GFM Battery Application for Weak Grid Conditions in the Chilean Power System

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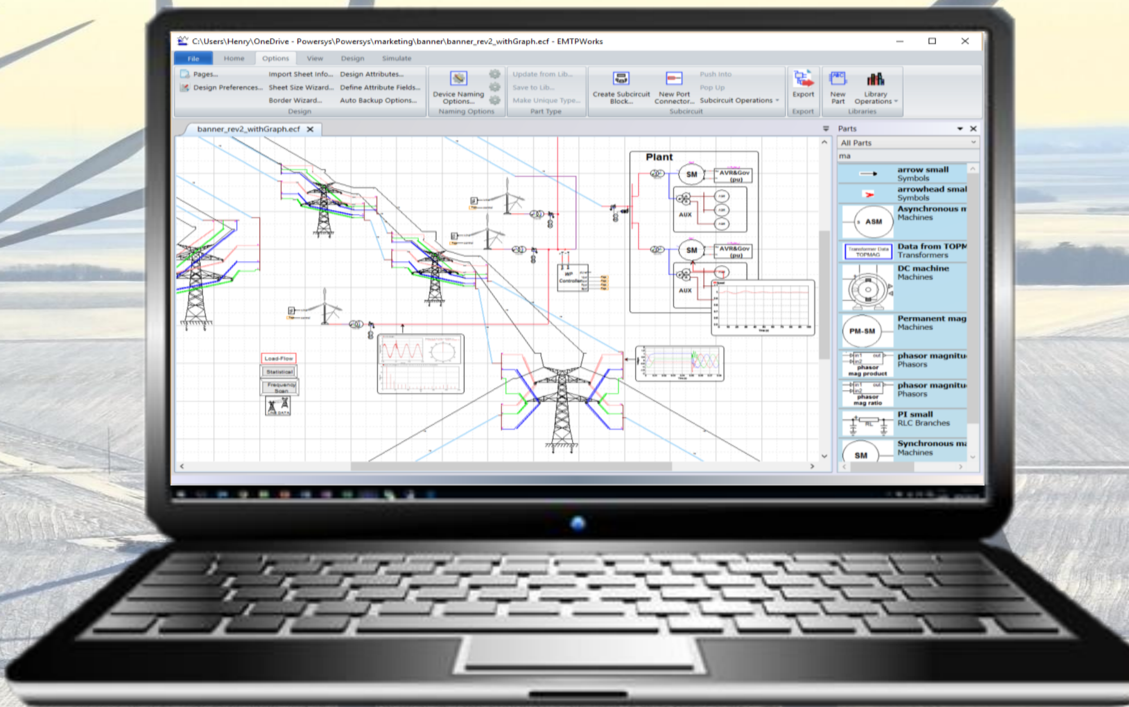

More info

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COORDINADOR ELECTRICO NACIONAL (CEN)

➢ Independent technical organization

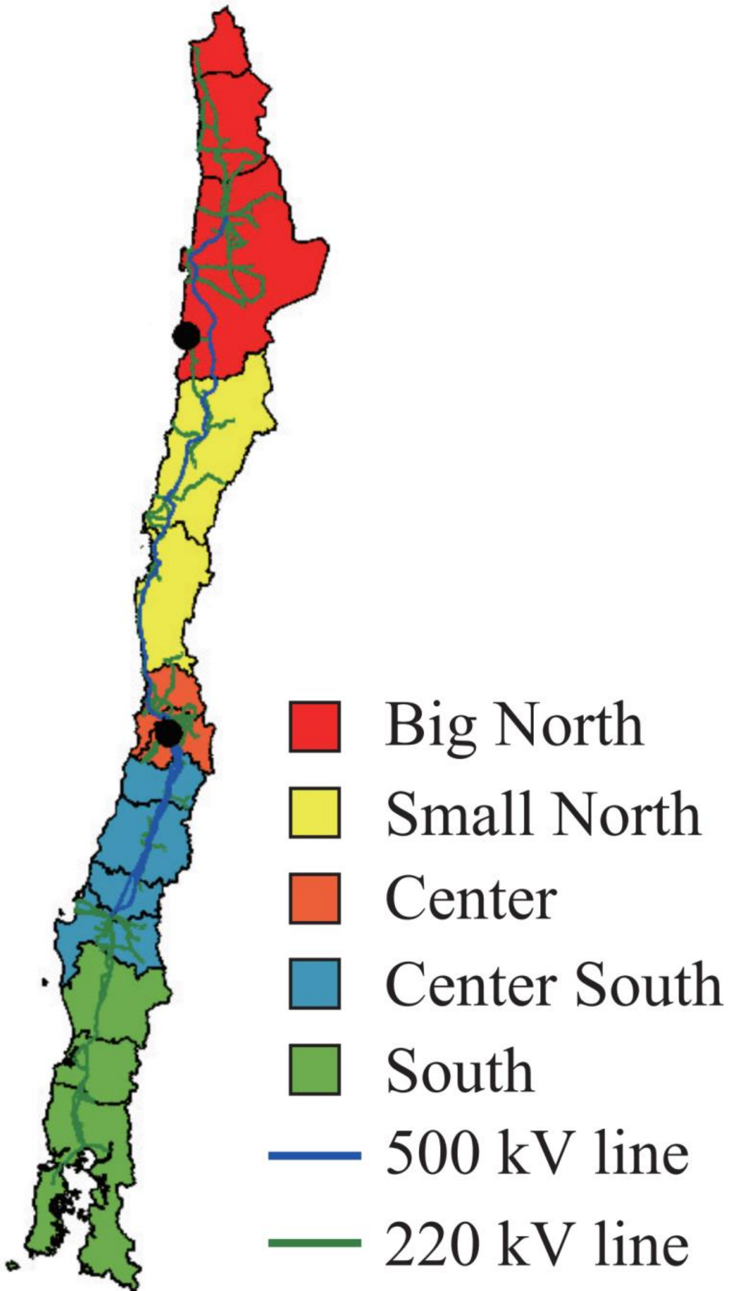
- Responsible for reliable, secure, and economic operation of the Chilean's grid

➢ Main functions

- Guarantee a secure and economic operation of the power grid
- Ensure open access to transmission system
- Administer wholesale energy, capacity and AASS markets
- Propose a plan for expansions of the transmission system
- Conduct international tenders for new transmission projects
- Manage interconnection process of new assets
- Monitor market competition conditions
- Promote innovation, research and development

