SMARTENERGY

May 2025, Manuel Costeira da Rocha

The Power Trio: Integrated Electrolysers, Renewables, and Battery Storage for Grid Stability and Services

EEM 2025 – International Conference on the European Energy Market, Lisbon 27-29 May 2025

Agenda

01 The 28th April 2025 Blackout

02 Grid Ancillary Services and the Role of Flexible Assets

03 Smartenergy research project

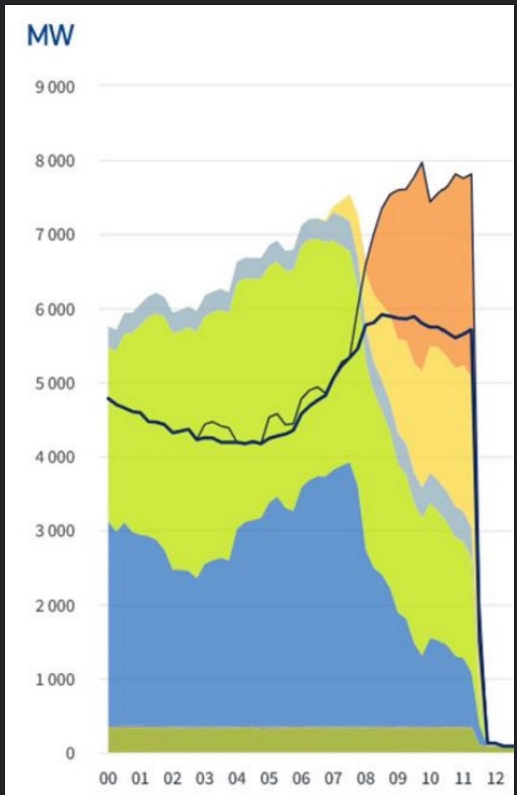
04 Conclusions, Challenges and Future Research Directions

01

The 28th April 2025 Blackout

The 28th April 2025 Blackout

Energy mix in Spain and Portugal before the blackout



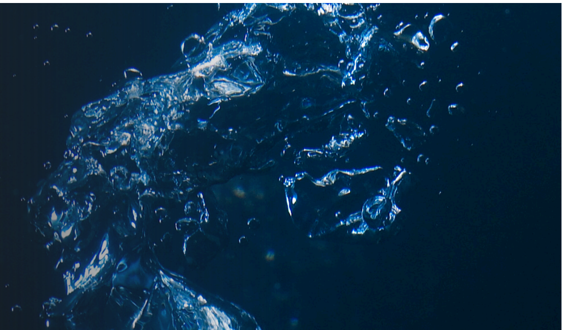
Generation (MW)*

Technology	Spain	syn MW/%	Portugal	syn MW/%	Iberia	syn MW/%
Solar PV	19340		1213		20553	
Wind	3416		839		4255	
Hydro			132		**132**	
Biomass	356	5956	211	588	**567**	6544
Nuclear	3384	21%		22%	**3384**	21%
Combined Cycle Gas	2216		245		**2461**	
Total Generation	28712		2640		**31352**	
Export /Import to Portugal	-2500		2500			
Hydro Pumping	-3048		-1172		-4220	
Consumption, net	23164		3968		27132	

