The Impact of Green Hydrogen on the Power System

Presented by

CESI
Shaping a Better Energy Future

EnerNex
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encoord
Coupling Energy Networks

Presenting Today

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Agenda

Hydrogen strategy in the U.S.

Value chain of hydrogen

Hydrogen strategy in the E.U.

Green Hydrogen: key factors and questions to be addressed

Possible schemes for hydrogen integration

Application to the Italian energy system considering a 2030 scenario

How to model and quantify green hydrogen

Conclusions and key takeaways

Q&A

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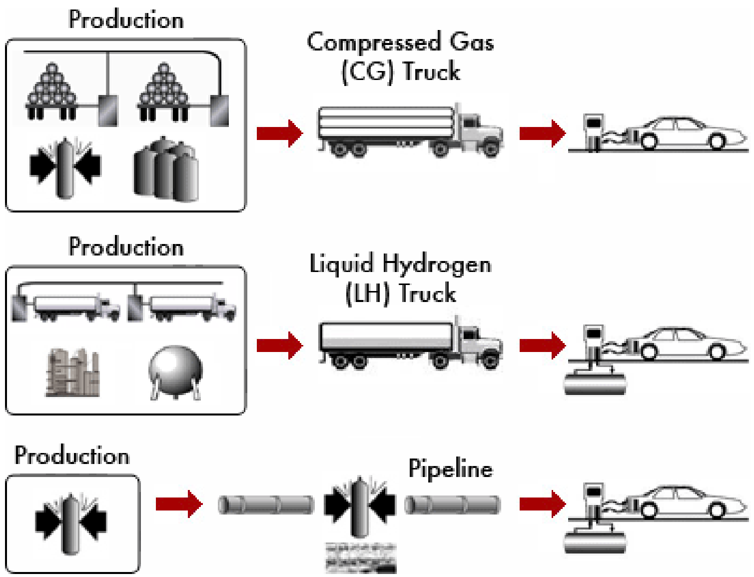
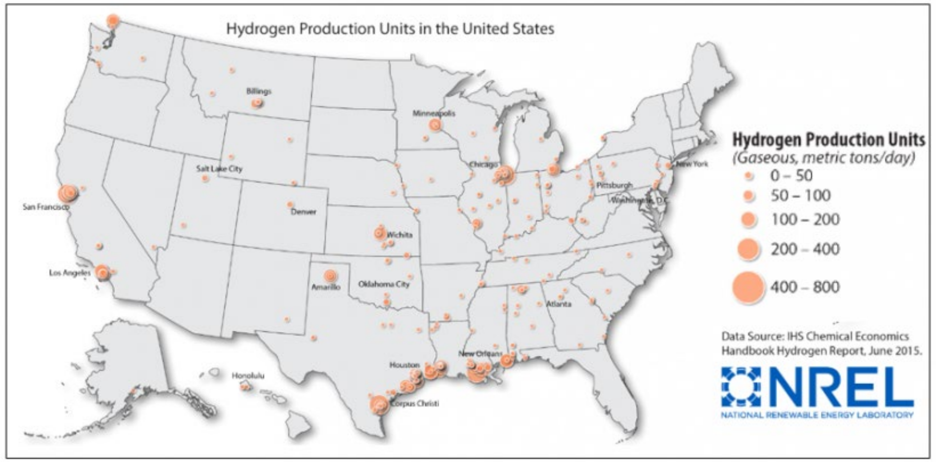
Hydrogen Distribution

- *Most hydrogen in the US is produced at or close to where it will be used*
  - Nationwide distribution infrastructure is still being researched and developed
  - Expensive to transport because it contains the lowest energy per unit *volume* than all other common fuels
- *3 main distribution methods:*
  - Pipeline
    - Limited due to only 1,608 miles of pipeline currently existing (Dec. 2020)
      - Located near large petroleum refineries and chemical plants in Illinois, California, and the Gulf Coast
      - 90% of the pipelines located along the Gulf Coast
  - High-Pressure Tube Trailers
    - Expensive
    - Used for distances 200 miles or less
  - Liquified Hydrogen Tankers
    - Liquification process is expensive but allows for more efficient transport over longer distances
    - Hydrogen must be consumed at or near the same pressure as it is delivered
      - Hydrogen will evaporate/boil off if delivery and consumption pressures are not carefully matched and monitored





U.S. annual hydrogen production
10 million metric tons

Largest Users in the U.S.

Petroleum Processing	68%	Fertilizer Production	21%

Source: https://afdc.energy.gov/fuels/hydrogen_production.html

Green Hydrogen in the US | Recent News

- US Energy Department Plans $8 billion in Hydrogen Initiatives (published via DOE, Feb 2022)
  - DOE announced in Feb 2022 it is requesting information on how to spend billions of dollars in new funding for hydrogen projects approved through the bipartisan infrastructure bill.
  - The hydrogen initiatives were among several projects announced as part of a Biden administration push to decarbonize the industrial sector, including a new "Buy Clean" task force that will encourage low-carbon federal purchases, new guidance and transparency requirements for carbon-capture projects, and funding for industrial energy assessment trainings.
  - The Energy Department will spend $8 billion on at least four hydrogen "hubs" across the United States that will build out a network for producing, processing, delivering and storing hydrogen.
  - DOE is aiming to reduce the cost of clean hydrogen by 80% within a decade to $1 per kilogram and announced $28 million for research and development of engineering projects for industrial, electricity and transportation-related clean hydrogen.
- Biden administration launches industrial decarbonization initiative, targets $9.5B for clean hydrogen (published via Utility Dive, Feb 2022)
  - Using funds from 2021's infrastructure law, the Biden administration has launched initiatives aimed at cutting greenhouse gas (GHG) emissions from the industrial sector, which accounts for nearly a quarter of all U.S. GHG emissions.
  - As part of the effort, the Energy Department is preparing to disburse $9.5 billion for three "clean" hydrogen programs, with $8 billion slated to go towards creating at least four regional hubs where hydrogen would be made.

The US Hydrogen Strategy

- *US DOE Hydrogen EarthShot $1/kg by 2030*
  - $400 Million in 2022
  - Electrolyzers used to produce green hydrogen.
  - Hydrogen supply chain components and fuel cell technologies.
  - Hydrogen storage technologies.
  - Fuel cell subsystems and components.
  - Analyses for hydrogen production pathways, storage and fuel cell systems

- *HyDeal LA Angeles Link*
  - <$2/kg by 2030
  - Solar/Wind to H2
  - Underground Storage
  - Gas Pipelines
  - Port of LA H2 Fleet / H2 Fuel Cell Aviation / H2 Homes
  - LADWP In Basin Power Plants
- *HyStor Mississippi Clean Hydrogen Hub*
  - 110k ton/year 70k ton underground storage
  - Renewable to H2
  - $1-$2/kg by 2030
- *SGH2 Lancaster*
  - 3800 tons/year
  - Renewable to plasma enhanced gasification of recyclable waste
  - $1-$2/kg now

Examples of Key DOE Hydrogen Program Targets

DOE targets are application-specific and developed with stakeholder input to enable competitiveness with incumbent and emerging technologies. These targets guide the R&D community and inform the Program's portfolio of activities. Examples include:

- $2/kg for hydrogen production and $2/kg for delivery and dispensing for transportation applications
- $1/kg hydrogen for industrial and stationary power generation applications
- Fuel cell system cost of $80/kW with 25,000-hour durability for long-haul heavy-duty trucks
- On-board vehicular hydrogen storage at $8/kWh, 2.2 kWh/kg, and 1.7kWh/l
- Electrolyzer capital cost of $300/kW, 80,000 hour durability, and 65% system efficiency
- Fuel cell system cost of $900/kW and 40,000 hour durability for fuel-flexible stationary high-temperature fuel cells

Source: energy.gov

Why hydrogen – The decarbonisation of the human activities

Announcements have been made to attain a carbon free economy…

BBC
Climate change: EU leaders set 55% target for CO2 emissions cut

The Washington Post
Biden calls for 100 percent clean electricity by 2035.

