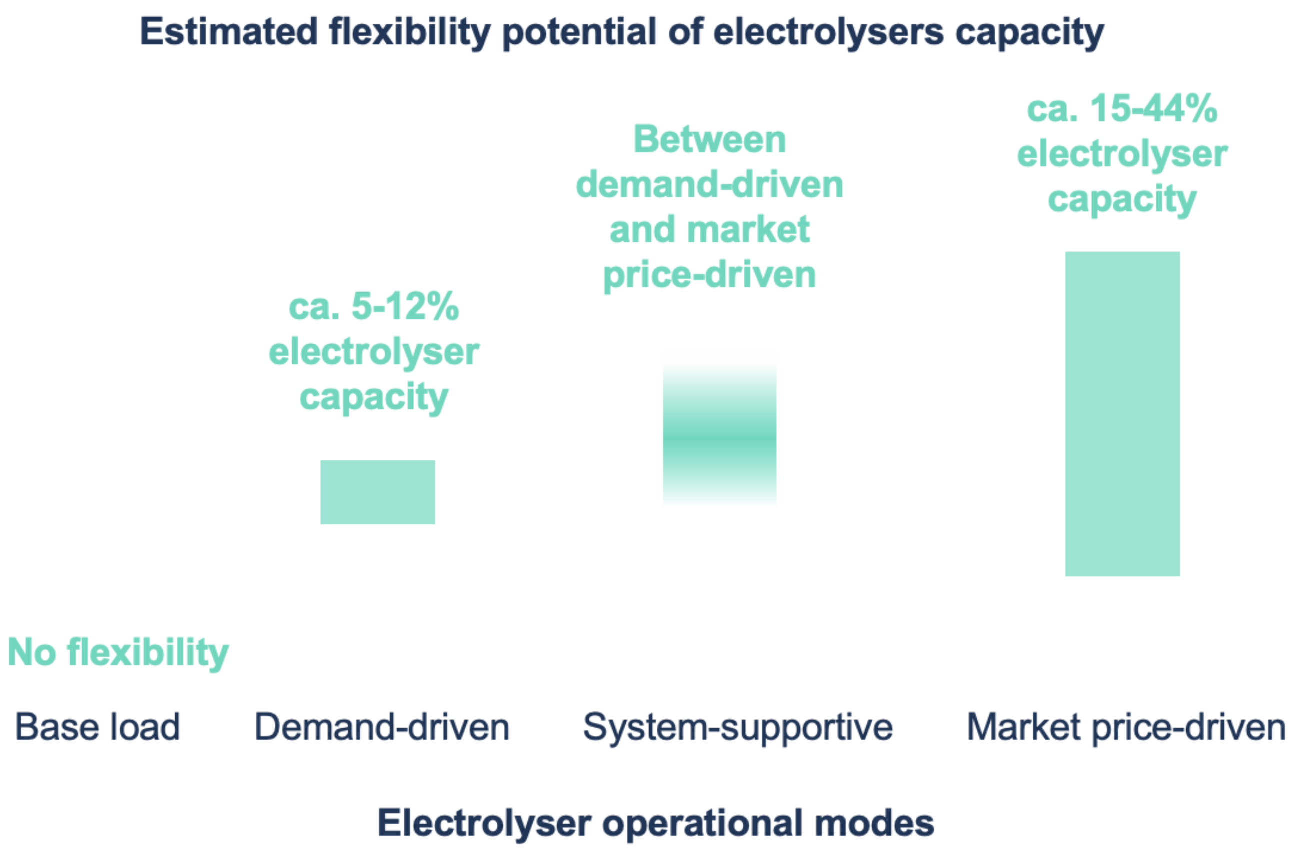
Quantification exercise of flexibility potential from electrolysers

A quantification exercise has been attempted as a methodology to estimate future flexibility potential.

Short duration flexibility:

- **Baseload mode** has intrinsically no flex
- **Demand driven** has flex if equipped with (at least) local storage
- **Market-price driven** automatically provides flex via demand response, implicit and explicit
- **System supportive** would be ideal, but only theorical at the moment

Long duration flexibility mostly depends on large, centralised underground storage and extensive pipelines



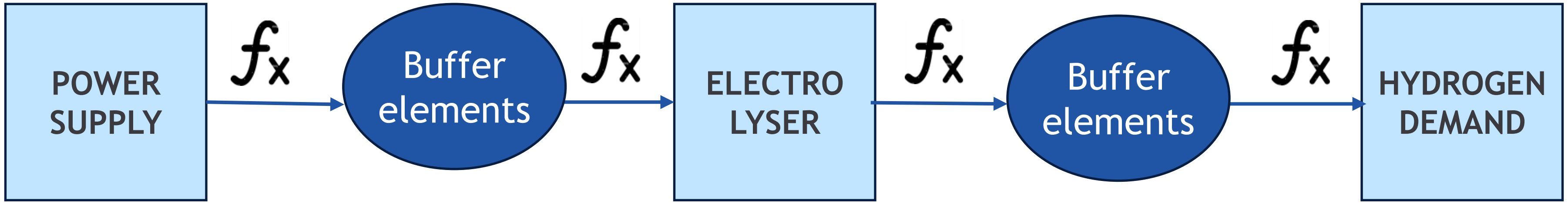
H2 infrastructure for flexibility and integration of electrolysers into the power system

