Sizing, Frequency, and Voltage Control of a Massive Off-Grid Power-to-Gas Production Facility

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Ensuring Frequency and Voltage Control in Off-Grid Power-to-Gas Projects

The next frontier for renewables is not just feeding national grids, but powering large-scale, off-grid production of green hydrogen and ammonia. These multi-GW facilities can decarbonize hard-to-abate sectors and generate export revenues, but they also push electrical engineering to new limits. Without synchronous generation and conventional balancing resources, the stability of islanded systems dominated by wind turbines and electrolyzers becomes a mission-critical design challenge.
This is precisely where EGI's expertise makes the difference. Our tools and methodologies for frequency, voltage, and stability management translate the promise of off-grid power-to-gas (P2G) into bankable, operable projects. We provide end-to-end insights into electrical architecture, balancing requirements, and stability strategies that ensure both technical robustness and economic viability.

Why Off-Grid Power-to-Gas Requires a New Electrical Playbook

- **Frequency Control**

Variable wind and low inertia mean frequency must be managed without the safety net of conventional generators. Balancing requires innovative strategies that combine back-up power, load flexibility, and advanced controls.

- **Voltage Stability**

In islanded systems, reactive power cannot come from synchronous machines. Voltage must be stabilized through power electronics, dynamic devices, and carefully placed synchronous condensers.

- **System Strength**

Weak grids are prone to cascading failures. Designing strength into the system—from topology to equipment placement—is essential to withstand disturbances.

Electrical Architectural Insights: Centralized vs. Decentralized

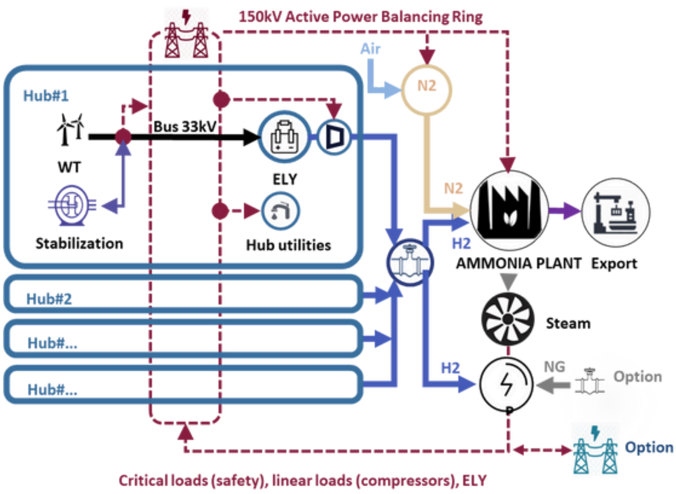
Multiple electrical architectures for the power-to-gas production facility were evaluated, and multiple criteria were carefully selected to rank these architectures in order to find the good trade-off between cost, flexibility and robustness.

While some architectures were found with high complexity and vulnerability to single-point failures, other architectures offer better resilience, modularity, and reduce the electric power transmission stress.

EGI assessed multiple configurations, weighing trade-offs between cost, resilience, and complexity.

- **Centralized electrolysers** smooth the wind profile by aggregating output over wide areas, but concentrate power flows into large transmission corridors with single-point-failure risks.
- **Decentralized electrolysers** reduce transmission stress, enhance resilience, and better localize balancing. Our analysis showed decentralization delivers superior system stability for multi-GW off-grid facilities.

Hybrid AC/DC architectures were also evaluated. While they offer scalability and long-distance efficiency (favoring DC), they add control complexity at shorter electrical distances. The optimal solution depends on project scale and geography.



Quantifying Balancing Needs

The backbone of stability is ensuring supply-demand balance at every timescale. EGI developed dedicated tools to:

- Quantify wind variability and identify largest transients by location.
- Size back-up power (MW, MWh) across intra-hour, intra-day, and inter-day horizons.
- Integrate electrolyzer flexibility into balancing, reducing storage and back-up capacity requirements.

The result is a clear investment framework: undersizing back-up power risks instability; oversizing inflates CAPEX. EGI's optimization ensures the right mix of fast-ramping (batteries, gas turbines) and slower-ramping (steam turbines, long-duration storage) assets.