REUTERS
Biden says U.S., Canada to work toward achieving net zero emissions by 2050

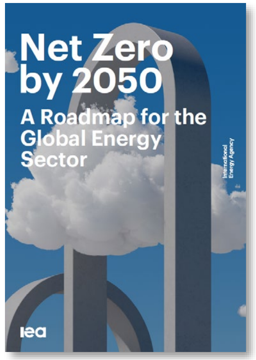
The Guardian
Theresa May commits to net zero UK carbon emissions by 2050

FINANCIAL TIMES
EU unveils plan to be carbon neutral by 2050

REUTERS
Italy says it plans to cut carbon emissions by 60% by 2030

CNN
China will become carbon neutral by 2060, Xi Jinping says

…declined in specific strategies and targets



Fit for 55
DELIVERING THE EUROPEAN GREEN DEAL
THE DECISIVE DECADE

2030 Targets	Green Deal
GHG reduction vs 1990	-55%
%RES on energy consumption	40%
Energy saving on consumpt.[1]	-36%

[1]Energy Savings evaluated against the 2007 Baseline projections for 2030

Foundation

Adoption of the "Paris Agreement" at COP21

"This Agreement aims to strengthen the global response to the threat of climate change… (a) Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels…"

Roadmap boosted by **"Glasgow Climate Pact" at COP26** *: additional pledges to limit the temperature increase to 1.5 °C above pre-industrial levels through stopping deforestation, global fugitive methane pledge, coal phase down…*

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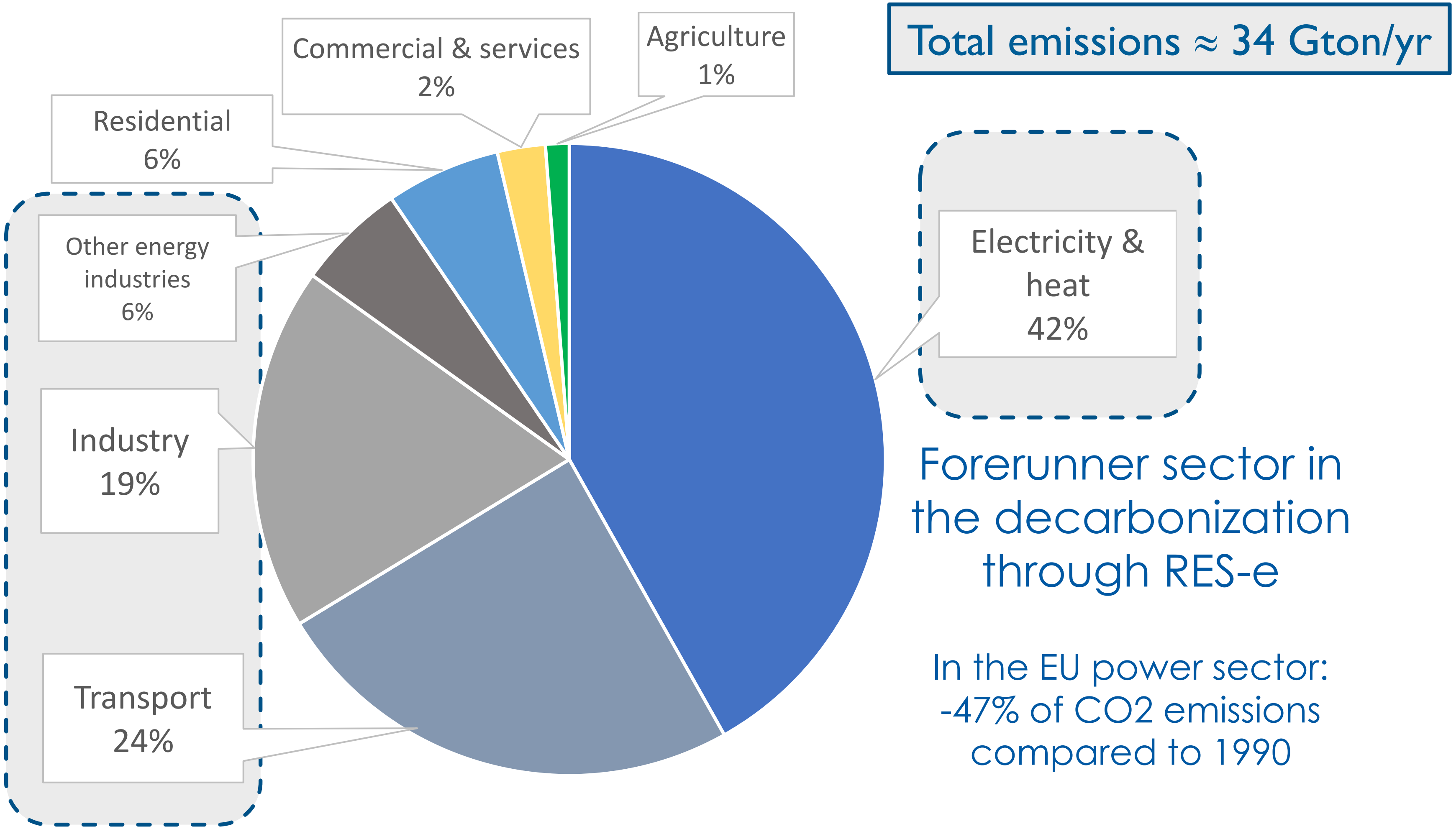
Why hydrogen – CO_2 emissions by sector

Sectors hard to decarbonize only through electrification

Role of **"green" hydrogen**



Forerunner sector in the decarbonization through RES-e

In the EU power sector: -47% of CO2 emissions compared to 1990

Source: IEA – CESI elaborations – data referred to 2019

Hydrogen final uses and production

Some sectors can hardly be decarbonized through electrification

Chemicals
- Fertilizers, ammonia
- Polymers
- Resins

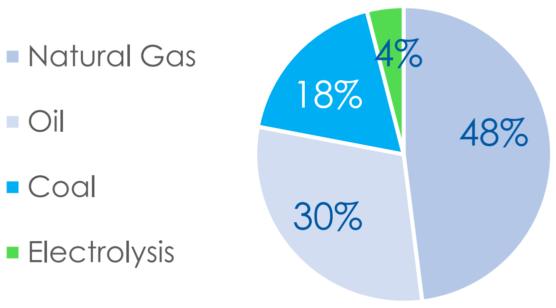
Refining
- Hydrocracking
- Plastics

Iron & Steel
- Thermal treatments
- Process gases

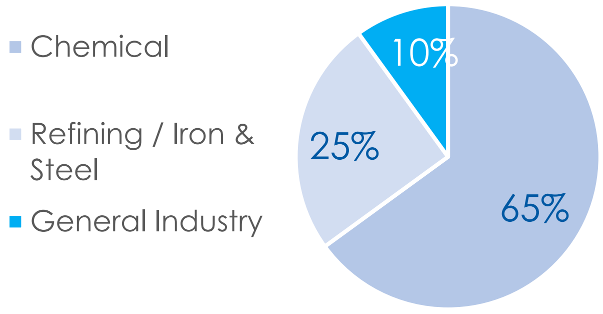
Other industrial uses
- Semiconductors
- Propellant fuel
- Glass production
- Hydrogenation of fats
- Cooling of generators

Heavy transports
- Trucks
- Ships
- Trains
- Aviation

Current hydrogen sources



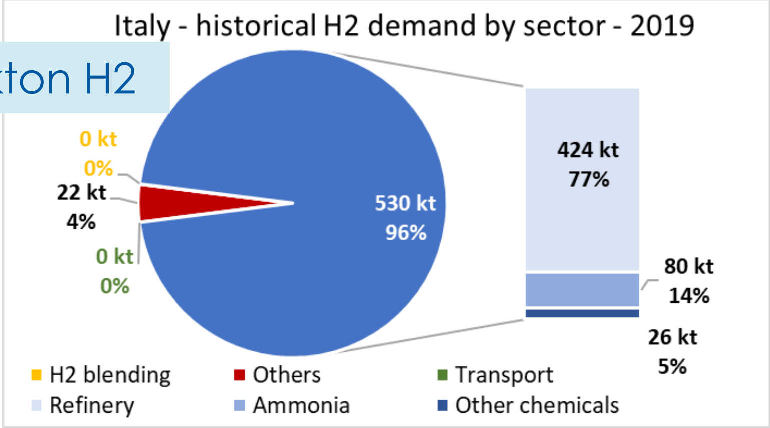
Current uses of hydrogen



Total H2 consumption worldwide: 110 Mton

Source: IRENA

552 kton H2

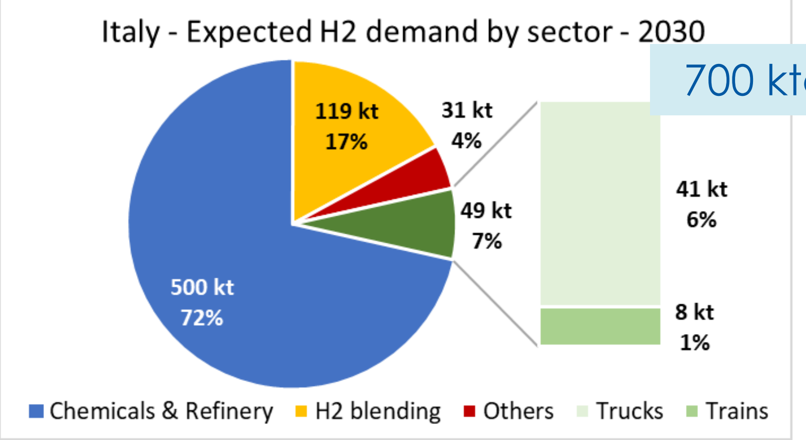


Source: Fuel Cells and Hydrogen Observatory (FCHO)