Impacts on the power grid
(positive and negative)

Operational mode	Storage & Transport	Grid congestions risk	Flexibility short-duration	Flexibility long-duration
Baseload	Without storage	YES	NO	NO
	With storage	NO	YES	NO
Demand-driven	Without storage	YES	NO	NO
	With storage	NO	YES	YES
System-supportive	Without storage	NO	YES	NO
	With storage	NO	YES*	YES
Market price-driven	Without storage	NO	NO	NO
	With storage	NO	YES*	YES

Flexibility means possibilities to multiple decoupling profiles

Flexible operation: decoupling profiles through grids, storage, demand response



Decoupling electrolyser input from electricty generation through physical devices and contractual arrangements

Decoupling electrolyser output from hydrogen demand through logistics and contractual arrangements

Part 3 | Analysis of market design and regulatory framework for a flexible hydrogen production.

Interdependencies between regulatory framework, electricity markets and future H2 market

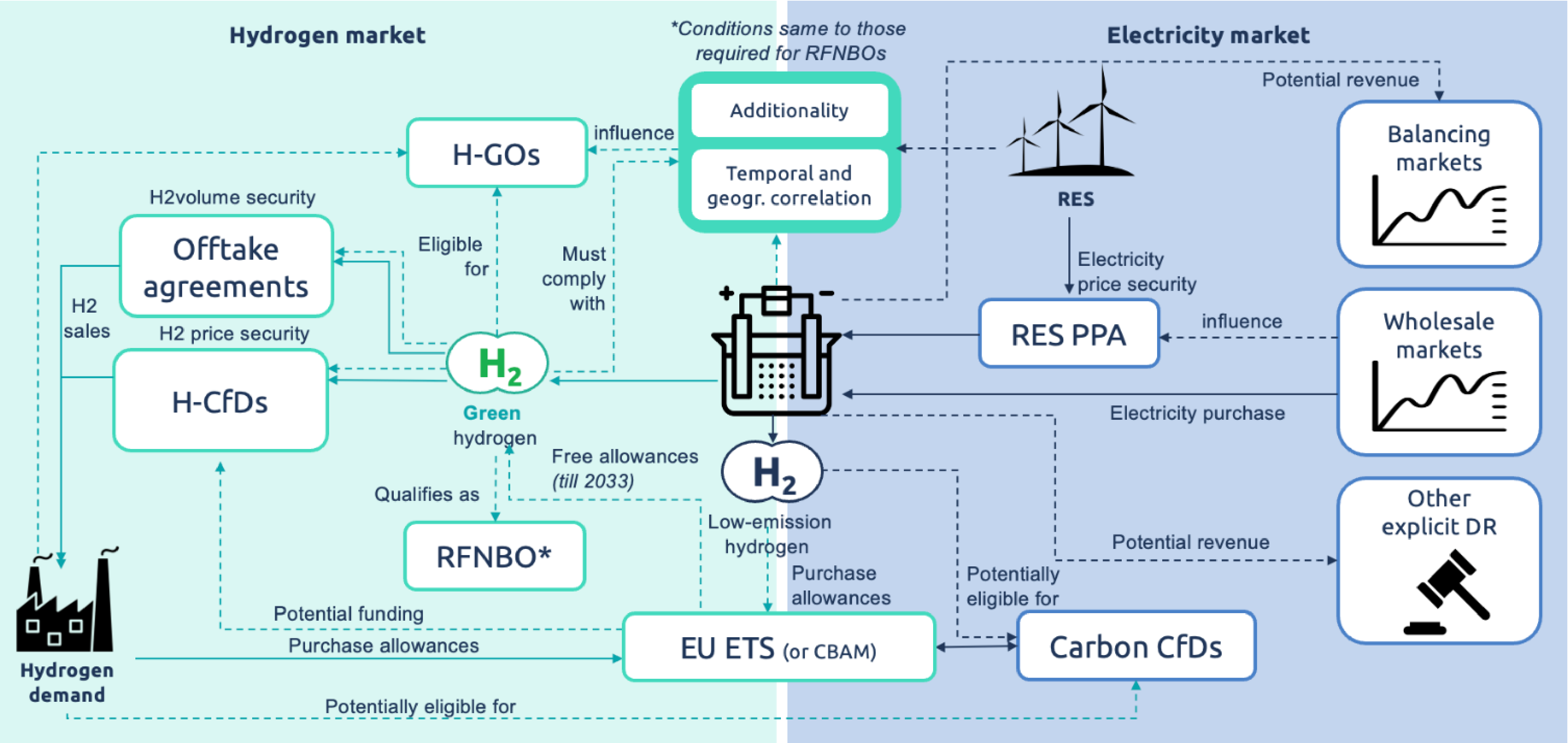
Research questions

- What are the **main cost** and **revenue drivers** of electrolysers?
- What kind of **support schemes** and **market arrangements** are conceivable for a viable investment case?
- What **measures** can be taken to enable **cost-efficient** and **flexible H2 production**?