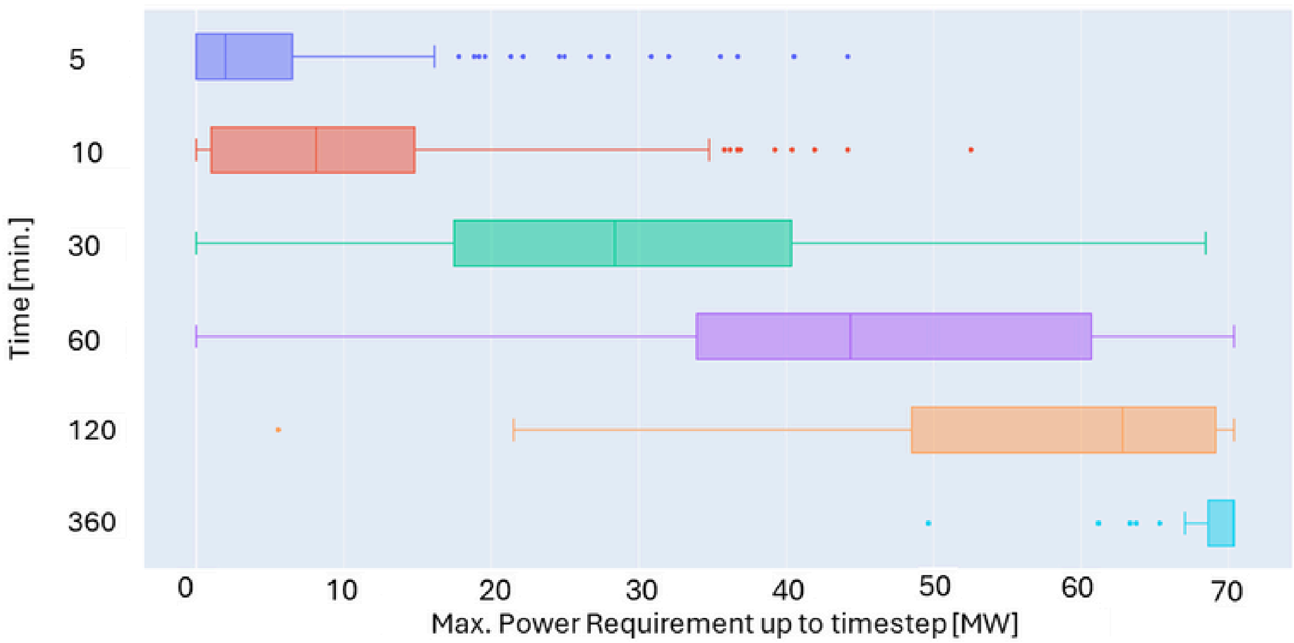


Figure 1 Back-up power requirements for different timescales. This serves as an input to the optimal sizing of fast-ramping (e.g., 5-30 minutes) and slower-ramping back-up power generating units.

Stability Solutions That Work

EGI's approach to stability in converter-dominated, off-grid systems rests on three pillars:

- **Synchronous Condensers**: mature, proven devices that inject inertia and voltage support, optimally sized and placed through our methodology.
- **Hub Coordinators**: local controllers that adjust electrolyzer loads to maintain frequency within tolerance bands.
- **Power Management Unit (PMU)**: – a system-wide coordinator that orchestrates balancing across hubs, ensuring resilience against faults, load variations, and interconnection losses.
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Dynamic simulations validate that these solutions deliver stable operation under realistic disturbances, making them applicable not only to islanded projects but also to hybrid grid-connected contexts.

Broader Applications

Although this study focused on a wind-dominated, multi-GW P2G facility, the principles scale across contexts:

- Industrial grids of various sizes.
- Solar-dominated systems.
- Configurations with or without grid connections.
- Hybrid renewable portfolios with flexible industrial loads.

EGI's methodologies ensure that wherever renewables dominate, stability and reliability can be engineered from the start

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ABOUT ELIA GRID INTERNATIONAL

The earlier we join your project, the greater the impact. From concept to boardroom and policy discussions, our multidisciplinary experts help you navigate complex power system challenges, anticipate risks, and turn uncertainties into confident decisions.

With successful projects in 20+ countries and 7 offices worldwide, EGI combines hands-on experience with innovative thinking. As part of Elia Group, a European leader in transmission and renewable energy integration, we bring proven expertise to de-risk your project from the start.

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