CAGR= 2.2%

evolving hydrogen final uses

700 kton H2



Source: Preliminary National Hydrogen Statategy

Hydrogen Strategies in Europe

The EU Hydrogen Strategy[1] – July 2020

- *2024: at least **6 GW** of green hydrogen electrolyzers – 1 MtonH_2/yr*
- *2030: **40 GW** of green hydrogen electrolyzers- 10 MtonH_2*
- *2050: **14%** of <u>energy demand covered by green hydrogen</u> - European Clean Hydrogen Alliance -*

United Kingdom

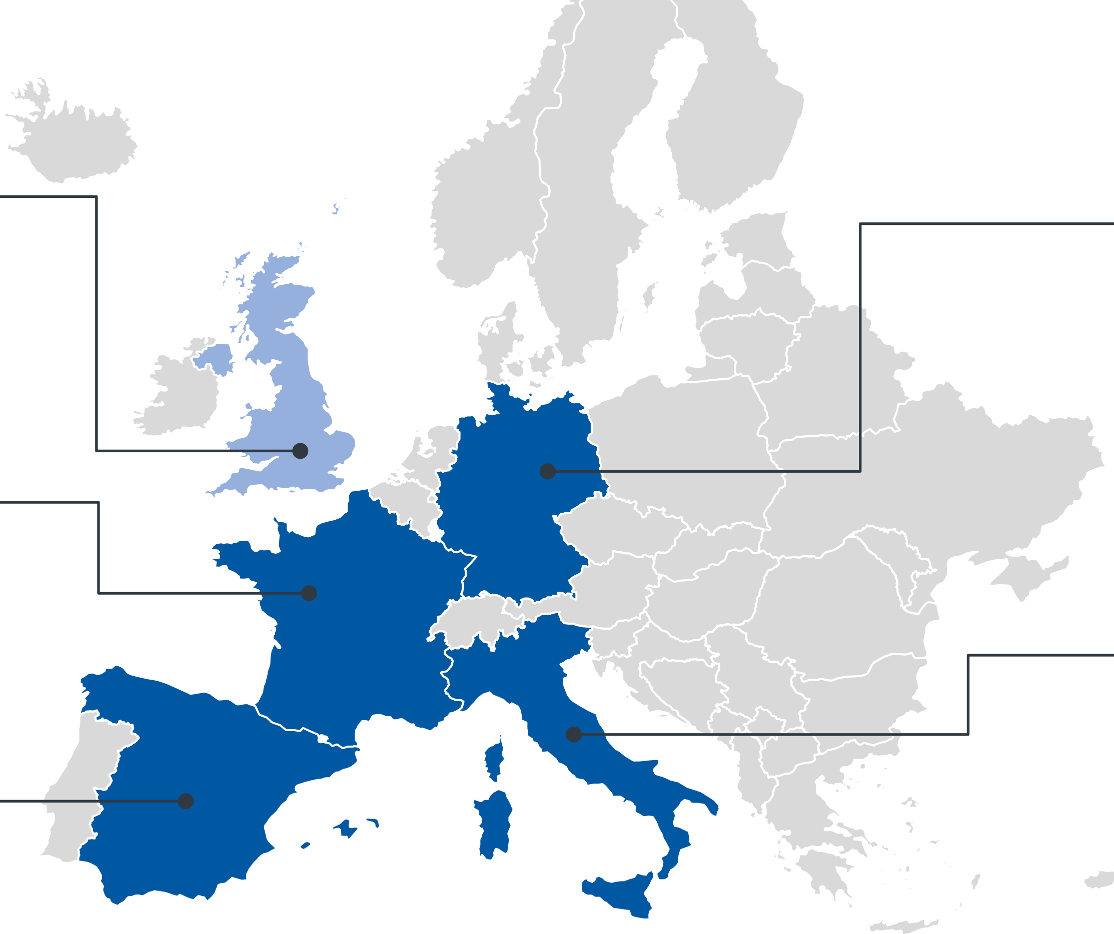
5 GW electrolyzers in 2030
(National Strategy 2021)

France

6.5 GW electrolyzers in 2030
(National Strategy 2020)

Spain

4 GW electrolyzers in 2030
(National Strategy 2020)



Germany

5 GW electrolyzers in 2030
(National Strategy 2020)

Italy

5 GW electrolyzers in 2030
(MiSe Preliminary Guidelines 2020)

Current hydrogen demand in the EU 27: 7.8 Mton/yr

[1] Already excluding UK

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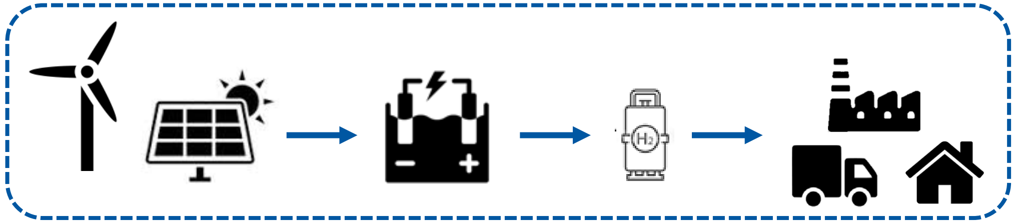
Possible schemes for integration of Green Hydrogen

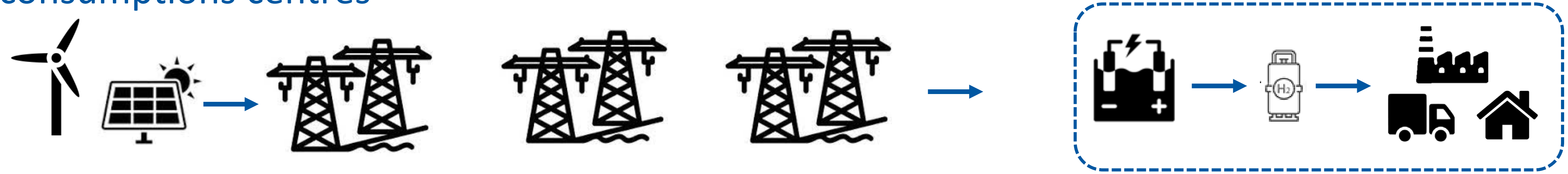
Three possible implementation scenarios for H2 production, transport and consumption:

- ✓ **Decentralized:** electrolyzers and V-RES at consumption centres

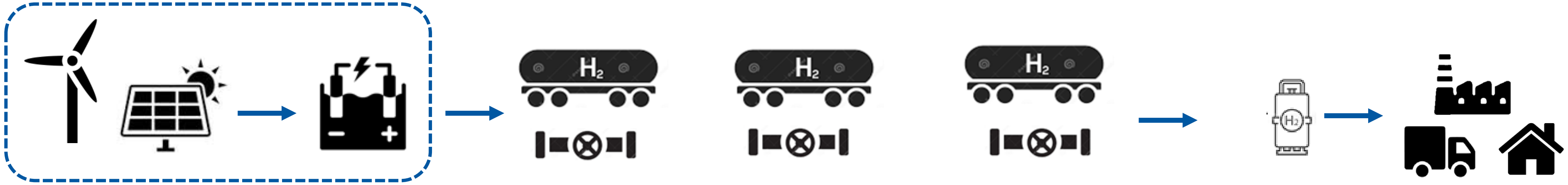


Co-location

- ✓ **Transport of electricity:** V-RES PP in most favourable areas with electricity transmission, electrolyzers at consumptions centres



- ✓ **Transport of H2:** electrolyzers and V-RES PP in the same locations with transport of H2



Key factors and questions to be addressed

Key Factors considered

- Network reinforcements
- V-RES intermittency and variability
- Power markets simulation
- Location of H2 demand
- Batteries
- H2 Pipeline infrastructure

Key Questions addressed

What are the implications of each implementation scenario on the power system?