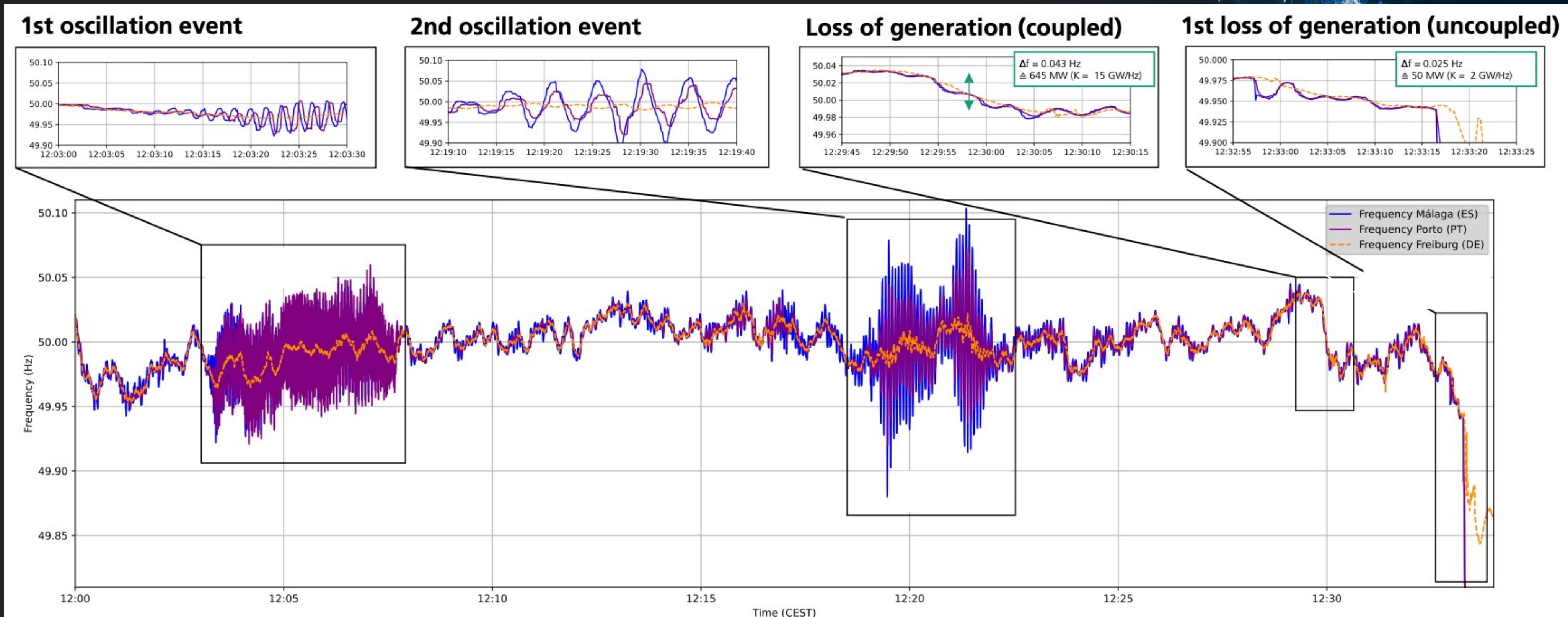
* 28/04/2025, 10h CET

The 28th April 2025 Blackout

Grid Frequency before the Iberian Peninsula Blackout



12:00 - 12:34 CEST



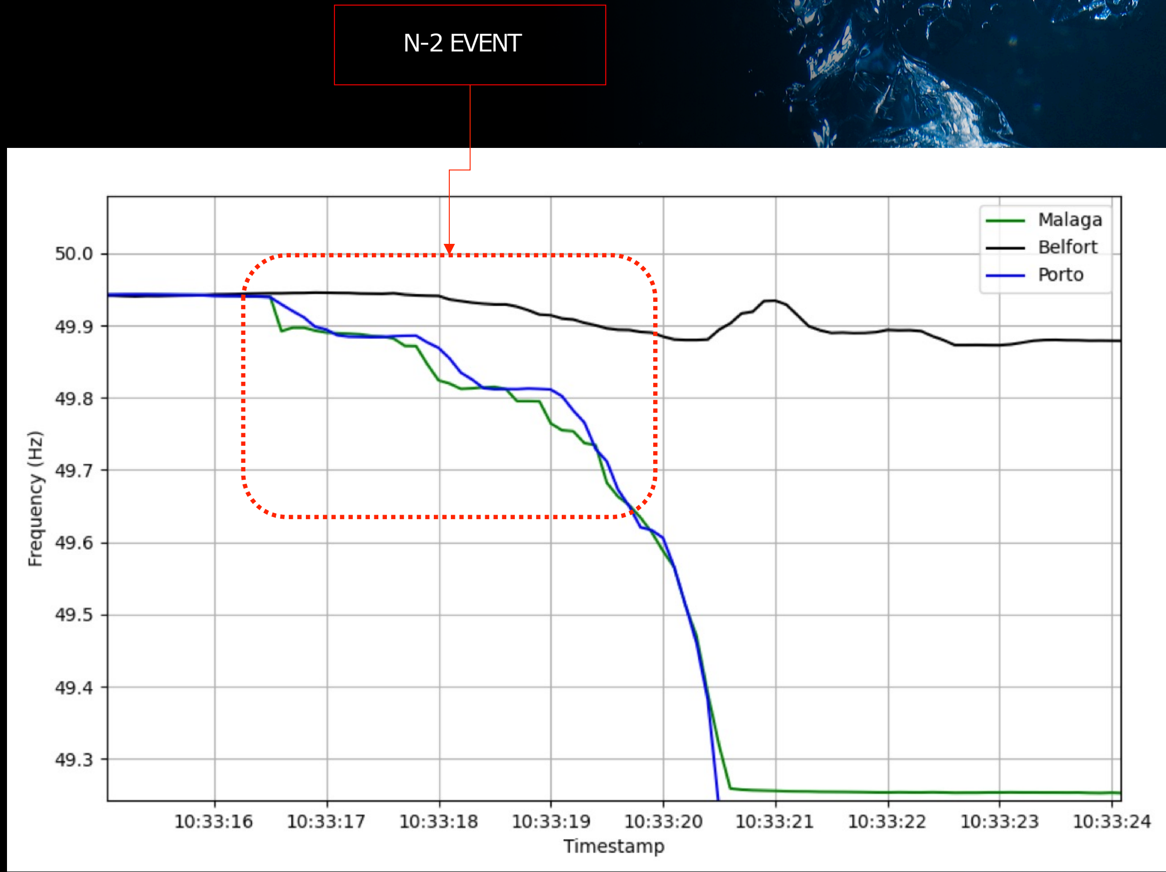
Source: Fraunhofer; Gridradar; Energy-Charts

The 28th April 2025 Blackout

Timeline of system blackout, frequency

12:33:16 - 12:33:24 CEST

11:33:16 - 11:33:24 GMT

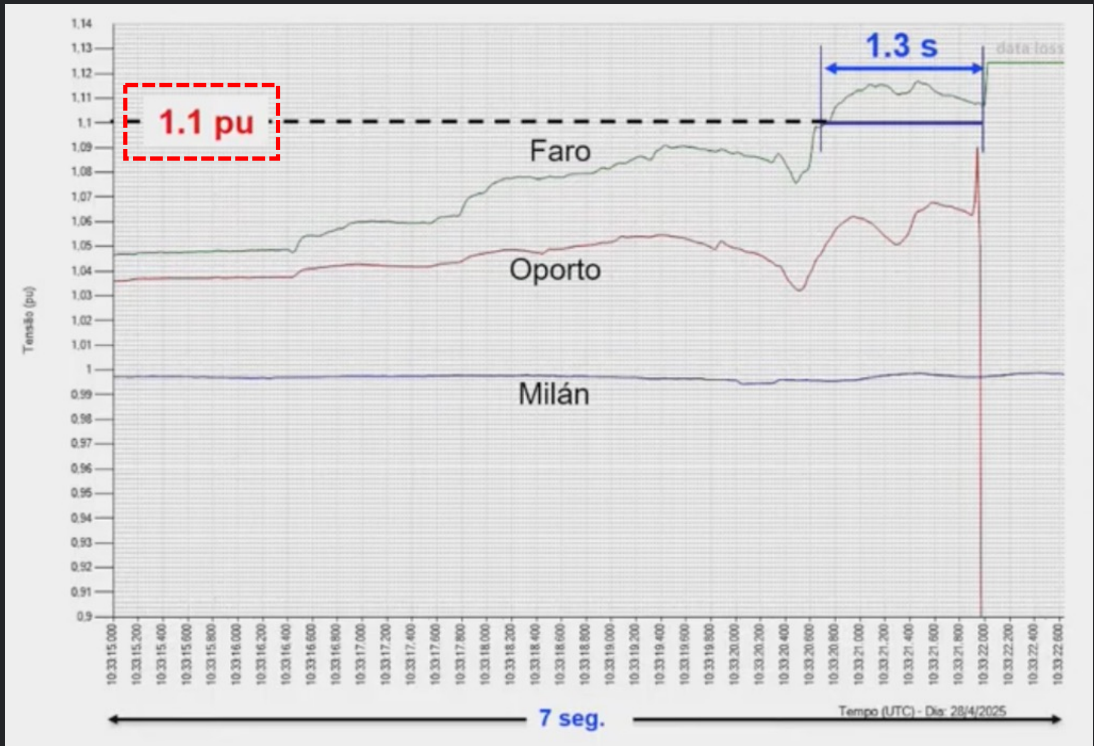


Source: x-Energy Lab (Inesc Tec); Gridradar

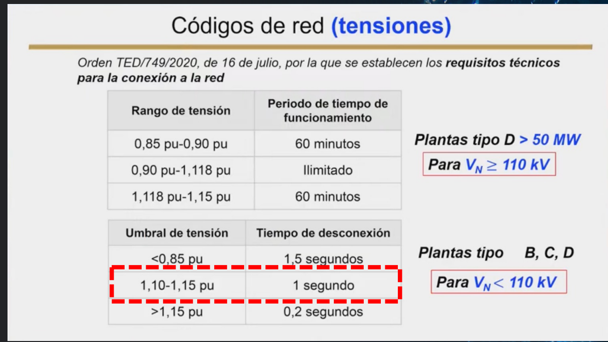
The 28th April 2025 Blackout

Timeline of system blackout, voltage level

Voltage Level before the trip



Source: Antonio Gomez Exposito; Inesc Tec



Códigos de red **(tensiones)**

Orden TED/749/2020, de 16 de julio, por la que se establecen los ***requisitos técnicos para la conexión a la red***