CHILEAN NATIONAL POWER GRID

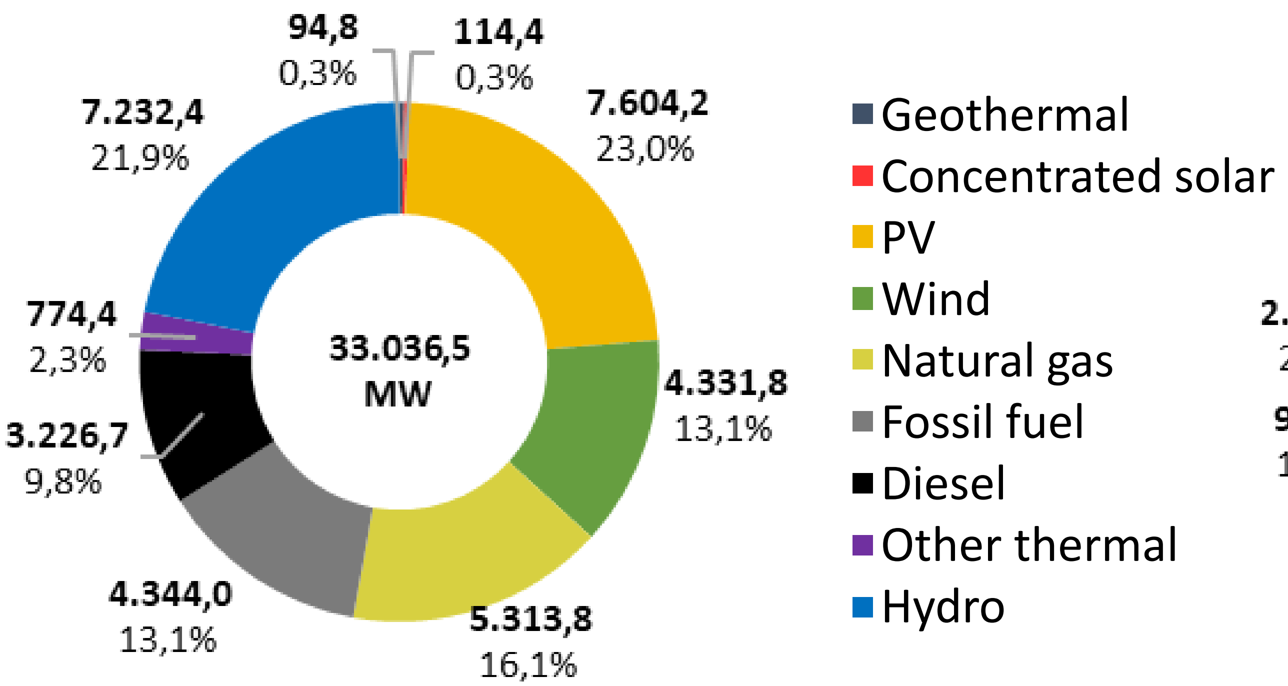
- Mostly radial 3000 km long network
  - One main 500 kV corridor
  - Islands in the southern part
  - **ESCR < 1.5 at several buses**
  - Transmission congestion
- PV generation in the North
- Wind generation in the South
- Consumption in North and Center/South
- VRE curtailment



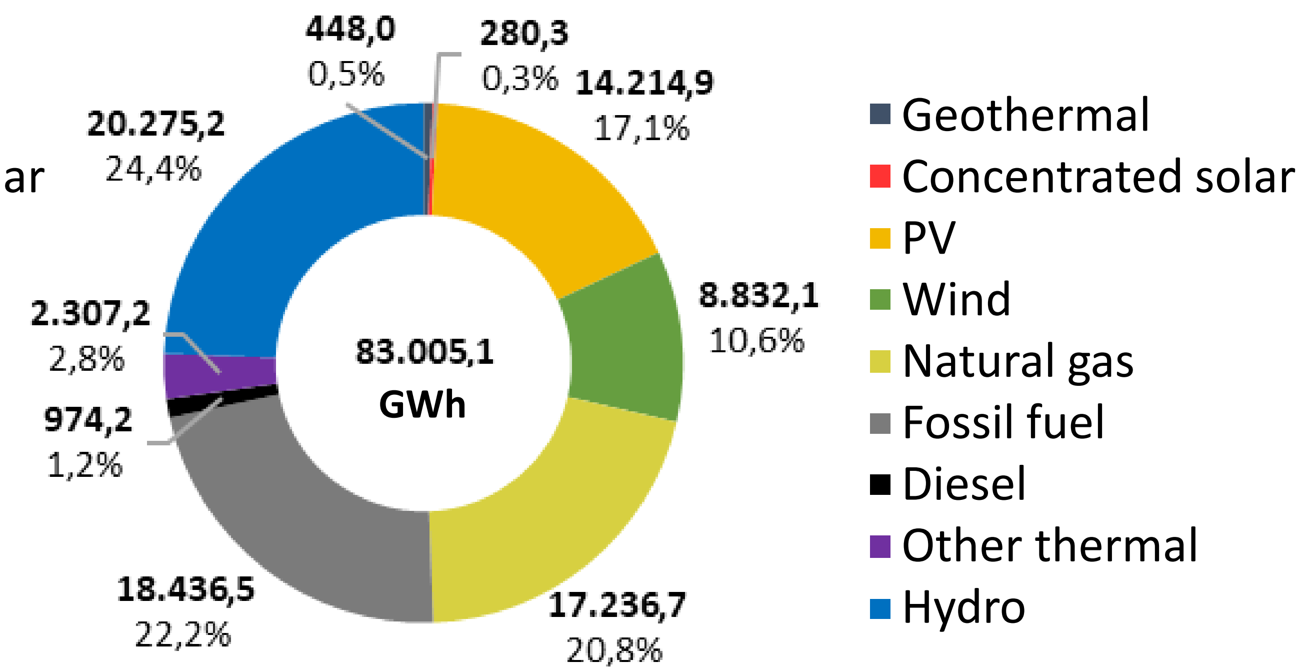
M. Agüero et al., "Virtual Transmission Solution Based on Battery Energy Storage Systems to Boost Transmission Capacity," in Journal of Modern Power Systems and Clean Energy, vol. 12, no. 2, pp. 466-474, March 2024

CHILEAN ELECTRICITY SYSTEM

- Installed capacity



- Energy Generation



ELECTRICITY SYSTEM STATISTICS

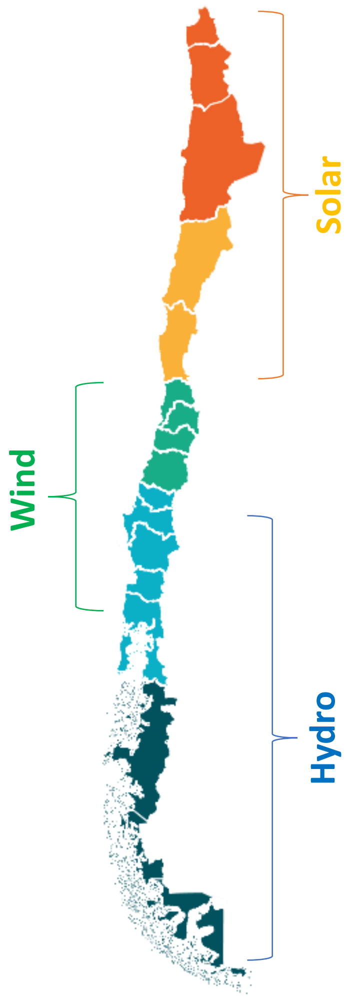
➢Statistics for 2022

- Installed Capacity : 33 036 MW
- Energy Generated: 83 005 GWh
- Peak Demand: 11 906 MW
- Transmission Lines: 38 160 km
- VRE Share / Peak: 28% / 68%
- Storage (BESS/CSP): 191 MW / 1 785 MWh