Which is the impact of electrolyzers on the power markets?

Would the electrolyzers be able to support the integration of renewables?

How much will 1 kg of H2 cost in the different implementation scenarios?

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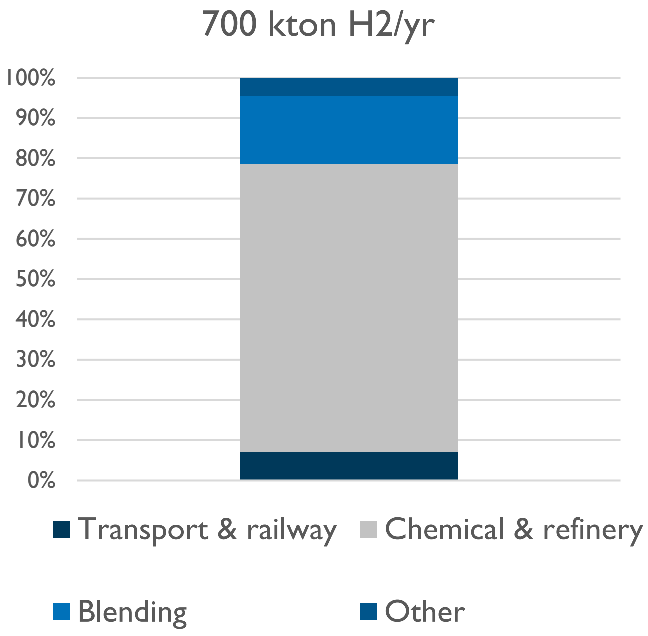
How to assess the Levelized Cost of Green Hydrogen - A practical study case applied to Italy

National Hydrogen Strategy: preliminary guidelines

✓ issued by Ministry of Economic Development – Oct. 2020

Targets and key figures:

- about **5 GW** of electrolyzers by 2030
- **2%** energy demand: 0.7 Mton/yr by 2030 [1]
- *2050 objective: up to **20%** of energy demand covered by green hydrogen*



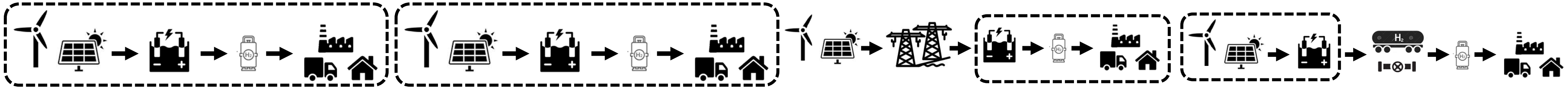
Preliminary **estimated benefits**:

- Up to **8 Mton** of avoided CO2 eq emissions
- about **200 k** temporary and **10 k** permanent jobs
- Up to **€ 27 billion** of additional PIL

[1] Current hydrogen demand: 0.5 Mton/yr

Overview of different hydrogen integration scenarios with pros and cons

	Off-grid*	Connection with power grid		
	1 - Decentralized	**2 - Decentralized**	**3 – Transport of Electricity**	**4 – Transport of H2**



	1 - Decentralized	2 - Decentralized	3 – Transport of Electricity	4 – Transport of H2
Description	RES and electrolyzers are installed close to hydrogen demand sites. RES capacity factor depends on location of demand sites and surplus of generation or insufficient hydrogen production cannot be managed through the power grid	RES and electrolyzers are installed close to hydrogen demand sites. RES capacity factor depends on location of demand sites	RES are built in market zones with a high capacity factor. Electrolyzers are installed close to hydrogen demand sites	RES and electrolyzer are built in the same market zone (with a high capacity factor). Hydrogen demand sites are potentially located in different zones
Pros	No transmission network costs	Lower cost for additional investments in power transmission No need of hydrogen transmission cost	RES can be installed in the most convenient sites enabling higher capacity factors No need of hydrogen transmission cost	RES can be installed in the most convenient sites enabling higher capacity factors Electrolyzers can better exploit zonal energy surplus avoiding RES curtailment and providing flexibility services
Cons	RES capacity factors could be lower in hydrogen demand locations Higher need for storage for the simultaneity constraint Oversizing of V-RES capacity to reach the target utilization factor of electrolyzers	RES capacity factors could be lower in hydrogen demand locations Potential additional cost to export exceeding power from RES (installed RES > electrolyzer capacity)	Potential additional cost to avoid power congestions between RES generation and electrolyzers consumption	Additional cost for hydrogen transmission from electrolyzers to demand sites

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Assumptions for the various Scenarios

H2 Demand location

- The **H2 demand has been split according to the indications provided in the "National Hydrogen Strategy"** with 2030 as horizon year, therefore considering the use of H2 in *Chemicals & Refining, Trucks, Trains, blending and others* (Hydrogen valleys, local public transport, biologic methanation, secondary metallurgy) and locating the demand according to current use and future needs

RES

- Additional RES to cover electrolyzers consumptions is dimensioned in energy: 700 kton/year with 50 MWh/ton efficiency → **35 TWh**
- RES location for scenarios 3 and 4 (sites with the best capacity factors/ lower Levelized Cost Of Energy (LCOE))

Electrolyzer

- Installed capacity of electrolyzers are fixed (5GW) as well as hydrogen target production (700 kton/year).
- Electrolyzer consumption profiles consider **7000 eq. hours of capacity factor** (as a consequence of the 5 GW-700 kton target).
- Electrolyzers are modelled considering two levels of flexibility:
  - ✓ **Low Flexibility**: low real-time coordination between RES/Electrolyzers, hence the system must compensate RES variability due to green hydrogen with additional system reserves
  - ✓ **High Flexibility**: high real-time coordination RES/Electrolyzers, no need of additional reserves for RES

Electrolyzers can operate as a special load able to yield **ancillary services**

Study methodology

Methodology

	Off-grid	Connection with power grid		
	1 - Decentralized	**2 - Decentralized**	**3 – Transport of Electricity**	**4 – Transport of H2**
Electrolyzer cost	Same calculation for all scenarios: expected cost per MW of electrolyzers in 2030 times the foreseen **5 GW installed capacity**			
New RES cost for hydrogen production	**Co-optimization of V-RES and batteries installed capacity to find the least cost solution**. Calculations consider hourly balances between generation, consumption and stored energy over a year.	**V-RES installed capacity sized to produce around 35 TWh** (needed to cover H2 demand of 700 kton) considering capacity factors of renewables **in H2 demand locations**	**V-RES installed capacity dimensioned to produce around 35 TWh** (needed to cover H2 demand of 700 kton) **considering highest capacity factors** of renewables in Italy	
Investment cost on power transmission grid and batteries		New investments needed to allow integration of the additional V-RES for H2 production are calculated on **iterative simulations of power markets for each implementation scenario***.		
Investment cost on H2 transmission grid	0	0	0	**Approximate length of 2000 km has been assumed** to connect electrolyzer (southern regions) with H2 consumption sites (spread in all regions)
Variation of costs in power markets (energy and ancillary)	0	Impact on power markets in terms of costs and integration of curtailed energy is estimated with simulations of energy markets and ancillary services market. **Use of simulation tools, developed by CESI, with a very detailed modelling of the Italian market framework. See next slide**		
Integration of curtailed energy due to electrolyzers	0			

* The current national development plan is considered as the baseline scenario 2030 and new network reinforcement are considered on top to the baseline.

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Power market simulations and computational tools (outline)

Power markets

Day-Ahead Market
Mercato del Giorno Prima (MGP)

Definition of withdrawals and injections schedules for the next day (24 hours)

Intraday Market
Mercati Infragiornalieri (MI)

Correction of schedules by market operators considering updated forecasts, unplanned unavailability, or because of technical unfeasibility.

Scheduling Ancillary Services Market
Mercati Servizi Dispacciamento Ex-Ante (MSD Ex-Ante)

Procurement of reserves margins and redispatching for network constraints which can be foreseen some hours in advance (Voltage control, lines congestion, …)

Balancing Market
Mercato di Bilanciamento (MB)

Activation of reserves margins in order to keep real-time balance between withdrawals and injections.
Real-time redispatching for network constraints.