Findings

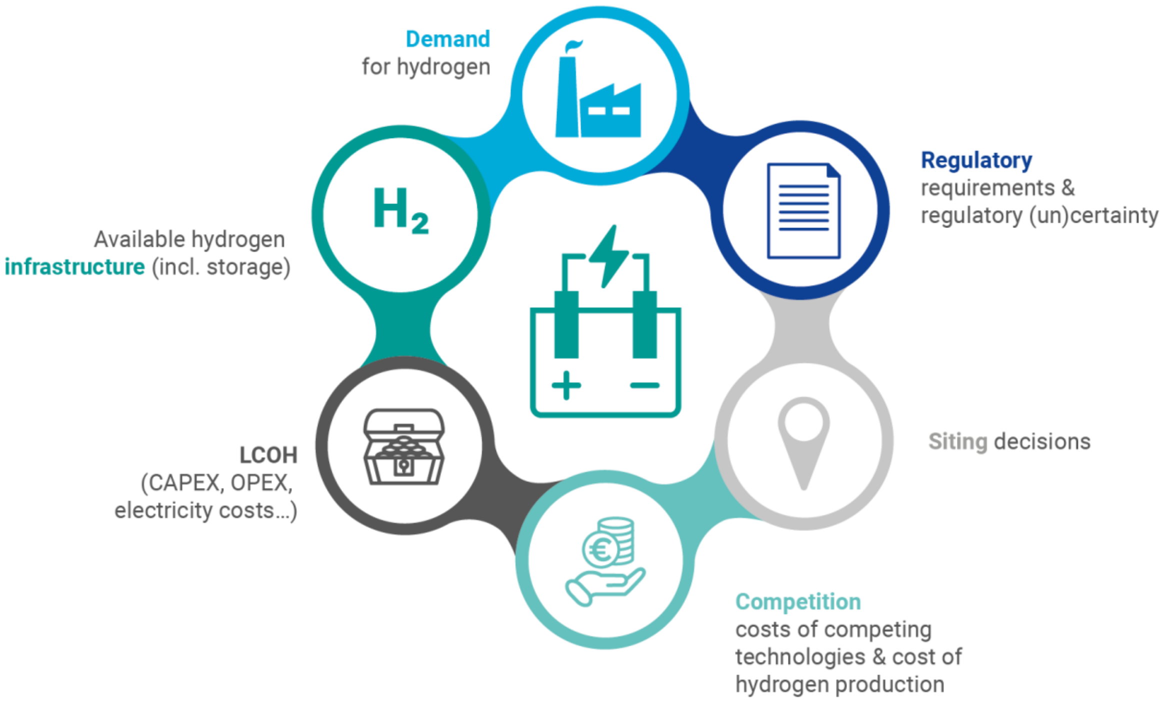
- **Locational-specific incentives** can help guide siting decisions of electrolyser operators.
- **Access** to **system service markets** is essential to ensure effective system integration of electrolysers.
- Regulatory requirements related to **green hydrogen certification** highlights some possible trade-offs between decarbonization goals and power system needs.
- Especially in ramp-up phase, **temporal correlation rules** should take into account the impact on operating costs to give electrolyser operators sufficient leeway to align production with system needs.