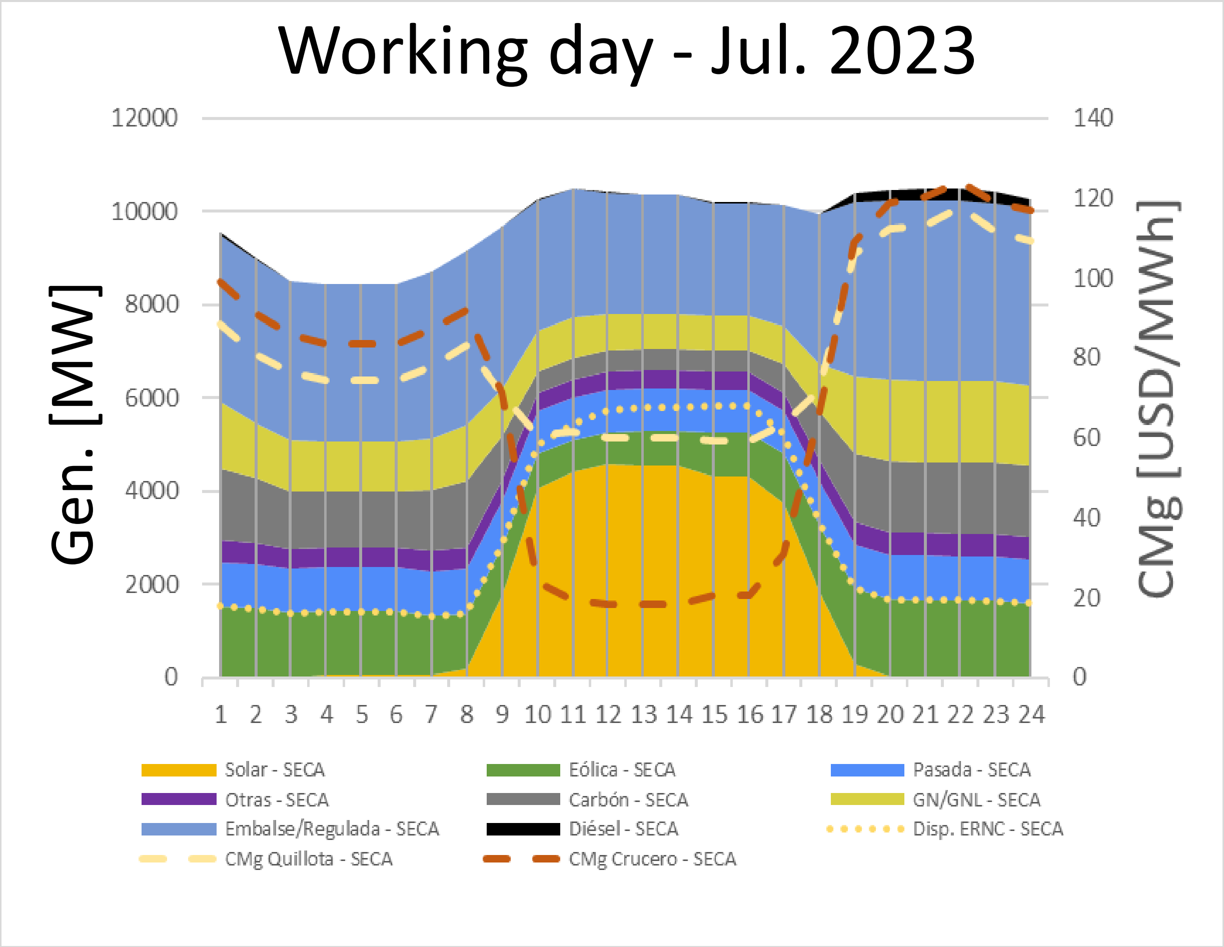
➢As of July 2023

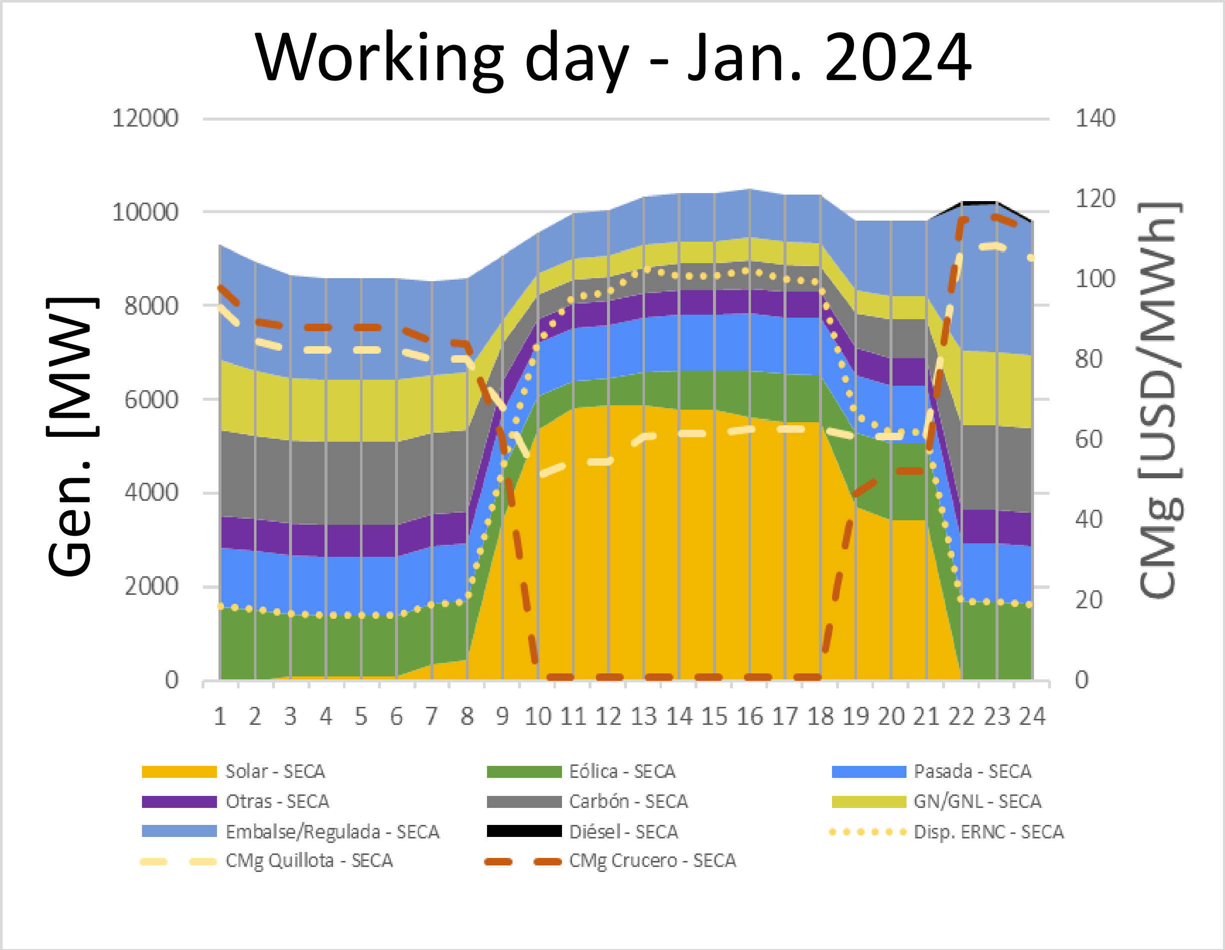
- VRE Capacity: 12 734 MW (4 060 MW U/C)
- VRE Share / Peak: 31% / 71%
- Storage (BESS/CSP): 303 MW / 2 346 MWh
- BESS U/C (2024): 621 MW / 2 391 MWh