Rango de tensión	Periodo de tiempo de funcionamiento
0,85 pu-0,90 pu	60 minutos
0,90 pu-1,118 pu	Ilimitado
1,118 pu-1,15 pu	60 minutos

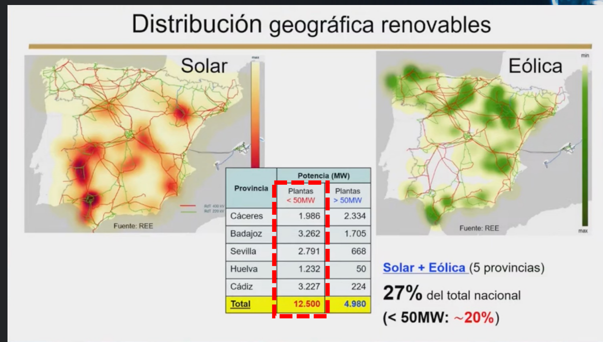
Plantas tipo D > 50 MW

Para $V_N \geq 110$ kV

Umbral de tensión	Tiempo de desconexión
<0,85 pu	1,5 segundos
1,10-1,15 pu	1 segundo
>1,15 pu	0,2 segundos

Plantas tipo B, C, D

Para $V_N < 110$ kV



Provincia	Potencia (MW)	
	Plantas < 50MW	Plantas > 50MW
Cáceres	1.986	2.334
Badajoz	3.262	1.705
Sevilla	2.791	668
Huelva	1.232	50
Cádiz	3.227	224
Total	**12.500**	**4.980**

Source: Antonio Gomez Exposito

Source: Inesc Tec

Lessons from a blackout

It is crucial that critical infrastructure operators are provided with a **suitable regulatory framework** that allows for investment planning incorporating system resilience criteria. This **planning** must also be **integrated,** considering the interdependencies between different infrastructures and considering the role of **new digital technologies** and the **flexibility of distributed energy resources** (i.e., renewable generation, energy storage systems, and flexible loads) as part of the solution.

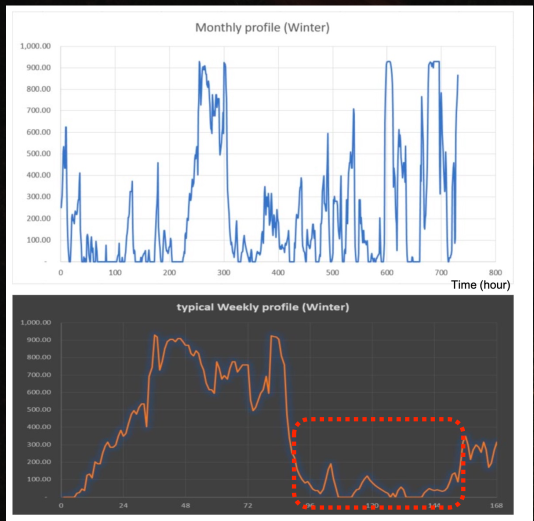
Source: Inesc Tec Source: Inesc Tec

02

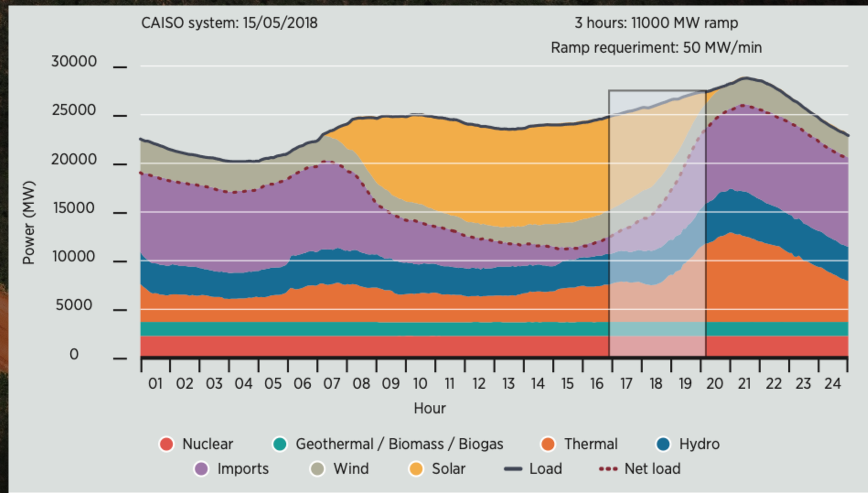
Grid Ancillary Services and the Role of Flexible Assets

The “Duck Curve”, the “dunkelflaute” and the need for Flexibility

“Dunkelflaute”
Winter wind profile, Portugal



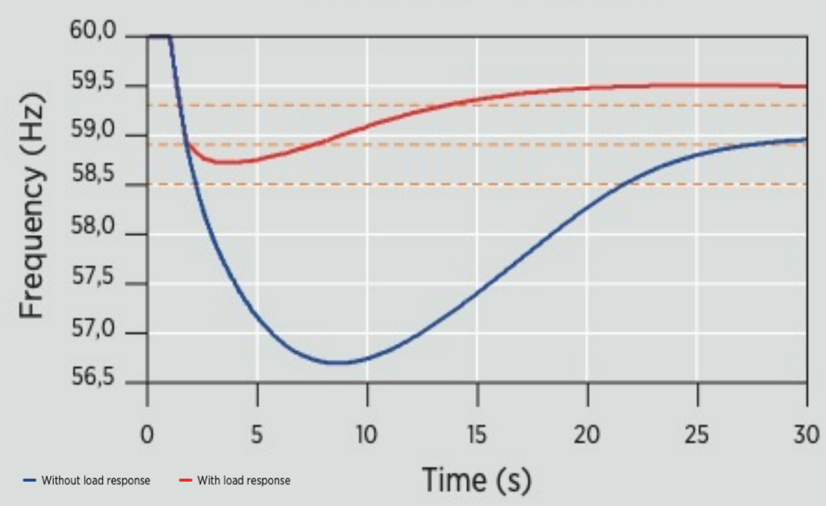
“Duck Curve”
Net load curve for california power system for 15 may 2018