Interface between H2 and Electricity Markets



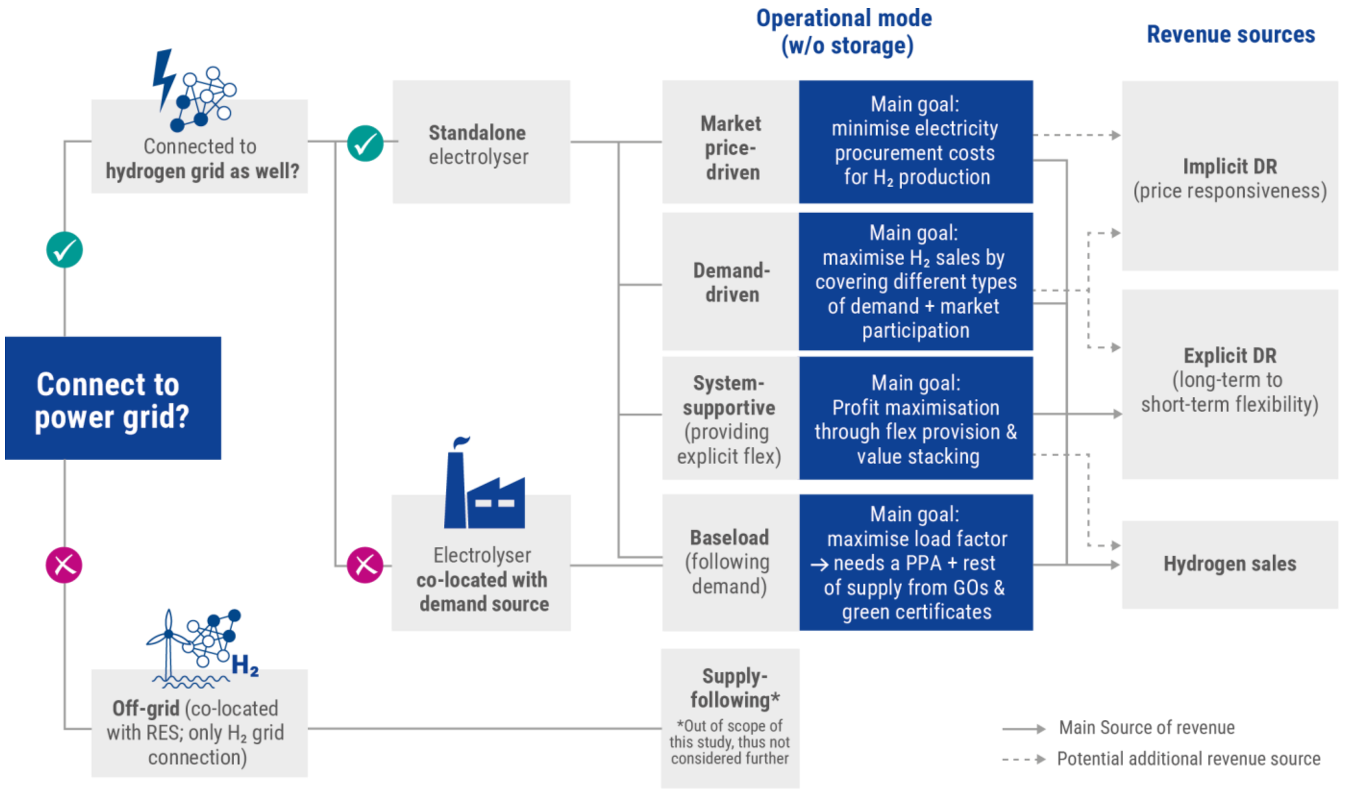
Costs drivers

- **Demand** for **Renewable H2**: critical to reduce CAPEX and improve supply chain efficiencies.
- **LCOH**: national differences in grid fees, taxes, and levies further influence LCOH, complicating regional competitiveness.
- **Infrastructure**: coordination across production, infrastructure, and demand scale-up is essential.
- **Regulatory framework**: factors such as additionality and correlation rules, subsidies affect H2 production costs and competitiveness.
- **Electrolysers location**: co-location with RES minimise grid costs, proximity to industrial H2 users reduces transportation costs and supports stable revenue.
- **Competitiveness**: renewable H2 prices must be compared to other decarbonisation options.