➢Renewable Potential

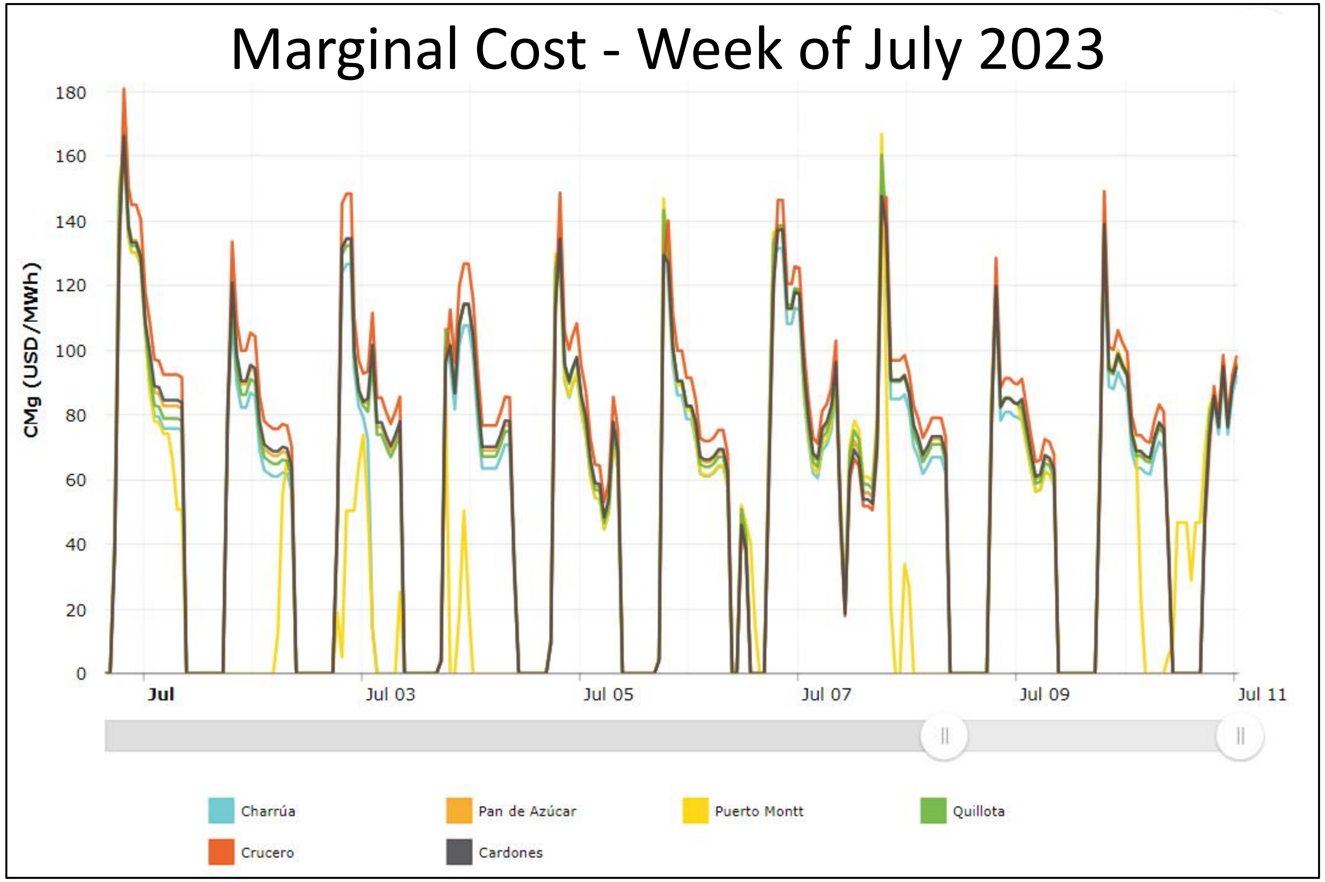


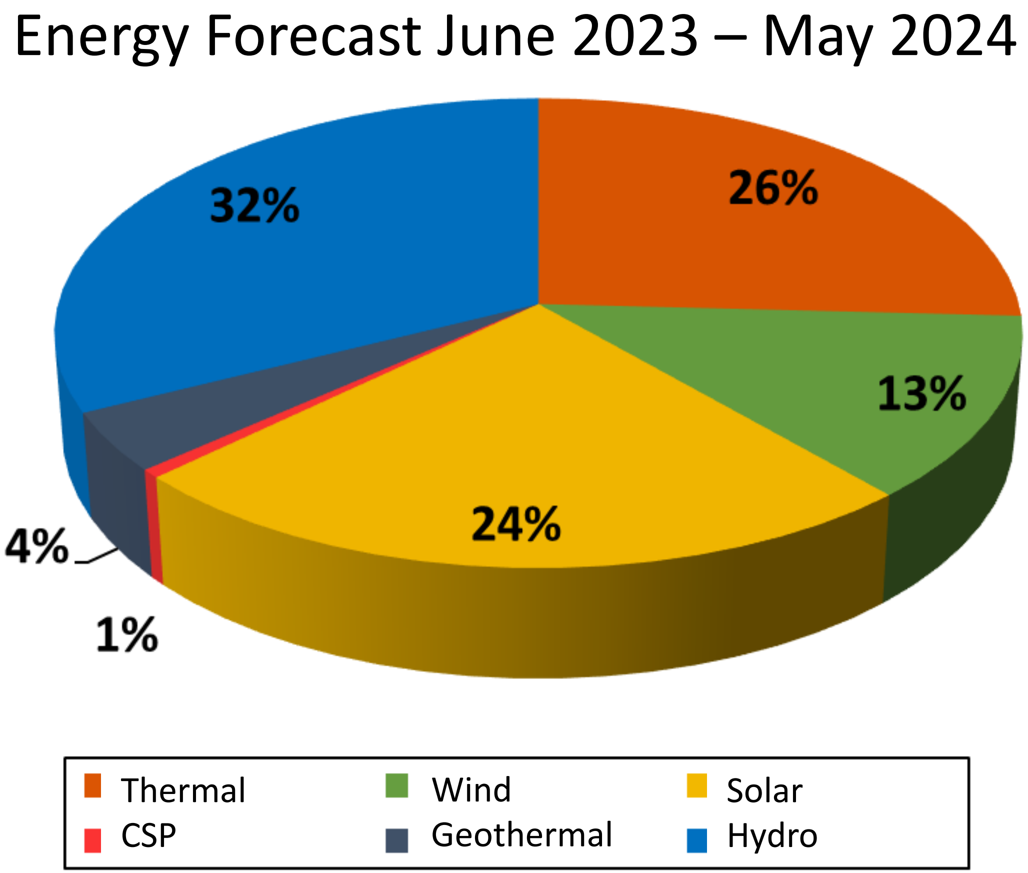
DAILY GENERATION PROFILE



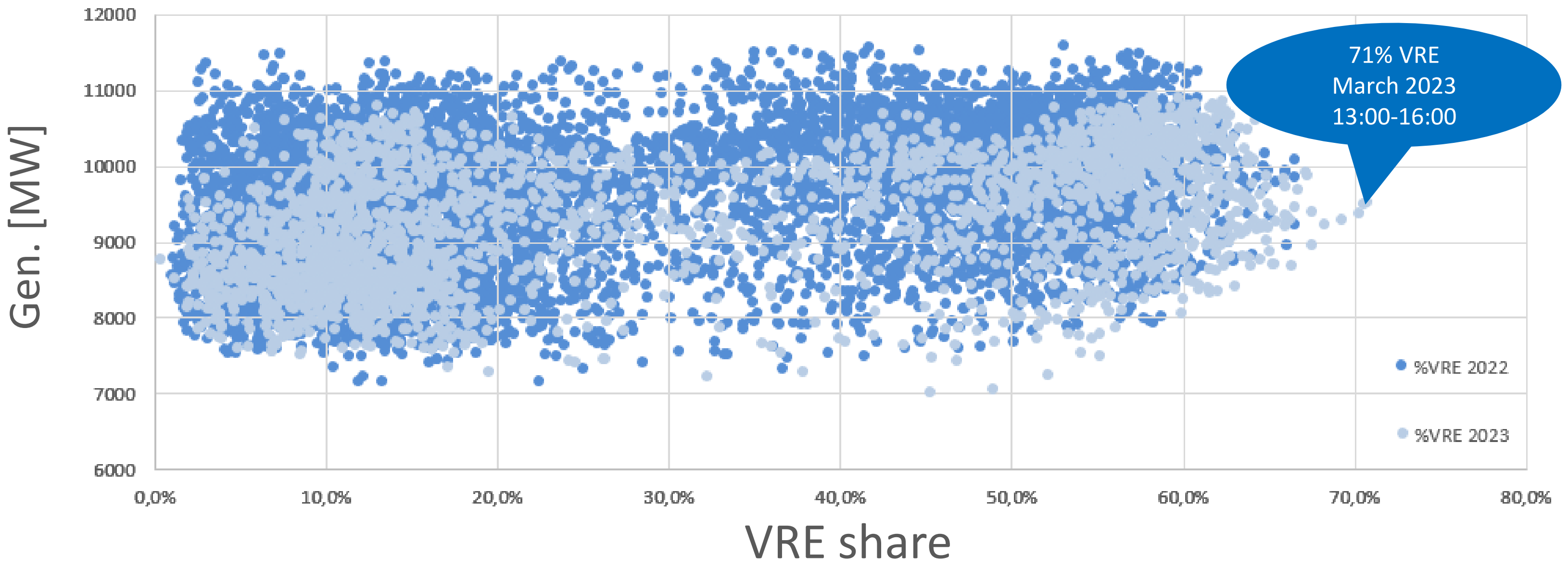


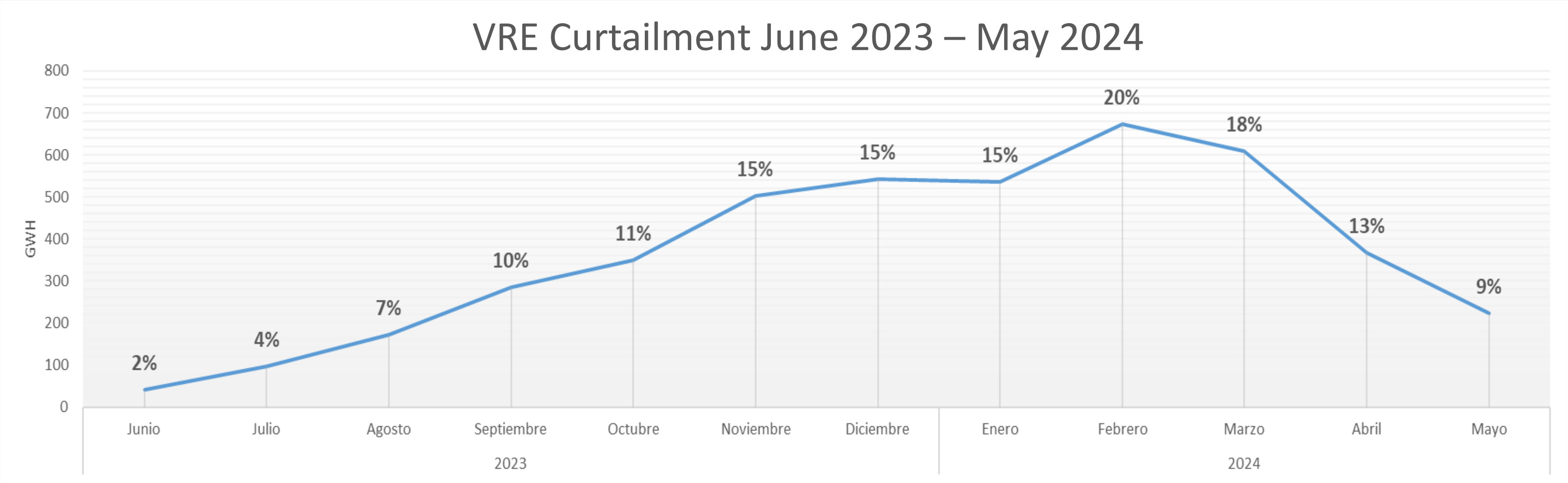
ENERGY MARKET





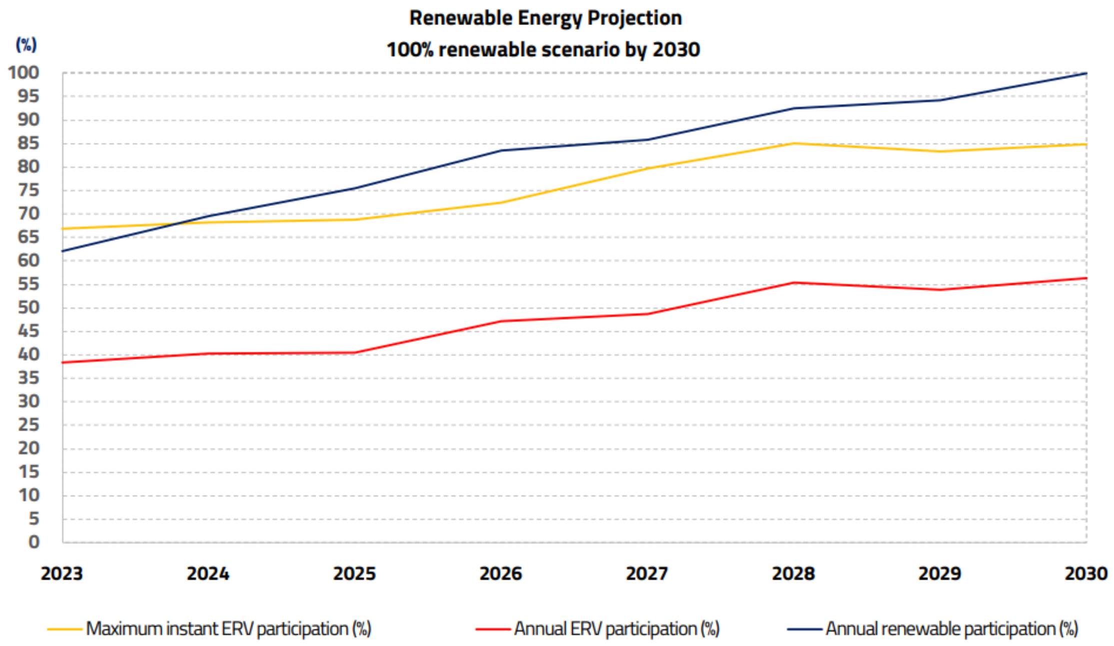
VRE GENERATION





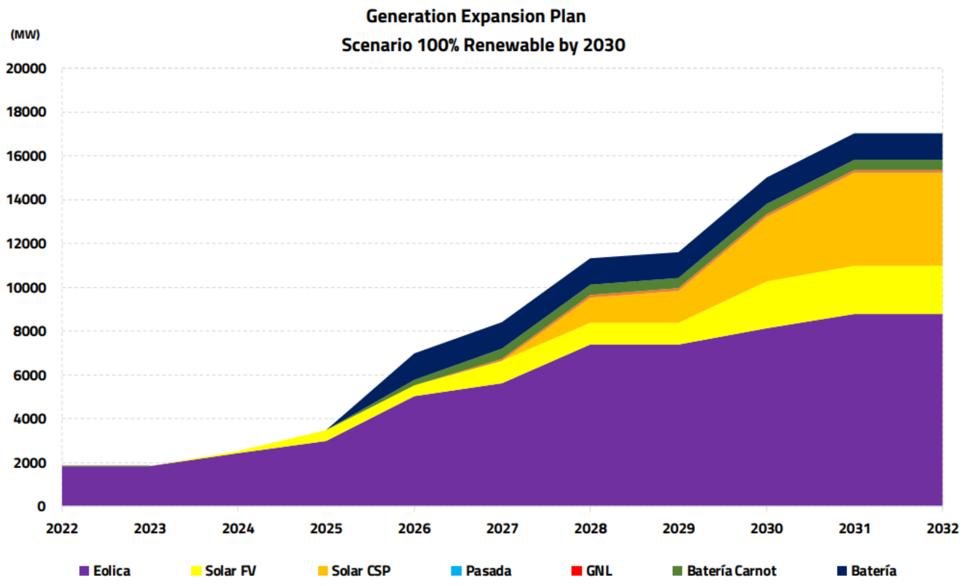
➢Long-term Renewable Goals

- 100% renewable scenario by 2030…
- Decarbonization Plan by 2040
  - Or earlier
- Carbon Neutrality by 2050



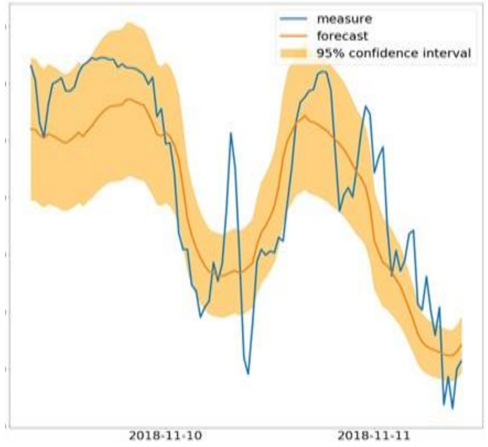