Electrolysers may provide demand side flexibility to support the grid in high solar and wind penetration countries, as Portugal and Spain

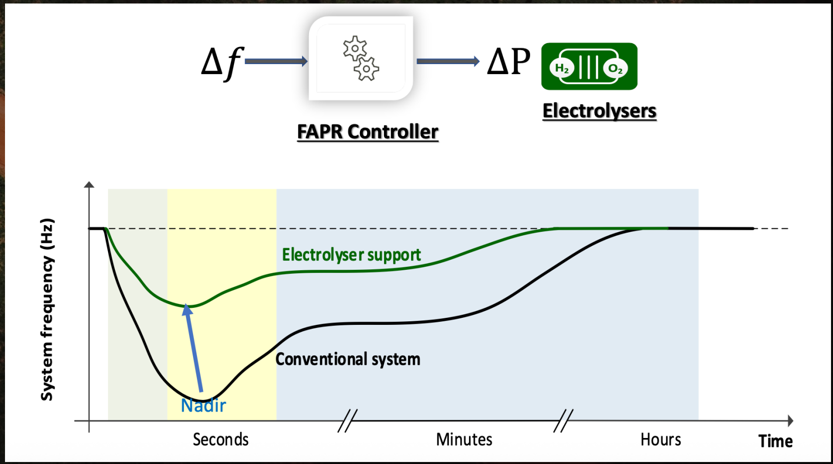
Electrolysers may provide Demand Side Flexibility to support the grid in high renewable penetration countries

Load response providing fast frequency response in ercot, with 80% renewable energy penetration



Source: IRENA

Fast active power regulation control strategies on renewable + electrolyser energy hubs



Source: Dr. José Rueda, Prof. Mart van der Meijden, TSO2020 Closing Event

Fast Frequency Response Services

Fast Frequency Response (FFR)

An extremely rapid response (sub-second to a few seconds) to counteract sudden and large frequency deviations. FFR is increasingly critical in systems with low inertia due to high penetration of converter-based resources like wind and solar power.

Frequency Containment Reserve (FCR) or Primary Control

An automatic, decentralized response from generators or controllable loads that activates within seconds to arrest frequency deviations and stabilize the system, typically operating for minutes.

Automatic Frequency Restoration Reserve (aFRR) or Secondary Control

A centralized, automatic response dispatched by the TSO to restore the system frequency to its nominal setpoint and to relieve activated FCR. This service typically operates within a timeframe of 5 to 15 minutes.

Manual Frequency Restoration Reserve (mFRR) or Tertiary Control

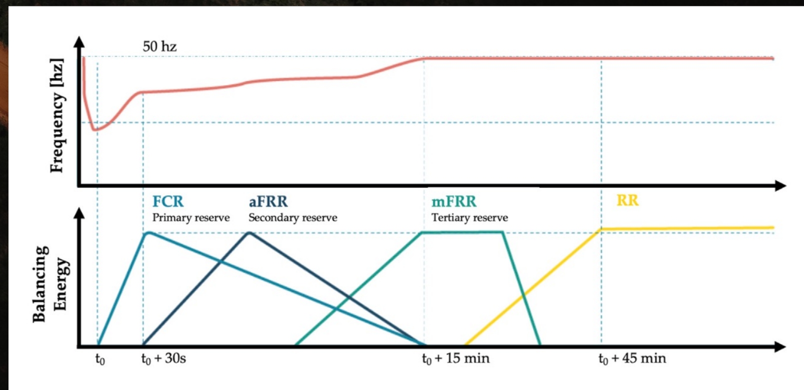
A slower, manually activated reserve, often dispatched by the TSO to fully restore frequency and rebuild other reserves over longer periods (tens of minutes to hours).

Replacement Reserves (RR)

Consists of restoring or sustaining the FRR to be prepared for any further imbalances in the system. It is activated semi-automatically or manually and has a minimum activation time of 15 min.

The evolving nature of power generation, particularly the integration of variable renewable energy, is driving a re-evaluation of how these services are defined, procured, and provided.

Frequency Reserve Services



Comparative Operational Characteristics of Electrolysers for Fast Frequency Response Services

Feature	PEM Electrolyser	Alkaline Water Electrolyser (AWE)	Solid Oxide Electrolyser Cell (SOEC)
Typical Ramp-Up Rate	10-80% Nominal/s; +/- 1 kW/s (40kW system)	0.3-20% Nominal/s	Seconds response at cell level; system limited by thermal inertia
Typical Ramp-Down Rate	~ -40% Nominal/s	~ -25% Nominal/s	Seconds response at cell level; system limited by thermal inertia
Response Time	Milliseconds to <1s	<1s (hot start) to <3s (standby); generally, seconds	Seconds
Minimum Operating Load	~10-25% Nominal	~10-40% Nominal (can be higher for pressurized)	~3% Nominal (hot standby)
Cold Startup Time	Tens of seconds to minutes	20-60 minutes	Several hours
Hot Startup Time	Very fast, <1s from warm standby possible	<1s to <3s	Seconds to minutes (from hot standby, depending on temperature drop)
Key Constraints for Freq. Reg.	H2 storage limits; PGM cost/degradation; efficiency off-peak.	Gas crossover at low load; longer cold starts; reverse current degradation.	Thermal stress from cycling; very slow cold start; material degradation at high temp.

Source: Dr. Thijs de Groot | Eindhoven University of Technology; Smartenergy

However, Electrolysers Ramp Rates have physical limitations behind, related with gas holdups changes

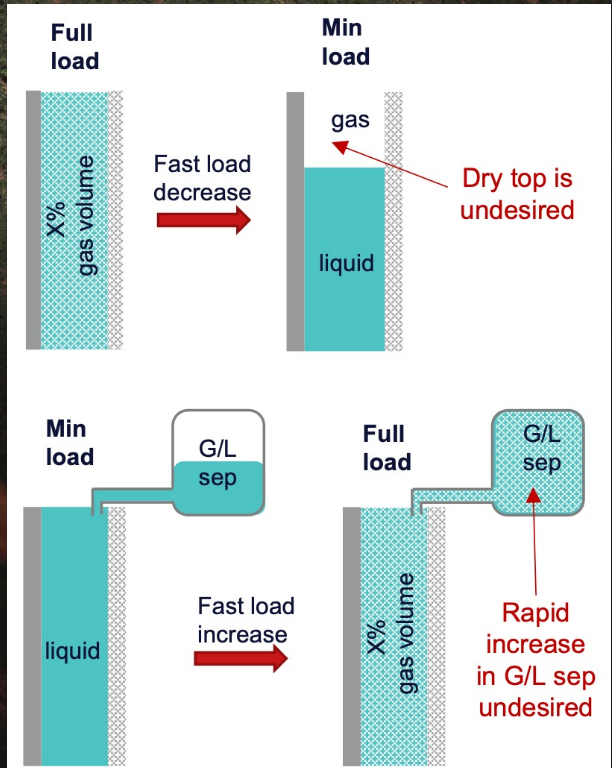
Flexibility KPIs in Water Electrolysis

- Minimum Load
- Ramp Rates
- Allowances nr. on/offs

What physical limitations are behind it

- Power Supply and Grid Limitations
- Oxygen Purity (Gas crossover)
- Gas holdups changes
- Reverse Curents