Market simulators

Promedgrid

CIGRE 2012 C5 - 101 '**Market integration in Europe**: a market simulator taking into account different market zones and the increasing penetration of RES generation"

CIGRE 2016 C1 – 317 "An innovative **cost-benefit analysis** to assess transmission projects: The Italian case"

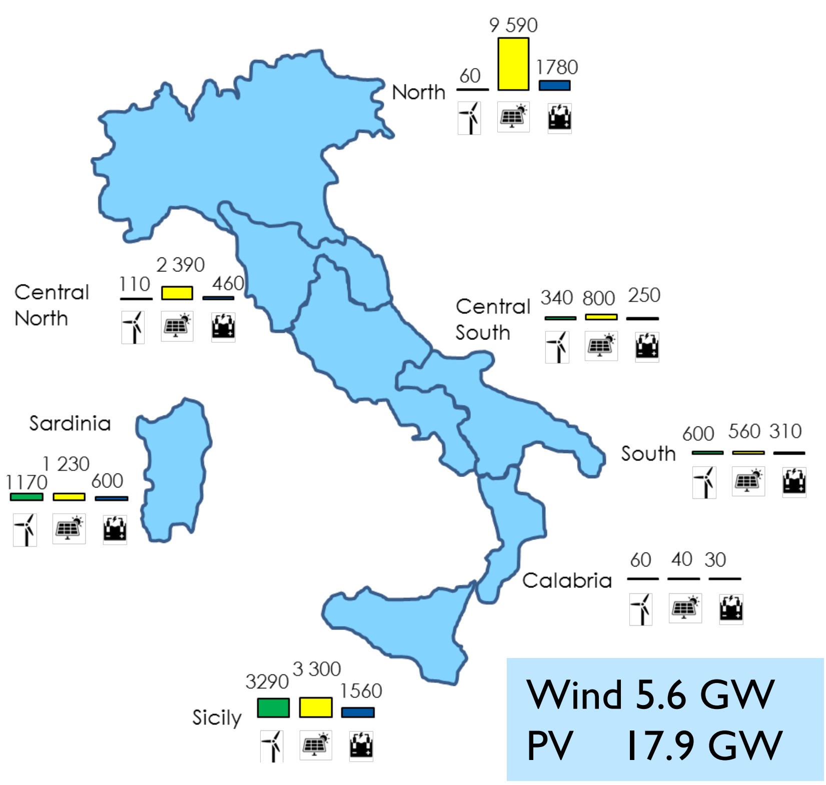
MODI$

CIGRE 2018 C1–103 "Assessing the impact of transmission investments on the Italian **Ancillary Services Market** using MODIS simulator"

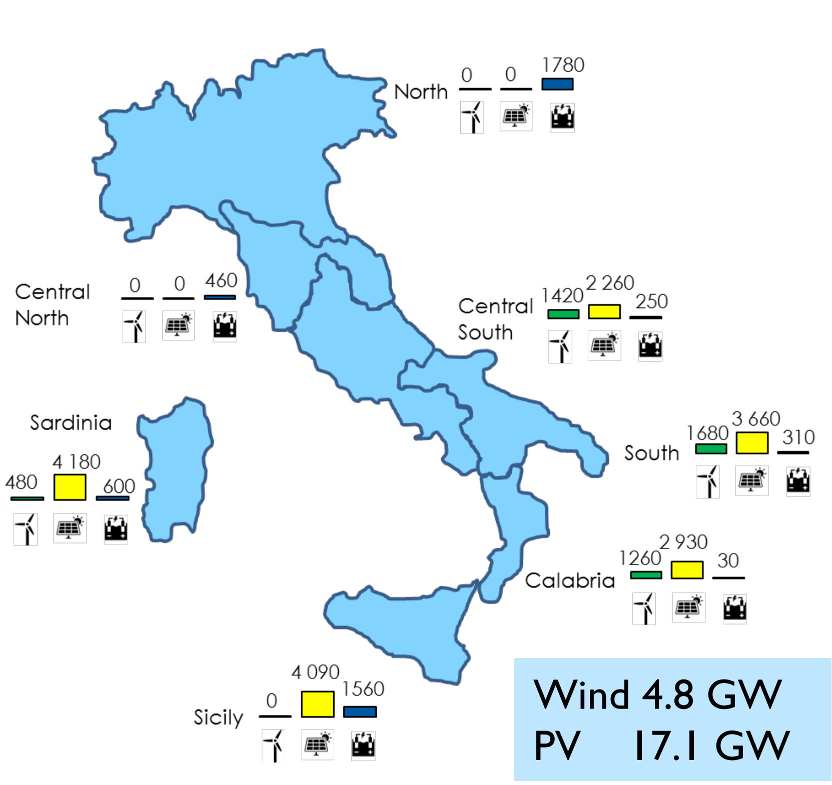
Scenarios: geographical location of electrolyzers and additional RES for green hydrogen

Wind installed capacity [MW]
PV installed capacity [MW]
Electrolyzers installed capacity [MW]

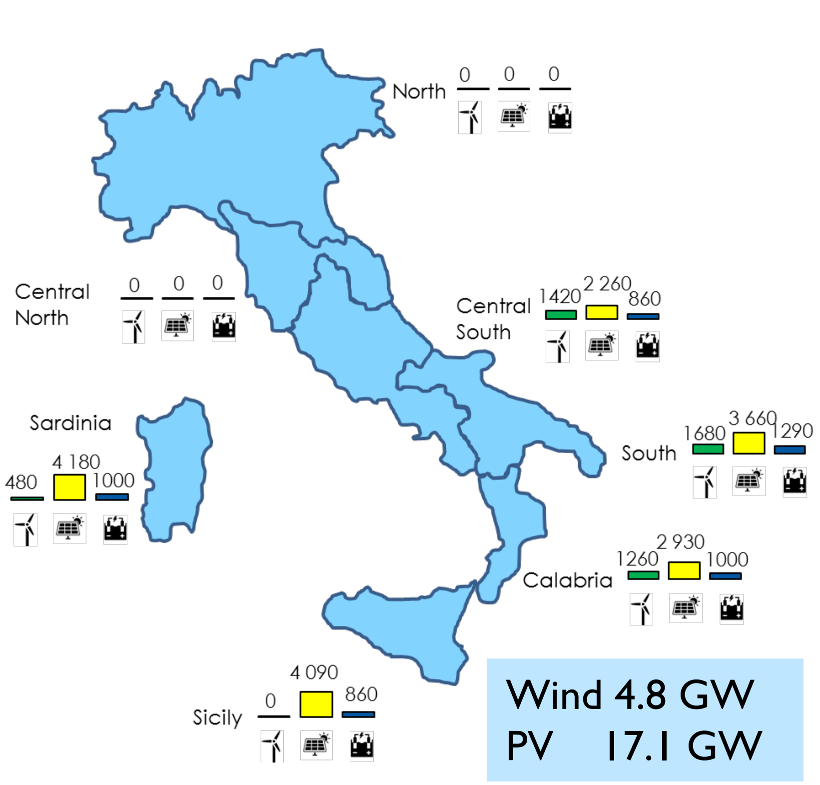
2 - Decentralized



3 – Transport of Electricity



4 – Transport of H2



Note: figures are based on the assumption that additional V-RES have to generate the energy needed to produce 700 kton of green hydrogen by means of 5 GW electrolyzers

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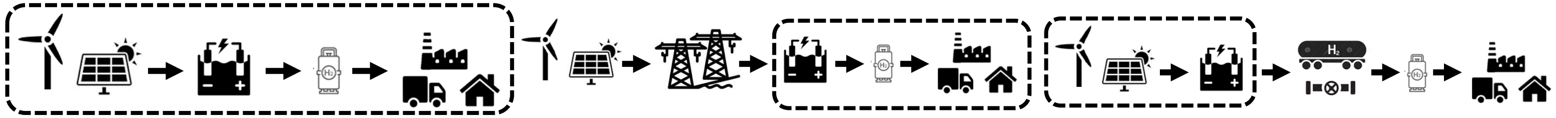
Scenarios: batteries and network reinforcements

For the grid-connected cases (2-3-4) the **installation of additional batteries** and **the realization of network reinforcements** have been considered to satisfy the Green H2 requirement of 100% RES and to support the deployment of the additional RES power plants required for Green H2 production

Criterion of "additionality"

Connection with power grid

2 - Decentralized	3 – Transport of Electricity	4 – Transport of H2
2000 MW North – Csouth (2x500km @ 400 kV)	**2000 MW** North – South (2x750km @ 400 kV)	**2000 MW** Cnorth– South (2x500km @ 400 kV)
1000 MW	**1500 MW**	**1500 MW**