➢Short-term: synch. condensers

- To be installed in the North (2026)
- Increase short-circuit capacity, inertia, dynamic voltage support
  - Good for IBRs
- Minimize thermal SG
  - Required today for reliability and stability



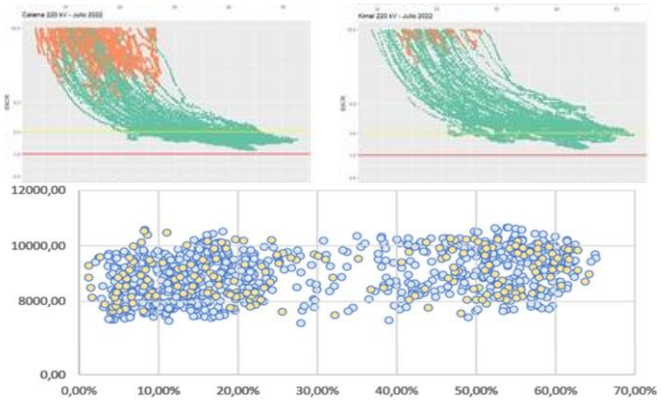
OPERATIONAL CHALLENGES

Variability & Uncertainty



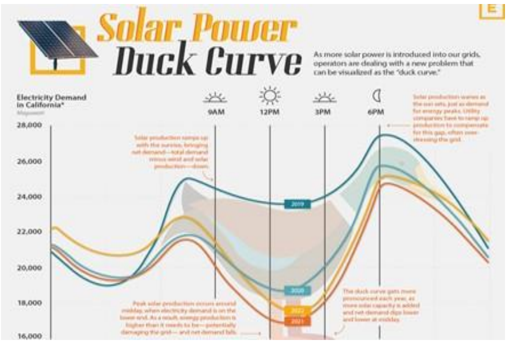
- ✓ VRE and load forecast complexity
- ✓ Intra-day optimization with VRE+BESS

Weak grid



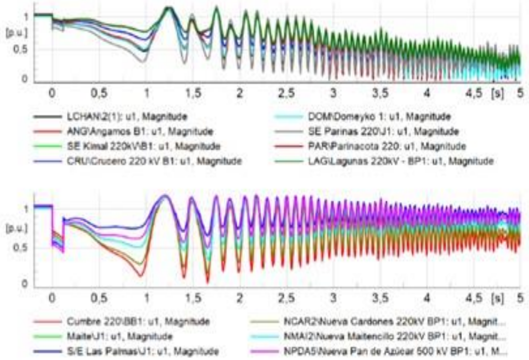