Minimum Load → Power Supply and Grid Limitations; Oxygen Purity (Gas crossover)
Ramp Rates → Gas holdups changes
Allowances nr. on/offs → Reverse Curents



Source: Dr. Thijs de Groot | Eindhoven University of Technology; Smartenergy

Studies on Electrolyser technologies for Frequency Regulation

Prof. Mart van der Meijden

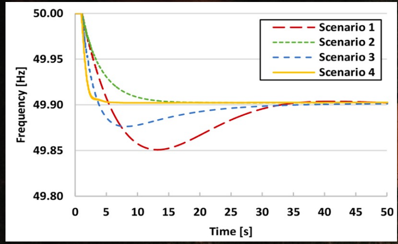
TenneT / Delft University of Technology

List of scenarios, FCR bid sizes per technology and obtained values of the freqnecy indicators

N°	Scenario	System inertia*	Sync. generators	PEM electrolyzer	PEM fuel cell	Nadir [Hz]	RoCoF [mHz/s]
(1)	Base case (2018)	100%	2 × 25 MW FCR bid	Not installed	Not installed	49.851	26.972
(2)	Base case with H_2 (2018)	100%	No FCR support	40 MW FCR bid	10 MW FCR bid	49.902	26.376
(3)	Energy transition (2030)	50%	1 × 25 MW FCR bid	20 MW FCR bid	5 MW FCR bid	49.876	53.882
(4)	Low inertia with H_2 (2050)	25%	No FCR support	40 MW FCR bid	10 MW FCR bid	49.902	99.600

* The value of the system inertia for the base case is 12 seconds.

Frequency response for the described scenarios



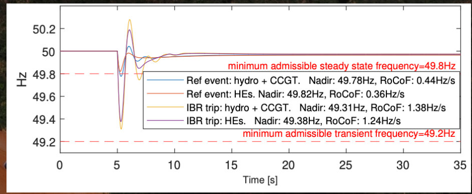
1. The synergy between the electrical system and the hydrogen system unlocks potential for new control principles to safeguard operational flexibility of the electrical system.
2. Electrolysers demand side response can significantly enhance the dynamic performance (milliseconds) of the electrical system, increasing its resiliency
3. Power rating, location and optimal controller design are key parameters for effective stability support by electrolysers.

Source:
Dr. José Rueda, Prof. Mart van der Meijden TSO2020 Closing Event;
Víctor García Suarez, Jose L. Rueda Torres, Arcadio Perilla, M. A. M. M. van der Meijden. Modelling and evaluation of PEM hydrogen technologies for frequency ancillary services in future multi-energy sustainable power systems. Heliyon 5 (2019) e01396. doi: 10.1016/j.heliyon.2019. e01396

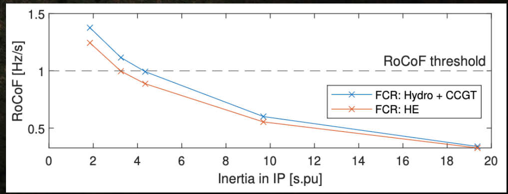
Prof. João Peças Lopes

Inesc Tec / Faculdade de Engenharia da Universidade do Porto

Frequency in Iberia (IP) after reference incident and IBR trip



Influence of system inercia on RoCoF, depending on FCR providers



1. Whether the contingency is the conventional reference incident (3GW loss in CE or 1GW in IP) or an IBR generation loss following a short circuit, both conventional plants (CCGT, hydro) and electrolysers achieve the main FCR objective.
2. Regarding RoCoF in the context of the IBR trip, either both conventional plants and electrolysers may lead to the violation of the maximum acceptable value (1Hz/s). However, electrolysers may minimize the need for compensation mechanisms.

Source:
F. J. Ribeiro, J. A. P. Lopes, F. S. Fernandes, P. J. Soares, and A. G. Madureira, "The Role of Hydrogen Electrolysers in the Frequency Containment Reserve: A Case Study in the Iberian Peninsula up to 2040," in Proc. 5th Int. Conf. Smart Energy Syst. Technol. (SEST), Eindhoven, Netherlands, Sept. 2022, pp. 1–6, doi: 10.1109/SEST53650.2022.9898458.

Summary of Key Pilot Projects for Electrolyser projects providing Grid Services

Project Name & Location	Lead Partners/ Key Participants	Technology (Electrolyser Type, MW, BESS if any)	Project Status/Timeline	Ancillary Services Tested/Provided	Key Technical/Economic Findings & Lessons Learned
Energiepark Mainz, Germany	Stadtwerke Mainz, Linde, Siemens	PEM, 6 MW (3x Siemens SILYZER 200)	Operational since 2015	Demand response, load following, ramping, renewable capacity firming, congestion relief, reserve power	Fast response (ms), flexible start-up (15s to 4MW). Efficiency 70.4% @ 2MW. AS revenue improves economics. H_2 price challenge.
Wunsiedel (WUN H2), Germany	Siemens, Rießner Gase, SWW Wunsiedel	PEM, 8.75 MW (Siemens Silyzer 300); Co-located with BESS	Operational 2022	Grid bottleneck alleviation, grid flexibility, sector coupling (heat/O_2 use)	Model for industrial green H_2 & sector coupling. Scalable. Waste heat/O_2 utilized.
Windgas Haurup, Germany	Energie des Nordens, Green Planet Energy, H-TEC SYSTEMS	PEM, 1 MW (H-TEC ME450)	Operational 2020	Surplus wind power utilization (curtailment reduction), grid stabilization, H_2 injection to gas grid	Saves 530 t CO_2/yr. Uses existing gas grid. Feed-in limits a challenge for expansion. Efficient part-load operation.
REFHYNE I, Germany	Shell, ITM Power, SINTEF, Element Energy	PEM, 10 MW (ITM Power)	Operational 2021, Concluded June 2024. Final report Sept 2024	Frequency Control Reserve (FCR) to TSOs, internal grid balancing	Validated ITM stack performance & flexibility. Lessons on large-scale integration, partner collaboration, standards. Paved way for REFHYNE II (100MW).
H2Future, Austria	VERBUND, Voestalpine, Siemens, APG, K1-MET, ECN	PEM, 6 MW (Siemens)	Operational 2019, Concluded Dec 2021	Primary, secondary, tertiary balancing services; demand-side management	Demonstrated H_2 for steelmaking + grid services. Impressive efficiency & flexibility. Addressed regulatory challenges for sector coupling.
Demo4Grid, Austria	MPREIS, SUNFIRE (IHT), FHA, INYCOM, FEN-SYSTEMS, DBC	Pressurized Alkaline, 3.2 MW (up to 4MW)	Operational, Project end Aug 2023	Primary/secondary balancing, intraday/spot market participation, surplus hydro use	Validated pressursised alkaline electrolyser for grid services in local context. Remote control developed. Business case focus.
NREL/DOE Projects, USA	NREL, Giner Inc., various industry partners	PEM & Alkaline (various sizes, e.g., ~40kW, 120kW stacks)	Ongoing R&D and demonstration	Frequency support, demand response, market participation simulation/testing	Demonstrated ms response for PEM/AEL. Validated for grid support. Cost reduction and efficiency improvements for PEM.