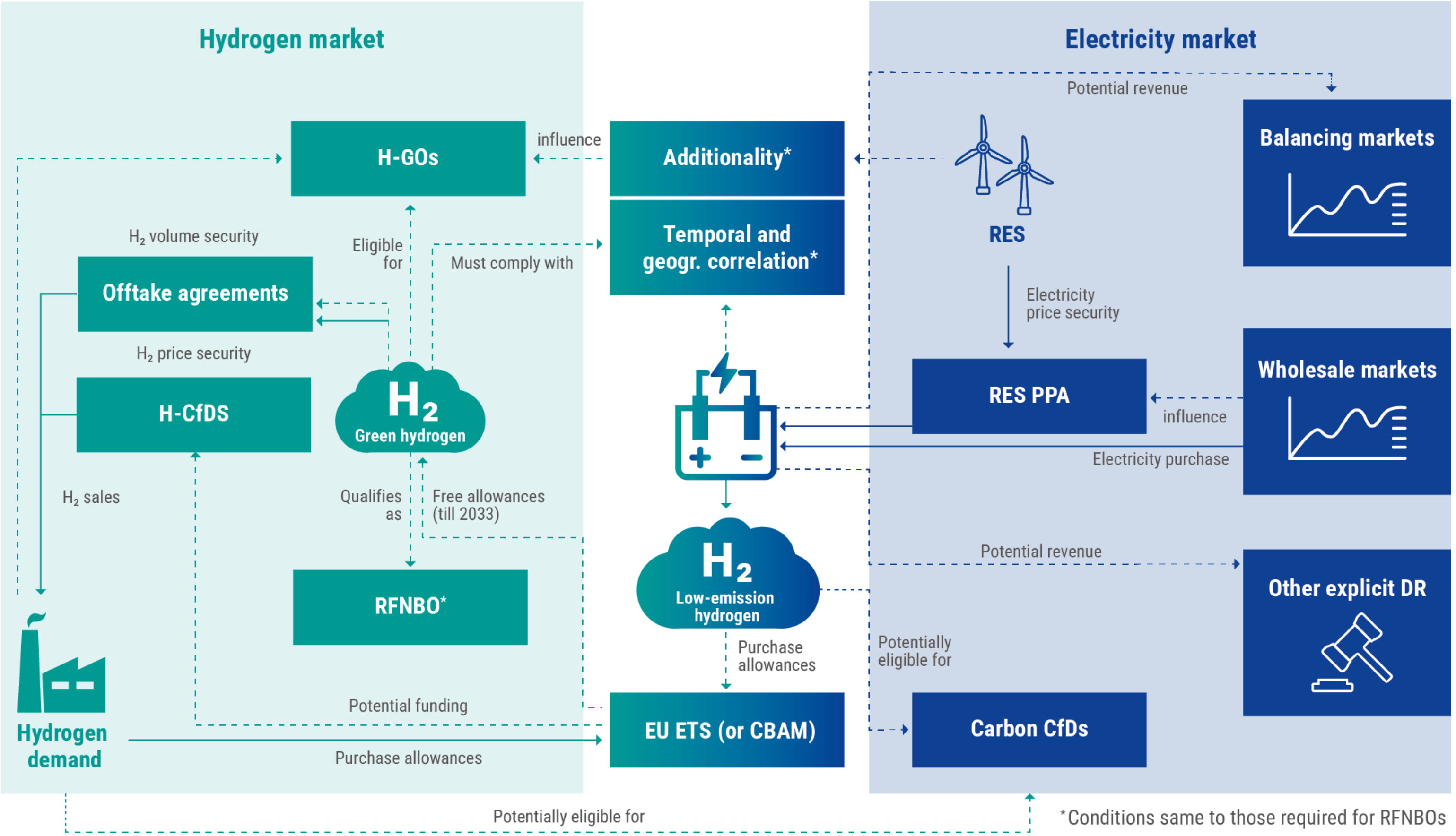
Potential revenue stream of hydrogen

- **H2 sales**: revenue stability depends on contract structure.
- **Intermittency**: seasonal demand variation and RES intermittency require storage and diversified sale profiles.
- **Side-sales:** Oxygen, heat for local processes, waste heat recovery (ex. District Heating)
- **System services**: balancing and congestion management, related revenues depend on connection type, technical requirements and operational modes, as well as on the competition with established technologies.



Arrangements affecting investment costs

- **CAPEX**: investment grants, tax incentives, and favourable financing conditions play a key role.
- **OPEX**: Power Purchase Agreements (PPAs) and operational support schemes, such as H2 contracts-for-differences (H-CfDs), cap-and-floor contracts or offtake agreements reduce costs and/or revenue risks associated with fluctuating prices or volumes.
- **Quotas** and **demand-side subsidies** create markets for renewable H2, but they risk market distortion, regional disparities, and financial burdens. They may limit operational flexibility by tethering production to demand rather than dynamic electricity pricing or system needs.



Regulatory framework

- **RFNBO**: to qualify H2 as renewable, H2 production must adhere to strict criteria covering temporal and geographical correlation and additionality
- **Guarantees of Origin** can play a significant role in certifying renewable H2 as RFNBO, but there is need for criteria alignment. While such a system could drive innovation and reduce curtailment, it poses challenges. Accurate tracking, real-time verification, and administrative oversight could increase costs and discourage smaller producers. It could promote advancements in storage and infrastructure, ultimately supporting a consistent renewable H2 supply and better market integration.

Implications:

- Need for high-cost infrastructure, the administrative burden of ensuring compliance, and the growing competition for renewable resources may delay or deter investments in renewable H2 projects.
- Electrolyser operators are unlikely to ensure that the produced H2 is fully renewable – unless they are co-located with dedicated RES.
- From the business-case perspective, an electrolyser operator is incentivized to be located close to demand. Conversely, the regulatory conditions incentivize them to be located close to production, which however restricts electrolyser operation to times when renewable energy is available.
- A mixed impact is expected in terms of electrolysers' flexibility potential.

Efficient support schemes

The type of support scheme chosen has significant implications on both the location and operational strategies of electrolysers.