- ✓ Low ESCR (<1.5)
- ✓ High share of GFL IBRs
- ✓ Outdated grid code

Ramp management (24/7)



- ✓ Short-term constraints: ramps, cycling, MRU, BESS+DER management

Modeling issues



- ✓ Inaccuracies and numerical instability issues
- ✓ Old and unrealistic models for (IBR) VRE

NEW ENABLING TECHNOLOGIES

HVDC Kimal – Lo Aguirre

- ✓ SCR > 2.5
- ✓ Training, and creation of new knowledge

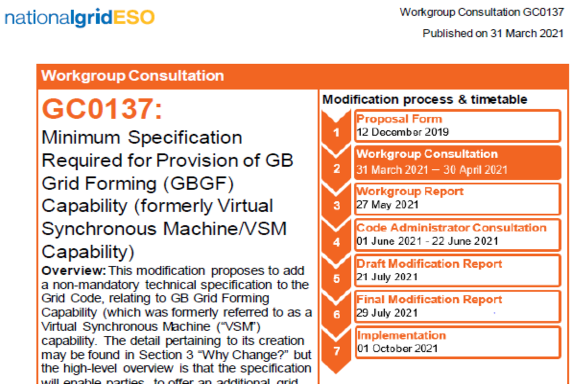
GET – DLR, PFC

- ✓ Data management and modeling
- ✓ Real-time operation

BESS (SD & LD)