Comparison of PV, Wind, and Hydro for Frequency Regulation

Feature	Solar PV	Wind Power	Hydropower (Conventional & Pumped)
Primary Energy Source	Solar Irradiance (Variable, Intermittent)	Wind Speed (Variable, Intermittent)	Water Flow / Stored Water (Dispatchable, Storable)
Inertial Response	Synthetic (via inverters)	Synthetic (via inverters & turbine kinetics)	Natural (from synchronous generator)
Response Speed (FFR, PFR)	Very Fast (milliseconds to seconds, inverter-based)	Fast (seconds, inverter & pitch/torque control)	Fast to Moderate (seconds to tens of seconds, depends on turbine type & hydraulics)
Duration of Response	Limited by de-loading margin or coupled storage	Limited by de-loading margin or coupled storage	Potentially Long (depends on reservoir size)
Reactive Power/Voltage Control	Excellent (fast, precise via inverters)	Excellent (fast, precise via inverters)	Good (synchronous generator capability)
Black Start	Possible with BESS & grid-forming inverters	Possible with BESS & grid-forming inverters	Traditional provider, often designed for this
Ramping Support	Good (with forecasting, controls, storage)	Good (with forecasting, controls, storage)	Excellent (highly flexible)
Energy Storage Capability	Requires separate BESS	Requires separate BESS	Inherent (reservoir/pondage); PHS is dedicated storage
Cost of Service Provision	Decreasing; depends on foregone energy sales if de-loaded, or BESS cost	Decreasing; depends on foregone energy sales if de-loaded, or BESS cost	Generally competitive; can increase with wear and tear from frequent cycling
Limitations	Intermittency, need for de-loading or storage for sustained upward reserve	Intermittency, need for de-loading or storage for sustained upward reserve	Water availability, environmental constraints, potential wear and tear, slower for some very fast services compared to inverters
Market Participation	Growing, often with storage or as VPPs	Growing, often with storage or as VPPs	Well-established, significant market player

Rationale for Hybridization: Complementing Strengths and Mitigating Weaknesses

Enhanced Grid Stability with High Renewable Penetration

Addressing Variability

As grids incorporate more variable renewables, the need for flexible resources to manage frequency fluctuations increases. This hybrid system provides a robust solution.

Providing Inertia-like Services

While renewables and electrolysers are inverter-based or controllable loads, BESS and advanced controls can help provide synthetic inertia or rapid active power injections that mimic inertial responses, crucial for low-inertia grids.

Synergistic Operation for Bidirectional Reserve

Upward Reserve (Frequency Drops)

1. BESS: Rapidly discharges power to the grid.
2. Electrolyser: Rapidly reduces its power consumption, freeing up power for the grid.
3. Renewables: Increase power output if operating in a de-loaded mode.

Downward Reserve (Frequency Rises)

1. BESS: Rapidly charges, absorbing excess power from the grid.
2. Electrolyser: Increases its power consumption to produce more hydrogen, absorbing excess grid power.
3. Renewables: Curtail their power output.

The bankability of projects that rely on ancillary service revenues can be challenged by the volatility of prices and uncertainties in market rules

1. **The primary value proposition** for most electrolyser projects remains the production of green or low-carbon hydrogen for use in industry, transport, or other applications. The provision of ancillary services typically serves to enhance this core business case by improving asset utilization, generating additional revenue streams, and potentially reducing the net cost of hydrogen production.

2. **The need for significant policy subsidies** in some modelled scenarios underscores the current economic challenges and the importance of supportive policies.

3. **The viability of any business case** is highly dependent on specific market conditions (electricity prices, ancillary service market depth and prices, hydrogen demand and price), the regulatory framework (market access rules, incentives), and the technical performance and cost of the chosen technology.

4. **For hybrid electrolyser-BESS systems**, the value proposition is further strengthened by their enhanced grid support capabilities. The BESS can enable participation in more lucrative or demanding ancillary service markets (e.g., very fast FFR), protect the electrolyser from excessive cycling, and optimize the overall energy management of the system.

5. **Ancillary service revenue streams** are often less predictable than long-term hydrogen offtake agreements.

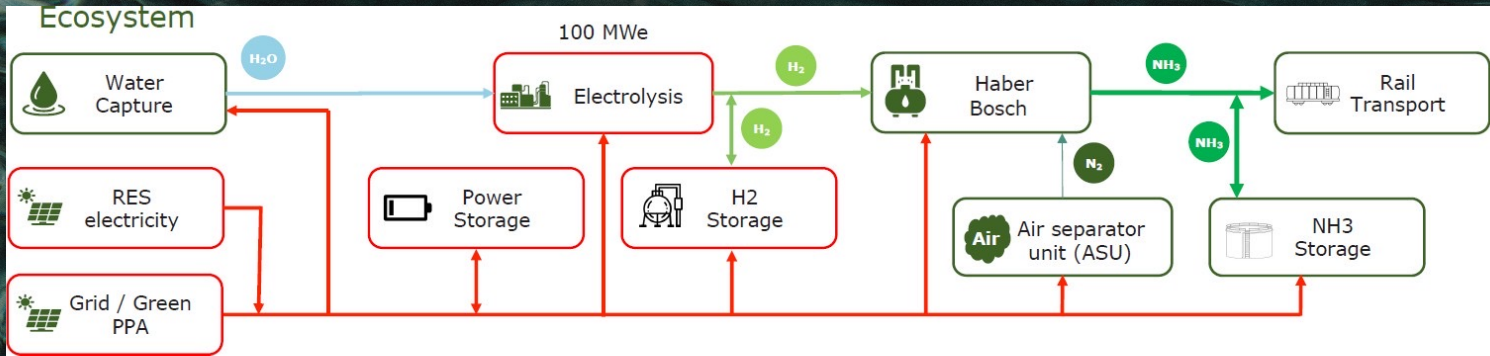
Developing more stable, long-term market frameworks or incentives for flexibility provision by **assets like electrolysers are crucial** for attracting the necessary **investment to scale up** their role in **grid support.**