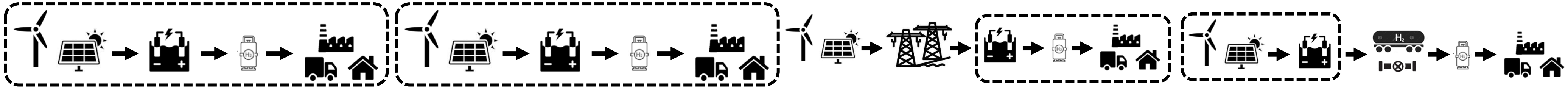


Batteries not utilized in Day-Ahead Market (MGP) and totally available in Ancillary Service Market (MSD)

Results – Low Flexibility Electrolyzers

Low Flexibility*

Off-grid	Connection with power grid		
1 - Decentralized	2 - Decentralized	3 – Transport of Electricity	4 – Transport of H2



Figures in M€/year

Total System Cost

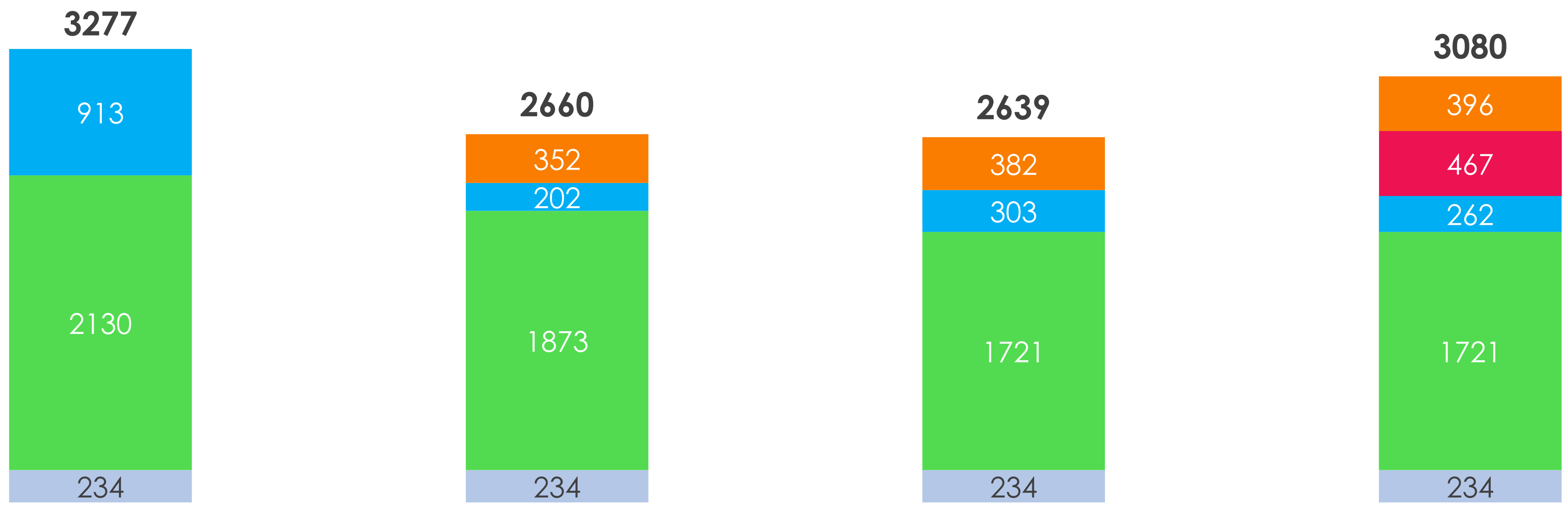
Variation of costs in power markets (energy and ancillary)

Investment cost on H2 transmission grid

Investment cost on power transmission grid and batteries

New RES cost for hydrogen production

Electrolyzer cost



System LCOH	4.7 €/kg_{H2}	3.8 €/kg_{H2}	3.8 €/kg_{H2}	4.1÷4.4 €/kg_{H2}
Avoided V-RES curtailment (<0 means increase of curtailment)	-6300 GWh	- 853 GWh	- 775 GWh	- 429 GWh

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* *Need of system reserves to compensate variability of RES dedicated to green hydrogen production*

Results – High Flexibility Electrolyzers

High Flexibility *

Figures in M€/year

Off-grid	Connection with power grid		
1 - Decentralized	2 - Decentralized	3 – Transport of Electricity	4 – Transport of H2

Total System Cost

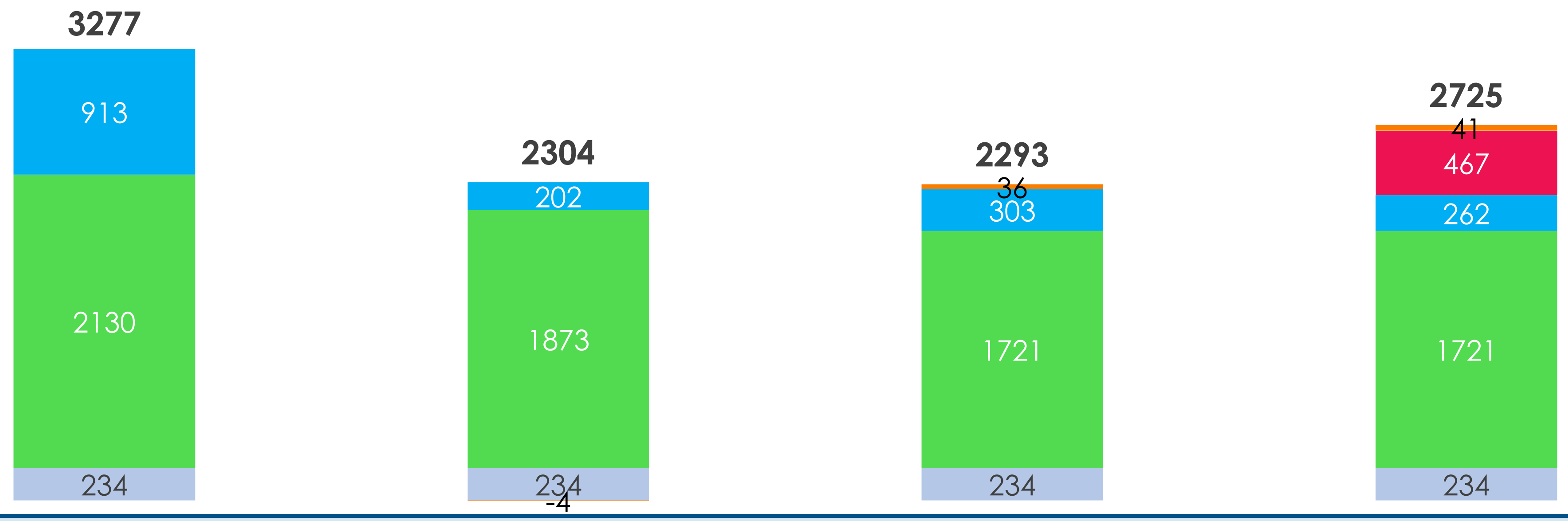
Variation of costs in power markets (energy and ancillary)

Investment cost on H2 transmission grid

Investment cost on power transmission grid and batteries

New RES cost for hydrogen production

Electrolyzer cost



	1 - Decentralized	2 - Decentralized	3 – Transport of Electricity	4 – Transport of H2
System LCOH	4.7 €/kg_{H2}	3.3 €/kg_{H2}	3.3 €/kg_{H2}	3.6÷3.9 €/kg_{H2}
Avoided V-RES curtailment (<0 means increase of curtailment)	-6300 GWh	447 GWh	425 GWh	671 GWh

* No need of system reserves to compensate variability of RES dedicated to green hydrogen production.