- ✓ Grid Booster: stability margin
- ✓ Control complexity
- ✓ LDES: optimal dispatch

Grid-Forming Inverters



nationalgridESO

Workgroup Consultation GC0137
Published on 31 March 2021

Workgroup Consultation

GC0137:
Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability (formerly Virtual Synchronous Machine/VSM Capability)

Overview: This modification proposes to add a non-mandatory technical specification to the Grid Code, relating to GB Grid Forming Capability (which was formerly referred to as a Virtual Synchronous Machine ("VSM") capability. The detail pertaining to its creation may be found in Section 3 "Why Change?" but the high-level overview is that the specification

Modification process & timetable

1. Proposal Form – 12 December 2019
2. Workgroup Consultation – 31 March 2021 – 30 April 2021
3. Workgroup Report – 27 May 2021
4. Code Administrator Consultation – 01 June 2021 - 22 June 2021
5. Draft Modification Report – 21 July 2021
6. Final Modification Report – 29 July 2021
7. Implementation – 01 October 2021

- ✓ Lack of standards and models
- ✓ Not proven at large scale

DYNAMIC STUDY

Dynamic Behavior of Grid-forming Inverters in Large-scale Low-strength Power Grids

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***Abstract*—The massive integration of variable renewable energy (VRE) generation based on grid-following inverters (GFL), along with the decommissioning of synchronous generators (SG), are**

necessary to prepare the grid to integrate new technologies, execute investments in VRE and energy storage projects, and review the technical requirement in the current grid code [3] to

J. Peralta, V. Velar, E. Quintana, J. Mahseredjian, H. Gras, H. Ashourian "Dynamic Behavior of Grid-forming Inverters in Large-scale Low-strength Power Grids", 2024 IEEE T&D Conference

EMTP MODELING

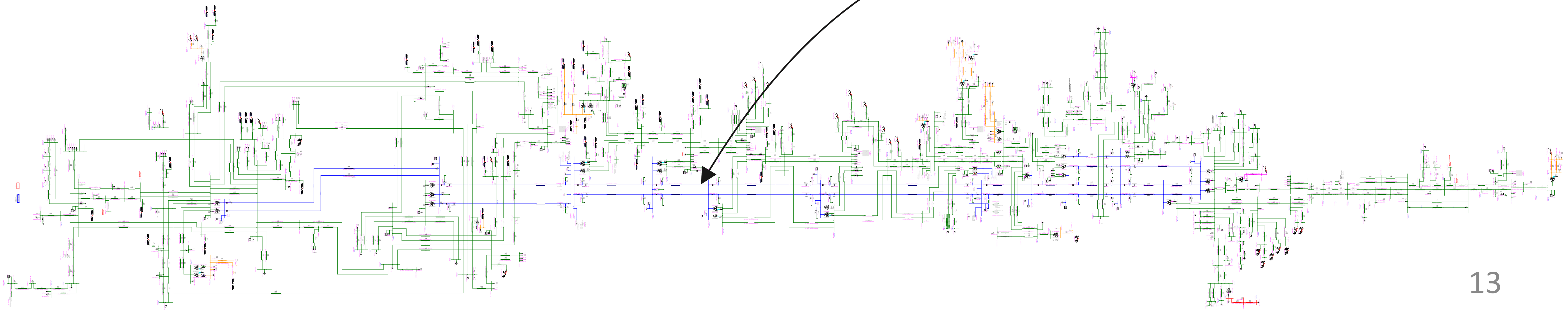
➢Grid Model

- 500 kV, 220 kV, 110 kV transmission lines
- ~8k electrical nodes
- ~80k control blocks

➢Homologated and generic models of assets

- 62 Synchronous machines with exciters and governors
- 59 Photovoltaic parks
- 32 Wind parks

Backbone: 500 kV transmission line Kimal - Charrua



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WIDE-AREA GFM IBRs ANALYSIS: Description

➢Objective:

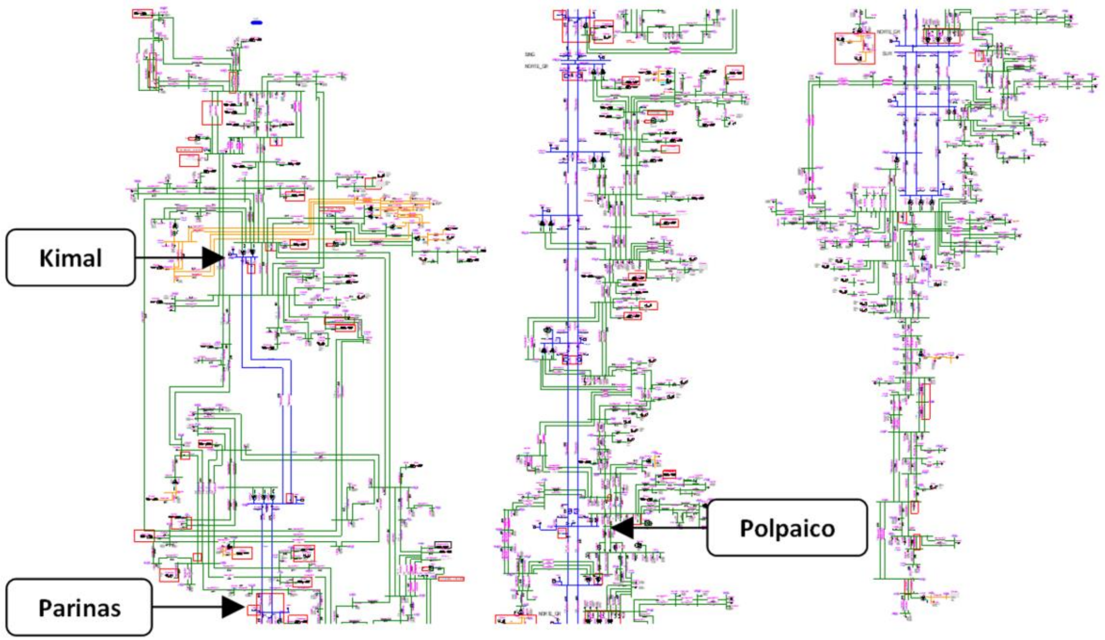
- Model GFM IBRs in the Chilean grid in EMTP
- Assess their dynamic behavior
- Scenario with 70% of VRE (wind + solar)

➢GFM IBR units:

- 4 locations with low ESCR (<1.5)
- Capacity: 4x150 (4x200) MVA
- Operated at 100 MW
- Type: BESS

➢Simulated contingencies:

- Worst N-1 fault condition
- Islanding a weak grid
- Loss of last SG



(a) Northern (b) Central (c) Southern

Total NPG	Value	Unit
Peak Generation	10,509	MW
VRE Generation	7,354	MW
Sync. Generation	3,155	MW
VRE Share	70.0	%
Northern Region		
Peak Generation	3,734	MW
VRE Generation	98.7	%
Central Southern Regions		
Peak Generation	6,775	MW
VRE Generation	54.2	%