03

Smartenergy research project

Smartenergy research project

Study of an energy hub that must be capable of feeding a 100 MW electrolyser to produce hydrogen and provide grid services



Task 5 Predictive model to optimize the hub operation

Task 6 Technical-economic feasibility analysis (inc. aFRR)

Task 7 Grid Code and reserves provision requirements

Task 8 Grid integration impact (on going)

Task 9 Islanded Operation (on going)

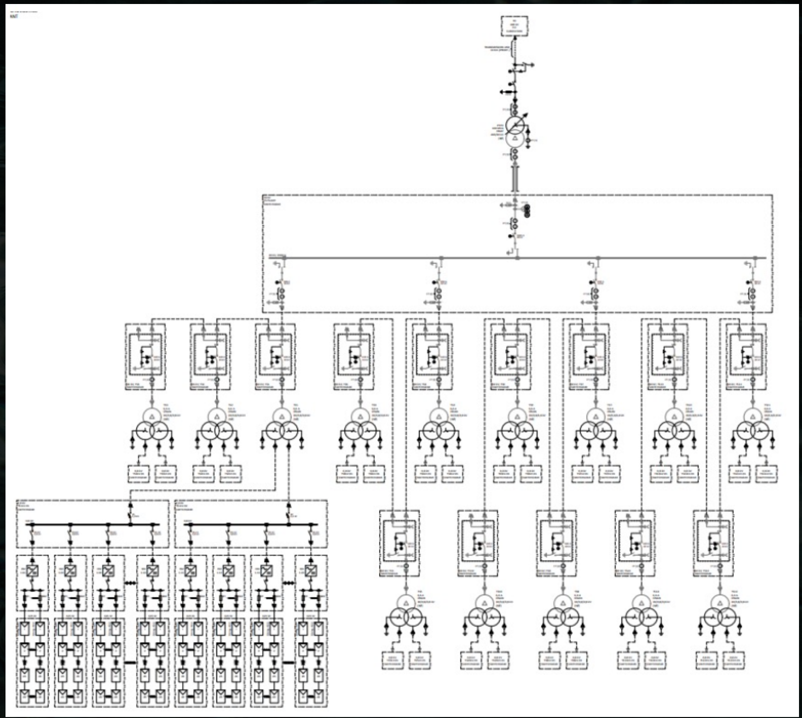
Task 10 Green Black Start (on going)

- Steady state, for different scenarios of operation (valley hours, solar PV peak generation hours and load peak conditions) with and without plant consumption from the grid.
- Dynamic analysis, frequency behaviour assessment to be evaluated using a three-area control system model (Central Europe, Spain and Portugal with corresponding interconnections) for disturbances like sudden loss of a large generation plant, evaluating the response of the battery system in grid tied mode and of the wind and solar PV converters.
- Electrolyser capability to provide FCR response

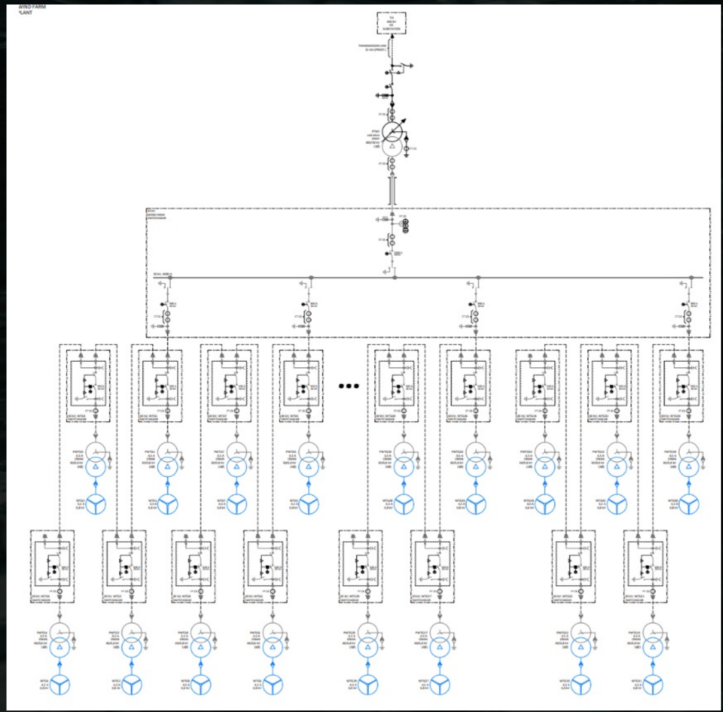
Smartenergy research project

Study of an energy hub that must be capable of feeding a 100MW electrolyser to produce hydrogen and provide grid services

PV Plant
Single line diagram



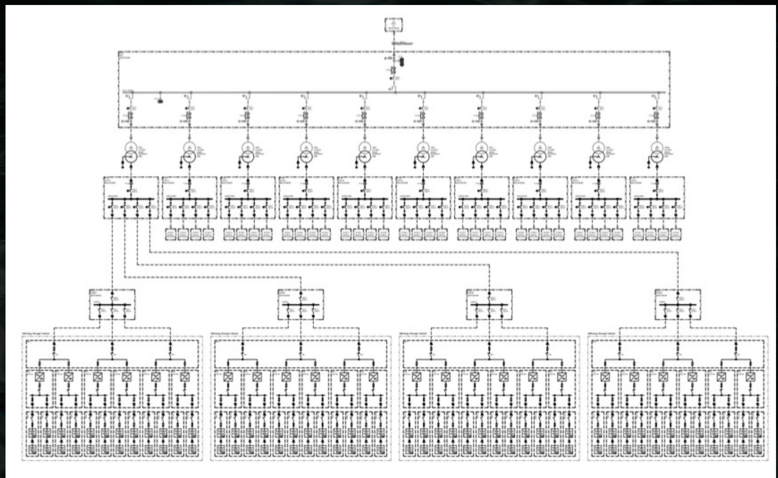
Wind Farm
Single line diagram



Smartenergy research project

Study of an energy hub that must be capable of feeding a 100MW electrolyser to produce hydrogen and provide grid services

BESS system
Single line diagram



Cable data
energy hub system

Diagram	Type	Configuration	From	To	Average distance (m)
Sin[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Sin[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Sin[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Sin[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Sin[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Sin[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Sin[illegible] energy hub	[illegible] overhead line	[illegible]	[illegible]	[illegible]	[illegible]

Transformers
parameters

Transformer	U_n (kV)	S (MVA)	X (%)
Step-up transformer BESS	[illegible]	[illegible]	[illegible]
Step-up transformer Wind Farm	[illegible]	[illegible]	[illegible]
Step-up transformer PV Plant	[illegible]	[illegible]	[illegible]
Wind Farm Substation	[illegible]	[illegible]	[illegible]
PV substation	[illegible]	[illegible]	[illegible]
H2 substation	[illegible]	[illegible]	[illegible]

Smartenergy research project

Preliminary remarks of the study:

1. The modelling covers the entire energy ecosystem, from hydrogen production (electrolyser, BoP/BoS) to battery storage and energy market participation.