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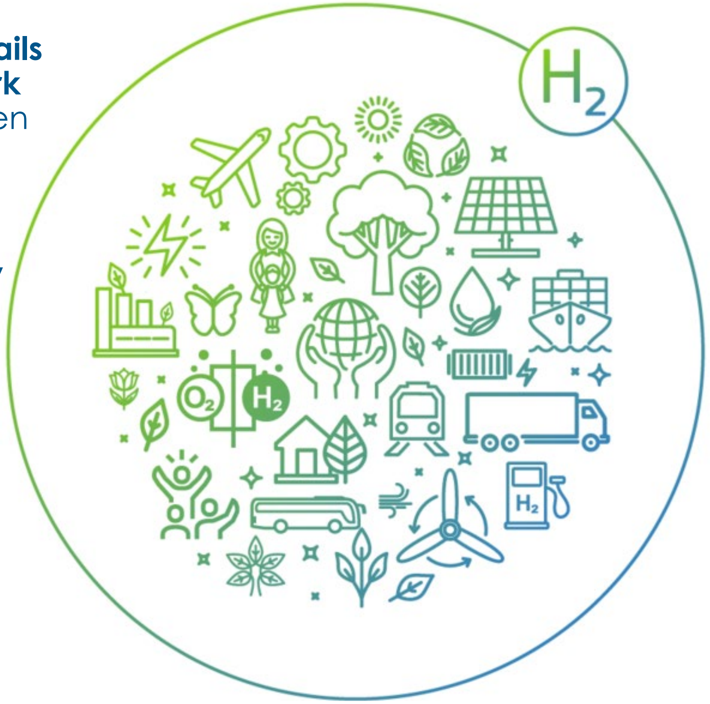
Key outcomes of the study case

Connection with power grid is the best solution compared to off-grid installation, the grid allows to export V-RES generation when their production exceeds the electrolyzer consumption. The same grid can also supply green energy to the electrolyzer when local V-RES generation does not reach the energy needed for hydrogen production

In the mid-term, with the current objectives for 2030, the option of a widespread hydrogen transport entails non-negligible investments on the hydrogen pipelines and also additional investments on power network reinforcements to cope with periodic V-RES surplus generation. On a further time horizon, when hydrogen demand will be higher and location of demand and profitable production sites will be clearer the opportunity of investments in a hydrogen transport infrastructure should be re-assessed



Electrolyzers allow to lower costs of balancing services thanks to their flexibility

A higher real-time coordination of electrolyzers and V-RES, reduces the costs on power markets and allows to reduce risk of V-RES curtailment, though it affects the hydrogen supply profile to consumption site.

Costs for the new RES installed capacity is the highest component of total system hydrogen costs. A more aggressive assumption with lower prices of PV and wind generation, **can bring to a System LCOH below 3 €/kg already in 2030.**

The current soared prices of NG (80÷90 €/MWh) and CO2 (80÷90 €/ton) emissions across Europe are making **green hydrogen** already now competitive with **blue hydrogen**, produced from SMR and coupled with CCUS

The above analyses require an accurate modelling of electrolyzers that can be seen as a "special load / component" linking the power and the gas systems

More info on this study case available on:
https://www.cesi.it/app/uploads/2021/10/CESI-Studies-Italian-Hydrogen-Strategy-1.pdf

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Presentation by encoord

Modeling the impact of hydrogen on power systems

Carlo Brancucci, Ph.D.
CEO

encoord
Coupling Energy Networks

encoord in brief

encoord
Coupling Energy Networks

- We are an American-German software company that provides tools to plan today's energy systems and their **transition to a decarbonized future**.
- Our core technology is the **Scenario Analysis Interface for Energy Systems** (SAInt), a flexible software platform to model energy networks and markets.
- Our clients use SAInt to inform a wide range of decisions, including planning for **hydrogen** by modeling its impact on electricity and gas networks and markets.

Hawaiian Electric

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

PERÚ Ministerio de Energía y Minas

clients in **10** countries

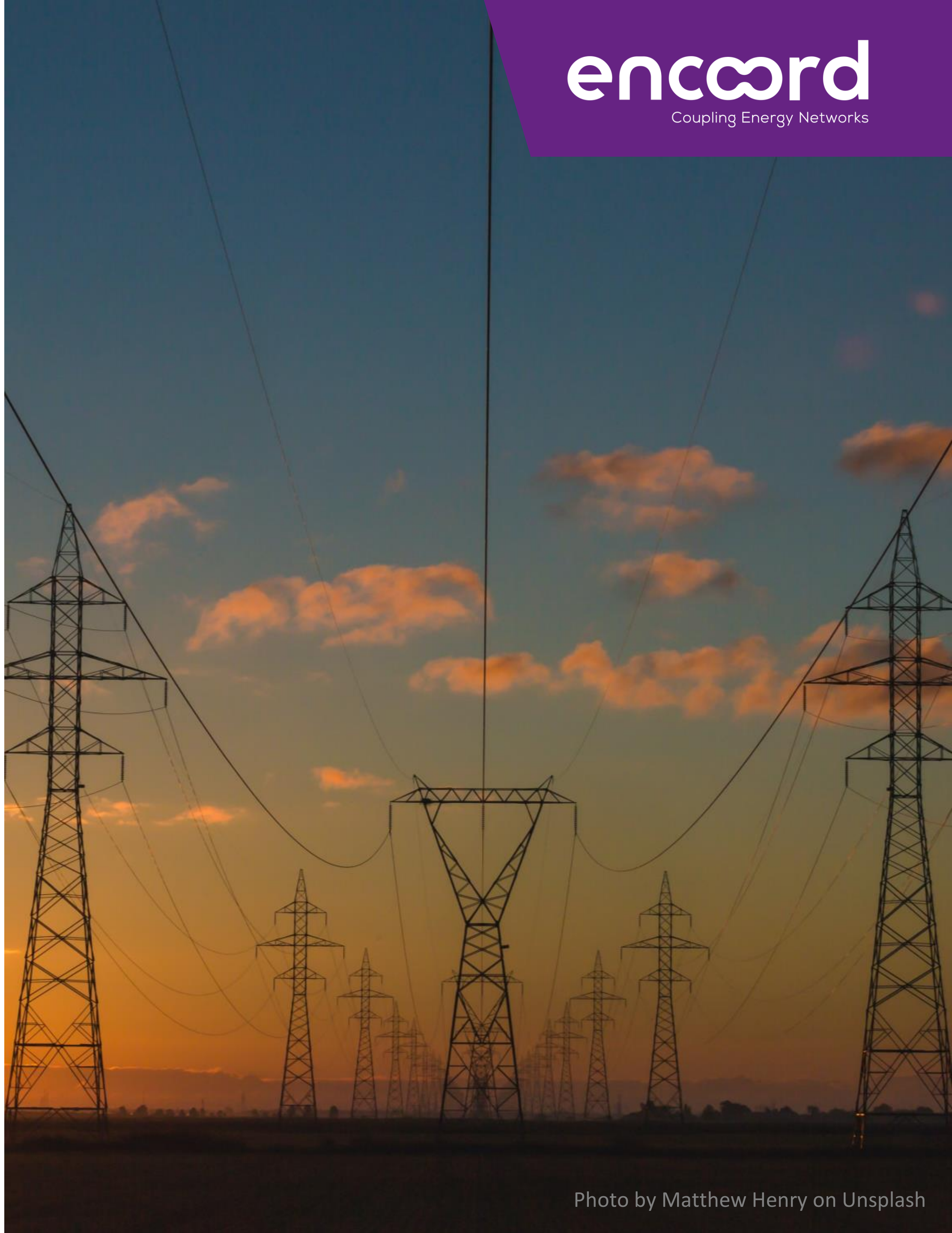
European Commission
Joint Research Centre

TenneT
Taking power further

DLR
Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

What is hydrogen for power systems?

- New demand
- Storage
- New fuel for gas turbines
- Flexibility resource
- Coupling with gas networks



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How will hydrogen impact power systems?