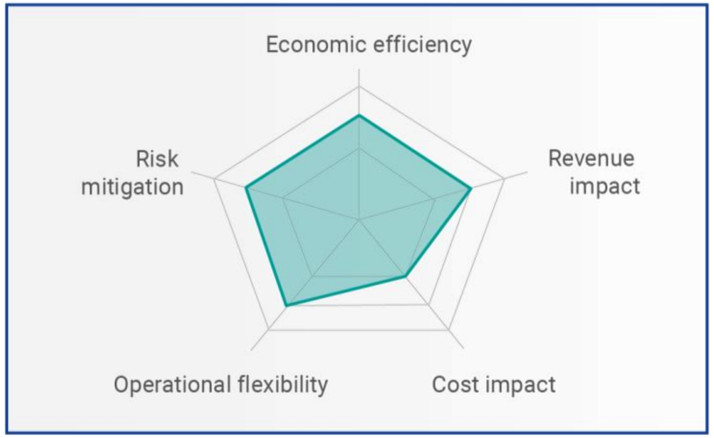
Support scheme or market arrangement	Pros	Cons
PPAs	› stable electricity prices › predictable operation and investment confidence	› limited flexibility › locations likely limited to areas with high shares of RES
H-CfDs	› revenue stability › supports *demand-driven* operational flexibility	› contract management complexity › regional limitations based on national policy
Cap-and-floor contracts	› Revenue protection against low market prices › Predictable financial outcomes	› limits maximum profit during high-price periods › limited flexibility › dependence on limited number of off-takers
Hydrogen off-take agreements	› revenue certainty through secured demand › easier project financing › depending on contract conditions, can support operational flexibility	› Reduced operational flexibility if contract requires hydrogen delivery in predefined time frames › Potential dependency on specific off-takers
Reduced levies	› cost reduction	› limited impact on its own
Provision of system services	› additional revenue opportunities › strengthens role in grid support	› may impact hydrogen output › high operational complexity and hydrogen infrastructure needs (pipelines, storage) › large national differences (available markets, market designs and entry conditions, price levels)

Measures to enable cost-efficient and flexible hydrogen production

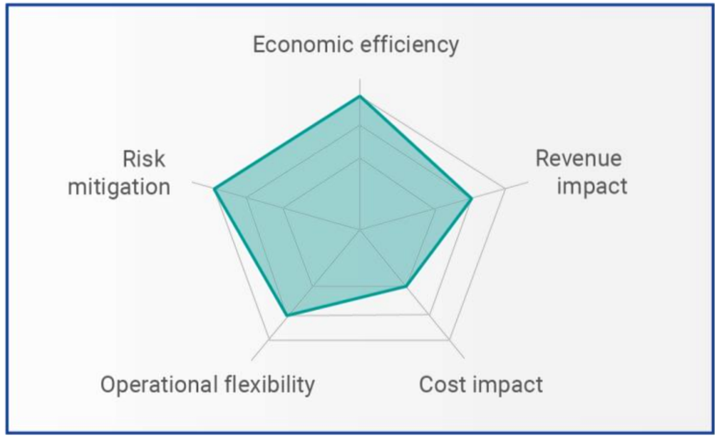
Six support mechanisms for electrolysers based on economic efficiency, revenue impact, cost impact, operational flexibility, and risk mitigation are all associated with trade-offs to be aware of.