2. Opportunities in the secondary reserve market are explored, maximizing profitability by strategically placing bids, enhancing financial returns.

3. Operational results highlight electricity consumption per system component important to gain knowledge on how the optimization algorithm solves the mathematical problem.

4. Relevant case comparisons based on a mix of wind and solar provide important insights for optimizing generation and storage assets on a hybrid approach.

04

Conclusions, Challenges and Future Research Directions

Conclusions

The integration of electrolyser-based systems, both standalone and in hybrid configurations with Renewables and Battery Energy Storage Systems, into power grids represents a significant opportunity to enhance system flexibility and support the increasing penetration of variable renewable energy sources.

Technical Feasibility

Electrolysers, particularly PEM and advanced Alkaline technologies, possess the dynamic characteristics (fast response times, ramp rates, and wide operational ranges) necessary to provide a suite of ancillary services, including various forms of frequency control and potentially voltage support. Pilot projects like Energiepark Mainz, H2Future, and REFHYNE I have successfully demonstrated these capabilities at multi-megawatt scales.

Hybrid System Synergies

The combination of electrolysers with BESS offers compelling synergistic benefits. BESS can provide instantaneous response for the fastest ancillary services (e.g., FFR) and buffer the electrolyser from harsh grid dynamics, potentially reducing degradation. The electrolyser, in turn, can offer longer-duration load flexibility and the co-benefit of green hydrogen production. Coordinated control strategies are crucial to maximizing these synergies.

Operational Challenges

Long-term degradation of electrolysers under dynamic cycling remains a critical technical and economic challenge. Understanding and mitigating these degradation mechanisms is paramount for ensuring the cost-effectiveness and reliability of electrolysers in grid-supporting roles. Non-technical challenges related to project management, stakeholder alignment, and permitting for large-scale, first-of-a-kind projects are also significant.

Economic Viability

Revenue from ancillary service participation can significantly improve the economic viability of green hydrogen projects by lowering the Levelized Cost of Hydrogen (LCOH) and enhancing overall project profitability (NPV/IRR). However, this is highly dependent on electricity costs, electrolyser CAPEX, stack lifetime under dynamic operation, and the specific ancillary service market prices and rules. Revenue stacking is a key strategy, but the bankability of projects can be challenged by the volatility and uncertainty of ancillary service revenues.

Market and Regulatory Evolution

Ancillary service markets in Europe, North America, and parts of Asia are gradually evolving to accommodate new flexibility providers like electrolysers and BESS. Initiatives such as the EU's Clean Energy Package and FERC Order 2222 are creating pathways for participation. However, significant barriers remain, including complex market rules, inconsistent regulations, inadequate product definitions for new technologies, and insufficient long-term price signals for flexibility.

Several regulatory and market barriers hinder the widespread participation of electrolysers and BESS in ancillary service markets

Grid Codes and Connection Requirements
Outdated or overly stringent grid codes can impose significant technical and financial burdens for connecting new technologies like electrolysers or BESS, particularly concerning fault ride-through, telemetry, and control system requirements.

Market Entry Barriers
Minimum bid sizes can exclude smaller installations unless effective aggregation frameworks are in place. Complex market rules, bidding procedures, and pre-qualification processes can also be daunting and costly for new or smaller participants.

Product Definitions and Suitability
Ancillary service products are often designed around the capabilities of conventional generators. These definitions may not always align well with the unique characteristics of electrolysers (e.g., primary role as a load, degradation concerns with certain cycling patterns), renewables or BESS (e.g., energy limitations versus power capabilities).

Revenue Uncertainty and Risk
Ancillary service market prices can be volatile and are subject to changes in market design, regulatory policies, and the evolving generation mix. This lack of long-term price signals and revenue certainty creates investment risks, making it harder to secure financing for projects that rely significantly on these revenues.

Permitting and Siting
As with any large energy infrastructure, obtaining permits for electrolyser facilities can be a lengthy and complex process, potentially delaying project deployment.

National Implementation (EU)
Despite EU-level directives (like the Clean Energy Package) aiming for harmonization, significant variations persist in how Member States implement these rules for flexibility services. This creates an uneven playing field, complicates cross-border service provision, and can act as a barrier to entry.

Future research on electrolyser hybrid projects is crucial to unlocking their full potential in providing grid services, such as demand response, frequency regulation, and energy storage.

Advanced Materials and Component Design:
optimized for dynamic operation and extended lifetimes.

Degradation Modelling and Lifetime Prediction:
Development of accurate models that can predict electrolyser degradation and lifetime under various dynamic operating profiles relevant to grid service provision.

Advanced Control and Optimization Strategies:
Research into sophisticated control algorithms (including AI and machine learning approaches) for standalone electrolysers and hybrid electrolyser-BESS systems, aiming to co-optimize hydrogen production, participation in multiple ancillary service markets, energy arbitrage, and minimization of degradation, all while responding to real-time grid conditions and market signals.

Hybrid System Integration and Design:
Further research on optimal sizing, configuration, and integration of electrolyser-BESS systems.

Techno-Economic Modelling and Business Case Development:
Development of innovative business models tailored to specific market and regulatory contexts.

Market Design and Regulatory Innovation:
Studies on regulatory reforms to remove barriers to participation, ensure fair compensation for flexibility, and create stable investment frameworks.

Large-Scale Demonstration and Validation:
Continued support for multi-MW to GW-scale demonstration projects is crucial to validate technologies and operational strategies in real-world environments, gather long-term performance data, and build investor confidence.

Sector Coupling Synergies:
Investigating how the flexible operation of electrolysers for grid services can be optimally coordinated with hydrogen demand from various end-use sectors and with the development of hydrogen infrastructure.

Thank you!

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