- Demand variability and uncertainty
- Transmission flows
- Renewable curtailment
- Emissions
- Production costs

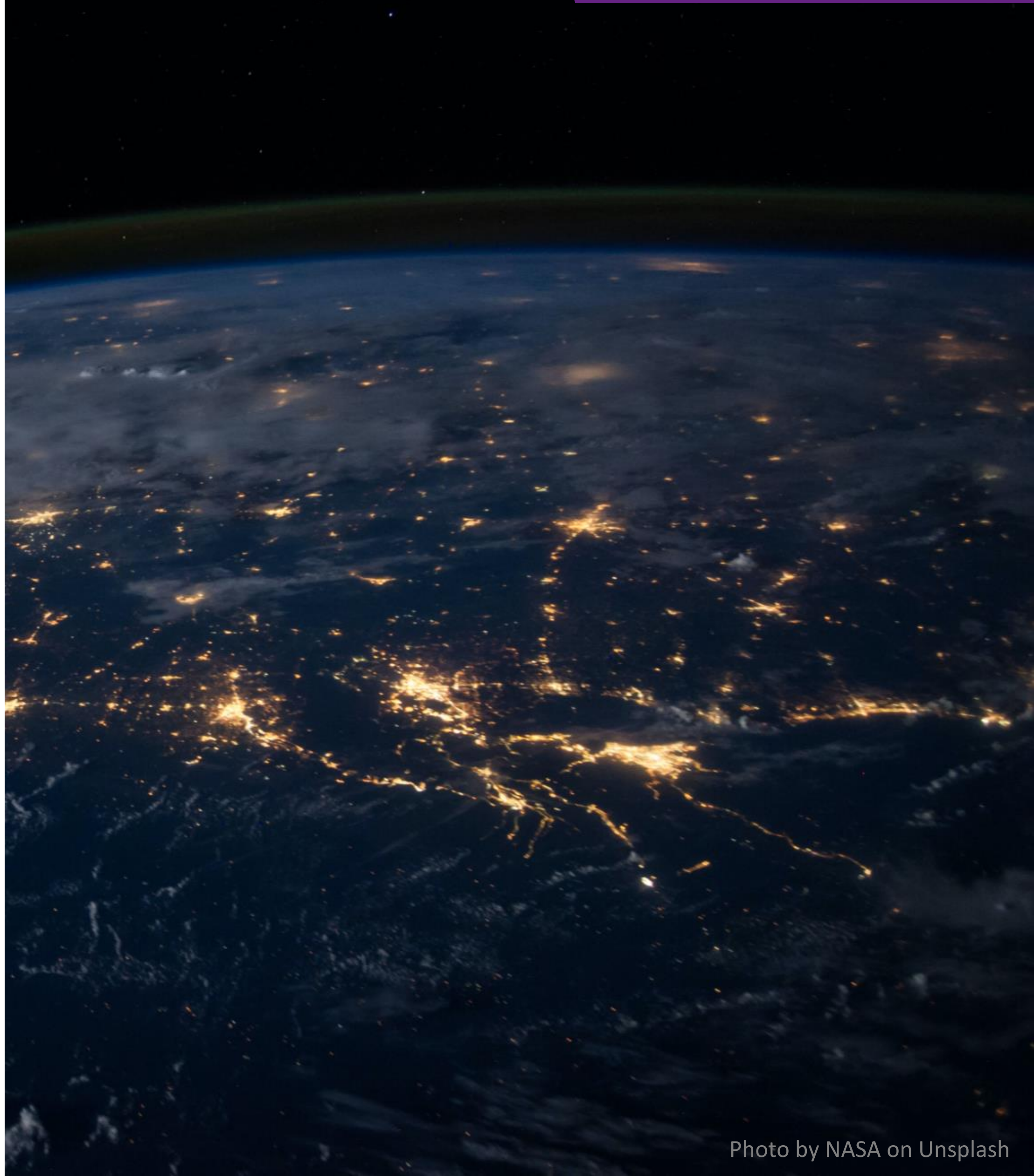
Photo by NASA on Unsplash

How will power systems impact the future of hydrogen?

- Availability of “green” electricity
- Price of electricity
- Transmission congestion
- Interconnection capacity & location (close to hydrogen consumers)

What decisions can power system modeling inform?

- Where should we build electrolyzers?
- How much flexibility can electrolyzers provide?
- What is the value of investing in electrolyzers?
- What is the value of investing in renewable generation or transmission to meet the needs of the hydrogen sector?

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How will gas pipeline networks impact the future of hydrogen?

- Transmission & distribution
- Underground storage
- Blending limits
- Pressure constraints

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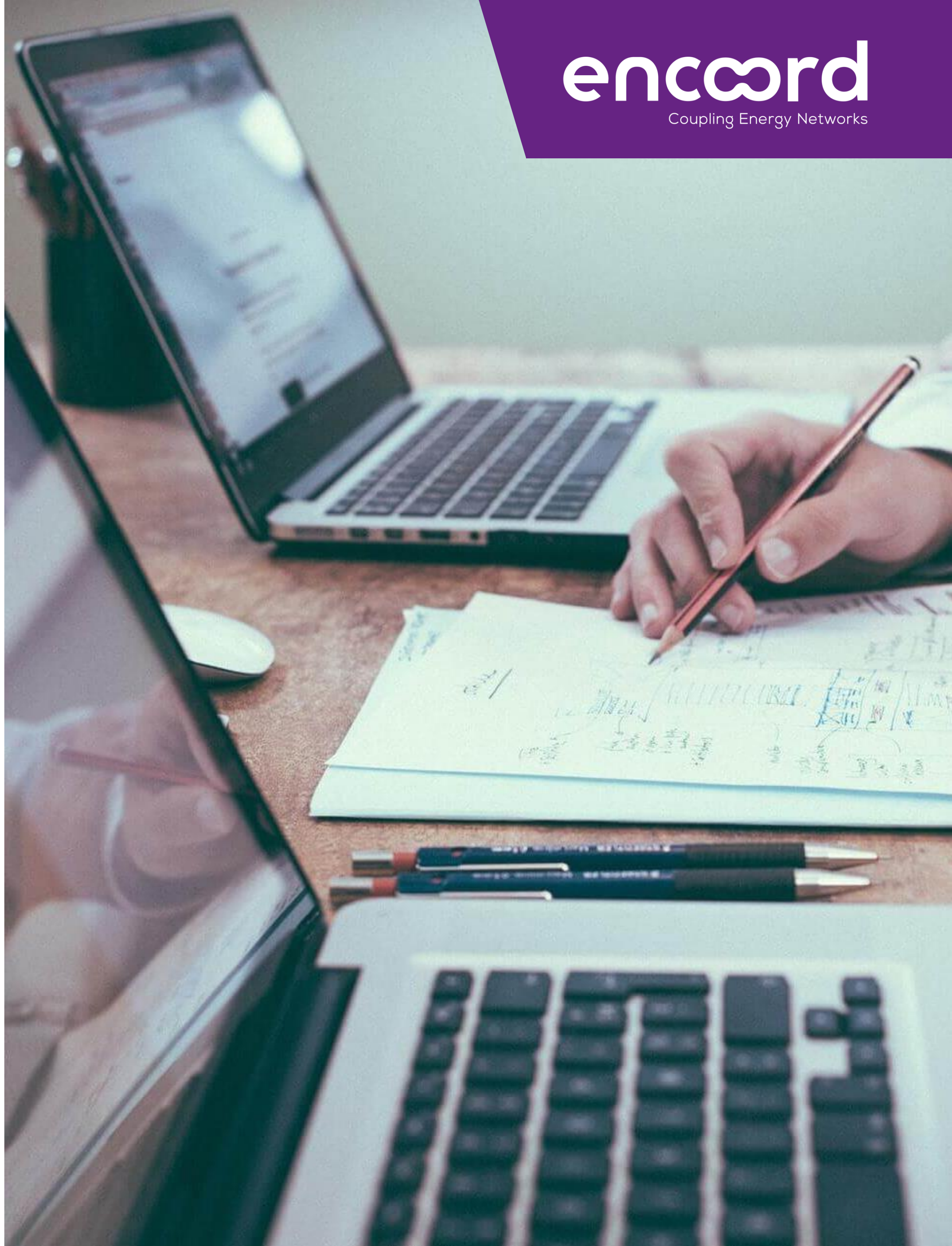
What decisions can the modeling of coupled electric and gas networks inform?

- How do gas network constraints impact the operation of electrolyzers (and gas turbines)?
- What are the tradeoffs between electric and gas (hydrogen) storage?
- What are the tradeoffs between electric and gas transmission investments?

Conclusions

- Modeling electricity networks and markets can help decision makers plan for (and invest in) the future of hydrogen.

- Modeling the coupling between electricity and gas networks (and markets) is necessary to quantify physical constraints and understand how hydrogen will impact (or leverage) their interdependency.



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Hydrogen markets will require a new generation of planning and modeling tools.

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Conclusions and Key Takeaways

- Use of hydrogen is an inevitable solution to be pursued for the decarbonisation of the «hard-to-abate» sectors
- A «green» supply chain for hydrogen shall be progressively created moving away from the current hydrogen production technologies
- Competitiveness of «green» hydrogen can be enhanced through a flexible operation of electrolyzers
- «Green» hydrogen produced by electrolyzers will be coupling power & gas markets: need for a new regulatory framework => see current initiative of the European Commission for a new Directive and Regulation on gases
- Electrolyzers shall not be seen as a generic additional load, but as an active component operating in the markets: need for an accurate modelling considering the technical constraints and performances
- In the mid-term the model of transport of «green» electricity to feed electrolyzers looks the most convenient.….

Any Questions?

Type your question into the chat box

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