PPAs

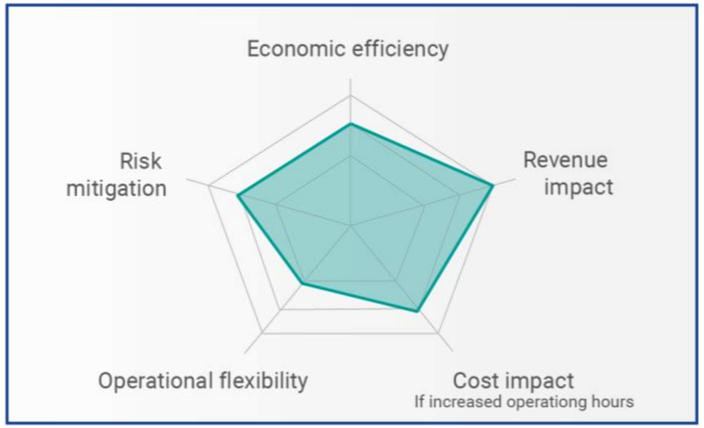
H-CfDs



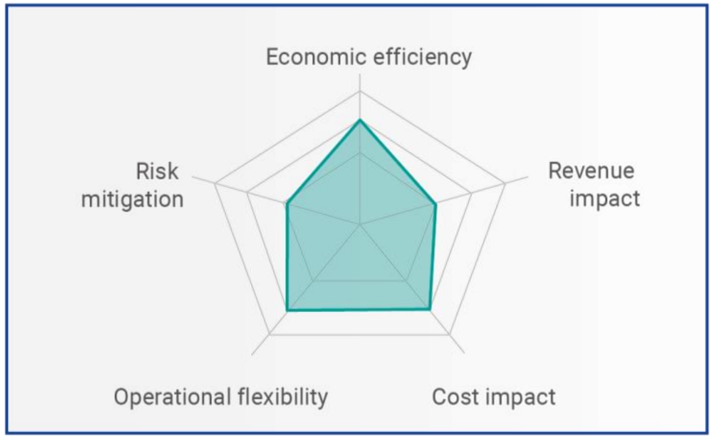
Cap- and floor contracts



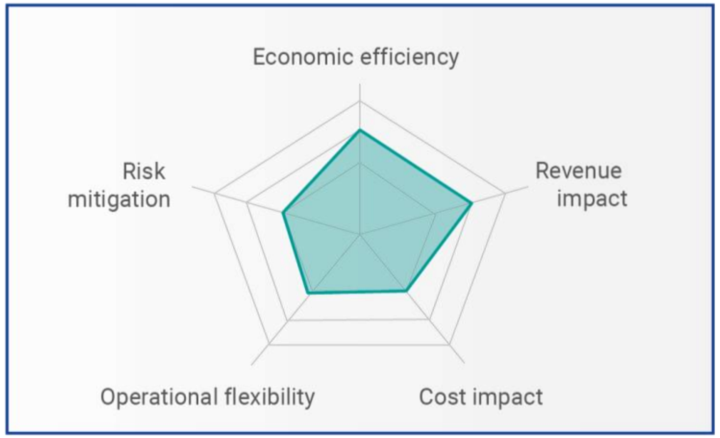
Off-take agreements



Reduced RES levies



GOs



Operational modes and revenues implications

Operational mode	Compatible support mechanisms	Challenges and caveats
Baseload	› RES PPAs › Off-take agreements › H-GOs	› Difficulty securing continuous RES generation › Potential mismatch between RES output and H_2 demand › dependence on specific off-takers
Market price-driven	› H-GOs › Reduced RES levies	› Unpredictable and potentially lower load factors › Administrative burdens for GOs
Demand-driven	› H-CfDs (production-based) › Flexible connection agreements	› Managing a mix of long-term and short-term agreements as well as multiple revenue sources › Production consistency challenges
System-supportive	› Removal of barriers to system service markets › Locational signals	› Requires high flexibility (and most likely storage) › Potentially lower hydrogen production rates › Additional administrative and operational effort

Trajectory to enable flexible operations

RAMP-UP
by 2030

Setting up the foundation

- TSOs to coordinate with electrolyser operators on their power grid location
- TSOs/ENTSO-E, gas TSOs/ENTSOG and HNOs/ENNOH to coordinate on infrastructure planning
- TSOs to plan for electrolyser participation in system service markets (connection requirements, baseline methodologies…)
- Offer direct financial support (e. g., capital grants, investment subsidies with a phased reduction combined with demand quotas – in line with cost-efficient compliance with decarbonisation objectives

GROWTH

Scaling & Stabilisation

- Flexibilisation of the electrolyser technology itself as a crucial prerequiste for the scale-up
- Reduce levies or taxes for operators prioritising electricity consumption during high-RES output periods and enable flexible connection agreements in congestion-prone areas
- Use off-take agreements or cap-and-floor agreements to shield electrolyser operators from volume or price risks and improve project bankability

MATURITY
2050

Route towards subsidy-free and flexible operation

- Phase out direct subsidies
- Use of competitive PPAs to maintain operational cost stability under stricter additionality and correlation criteria.
- Provide explicit demand response and system services (e. g., balancing, congestion management)
- Make use of advanced hydrogen storage and infrastructure

Key messages of the study - synthesys

1. Planning coordination between electricity systems and H2 system (electrolysers, H2 grids and infrastructures) is paramount, to best satisfy the connection requests, to optimise the possible sitings, to avoid over dimensioning /stranded assets in the value chain targeting overarching system benefits (=consumer benefits).

2. Operational synergies should be pursued, depending on: location of electrolysers (on/off grid); business model (providing also grid and system services, beyond H2; operational modes (base load, electricity price-driven, demand-driven), leading to win-win situations. Today, grid issues are NOT ENOUGH IN RADAR of H2 developers

3. Flexibility: electrolysers can provide short duration flexibility through implicit and explicit demand response, for balancing and congestion management. Long duration flexibility can also be provided through H2 infrastructure (transport and storage), which investments must be coordinated with RES and electrolysers

4. Resource adequacy: H2P (H2 fuelled generation) can contribute to resource adequacy (demand response and last resource reserve).

5. Public support/incentive for deploying H2 ecosystem can be on production or on demand: they should be designed and applied targeting an efficient decarbonisation effect.

6. Rules for definitions and application of renewable hydrogen should target an efficient decarbonisation effect and overall energy system efficiency.

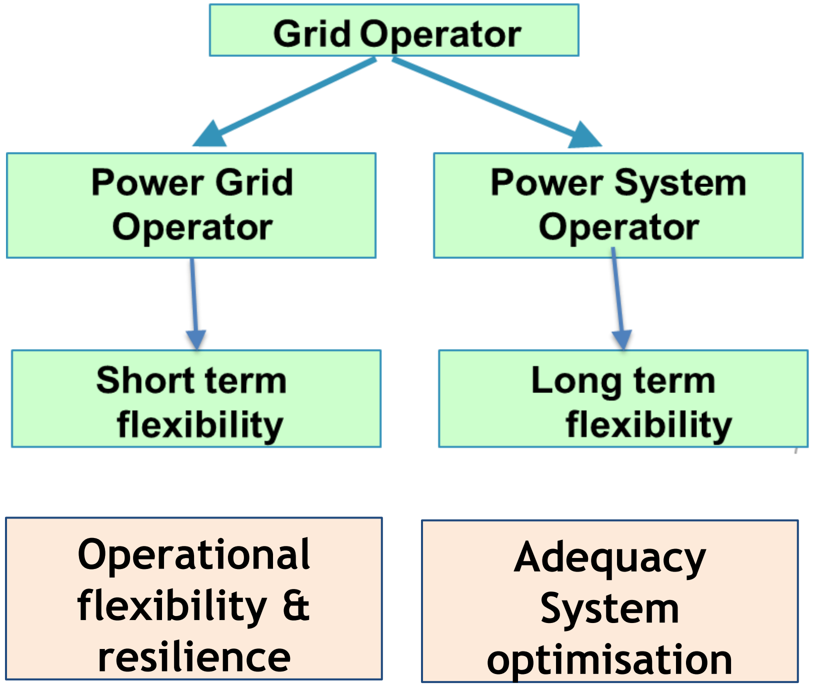
Key messages: grid planning & infrastructure investments

1. Electrolysers and hydrogen-fuelled generation will become new components of an **integrated energy system**

2. Electrolysers configuration, connection type and siting impact both power grid **planning and its operation**

3. Only a fraction of final H2 demand shall impact the electricity system, **excluding imports, blue H2 and off grids** electrolysers

4. Planning coordination of **electricity, gas and H2 infrastructures** (including H2 grids, distribution, storage, ports and logistics) is paramount to best **satisfy connection requests**, to **optimise siting decisions**, to avoid over dimensioning and **stranded assets** → targeting overarching system benefits



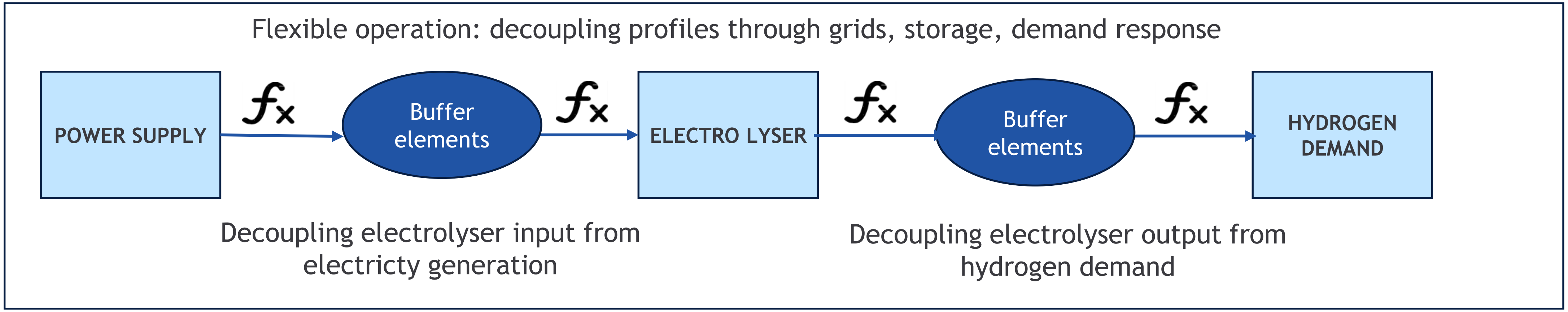
Key messages: operational modes and flexibility provision

1. Operational **synergies** should be pursued, depending on **business model**, operational modes (base load, electricity price-driven, demand-driven), leading to win-win situations. Today, grid issues are **not in radar** of H2 developers/operators.

2. **Electrolysers can become a promising source of short-duration flexibility** through implicit and explicit demand response, for balancing and congestion management.

3. **Long-duration flexibility** can in the future be provided through well-developed H2 **transport & storage facilities** for re-electrification in prolonged RES scarcity periods.

4. H2-fuelled generation can contribute to resource **adequacy** (demand response and last resource reserve).



Key messages: Market Design & Regulatory Framework

1. **Public support mechanisms & regulatory incentives** facilitate the development of renewable hydrogen ecosystem targeting either **hydrogen production or hydrogen demand**, especially in the ramp-up phase. They should be carefully designed to achieve an **efficient decarbonisation effect & to incentivise** flexibility for the power system.

2. **Supply side:** OPEX incentives (cap & floor, CfDs, reduced RES levies) need to be well designed to incentivise operation **in line with market conditions** (e.g. low spot prices) **& system needs** (e.g. avoiding grid congestions), not only with hydrogen demand; **CAPEX incentives** can be more appropriate for that.

3. **Demand side**: supporting H2 offtake and investments in H2 storage can solve the **chicken-egg** problem unlocking the potential of the full value chain. Facilitating and **de-risking PPAs** can also support reaching this aim.

4. **Constraints for labelling renewable hydrogen** (e.g. RFNBO requirements and GOs) could contemplate in the ramp-up phase some **flexibility of application**, to balance impacts on hydrogen sector and on power system, under an overarching frame of efficient decarbonisation.