WIDE-AREA GFM IBRs ANALYSIS: GFM control

➢Generic Primary Control Model:

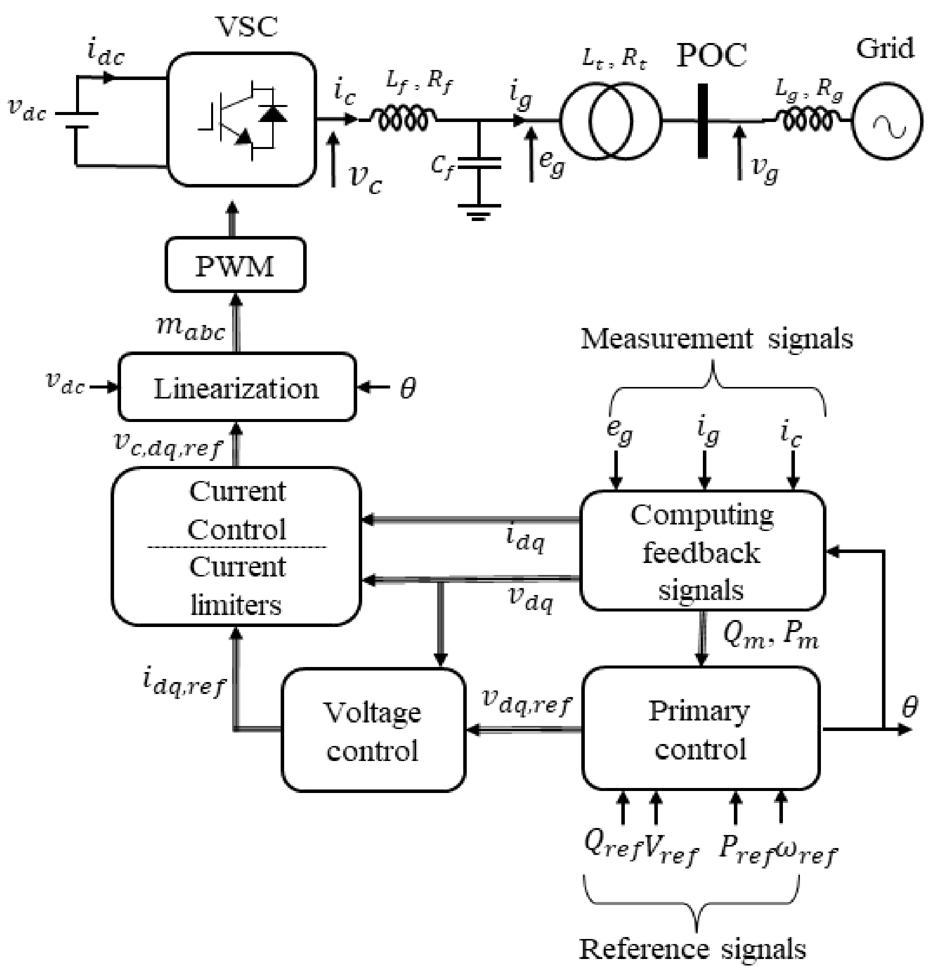
$$\tau_f \frac{d\omega}{dt} = -\omega + \omega_0 + k_d(\omega_g - \omega) + k_f(p_{ref} - p_m) \qquad (1)$$

$$\tau_v \frac{dV}{dt} = f_v(\mathrm{V}) + k_v(q_{ref} - q_m) \qquad (2)$$

$$\tau_p \begin{bmatrix} \frac{dp_m}{dt} \\ \frac{dq_m}{dt} \end{bmatrix} = -\begin{bmatrix} p_m \\ q_m \end{bmatrix} + \begin{bmatrix} p \\ q \end{bmatrix} \qquad (3)$$

➢GFM control methods tested:

- Droop
- VSM
- Dispatchable VOC (dVOC)
- Different GPCM coefficients for each method:
  - τ_f, k_d, k_f, τ_v, k_v, τ_p, f_v



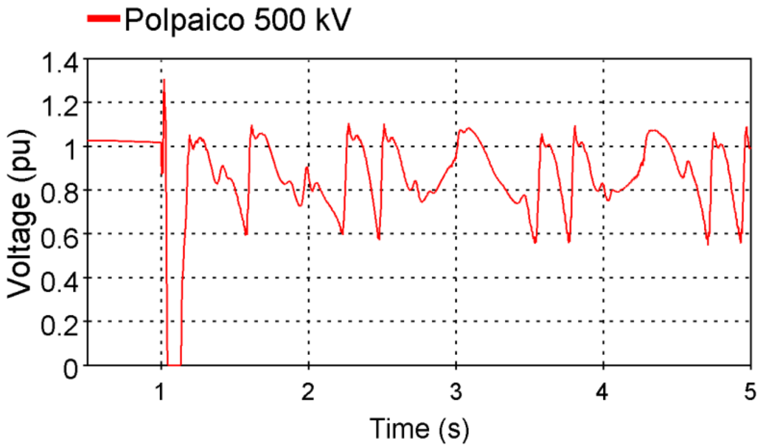
D. Ramasubramanian, et al., "**A Universal Grid-forming Inverter Model and Simulation-based Characterization Across Timescales**," *56th Hawaii International Conference on System Sciences (HICSS)*, Maui, HI, USA, 2023.

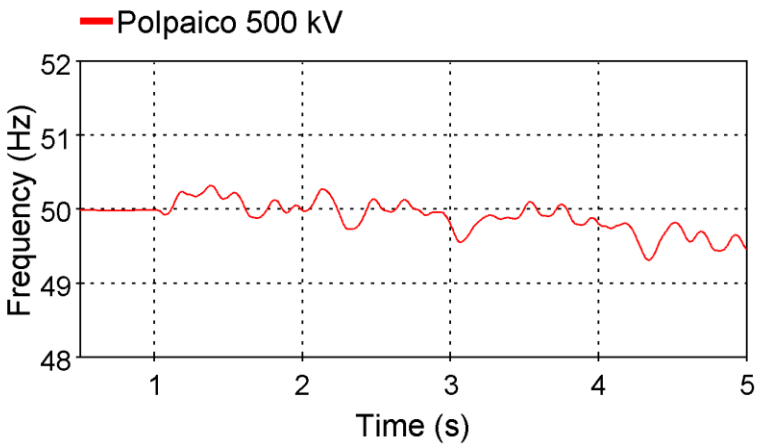
WIDE-AREA GFM IBRs ANALYSIS: results (1)

➢ Fault near Polpaico substation

- Base case (no synchronous condensers, no GFM IBRs)
- System is unstable
  - Low inertia, low ESCR in the northern region
  - Only GFL IBRs, reliance on a PLL type of control
  - Lack of energy headroom, little capability to provide grid services
- Frequency does not recover

- *Worst N-1 fault condition*
- *LLG fault at 500kV line*
- *Line trips after 120 ms*
- *Low contribution from SG (only 50 MW)*
- *High levels of GFL VRE (70%)*
- *Weak-grid operating scenario*

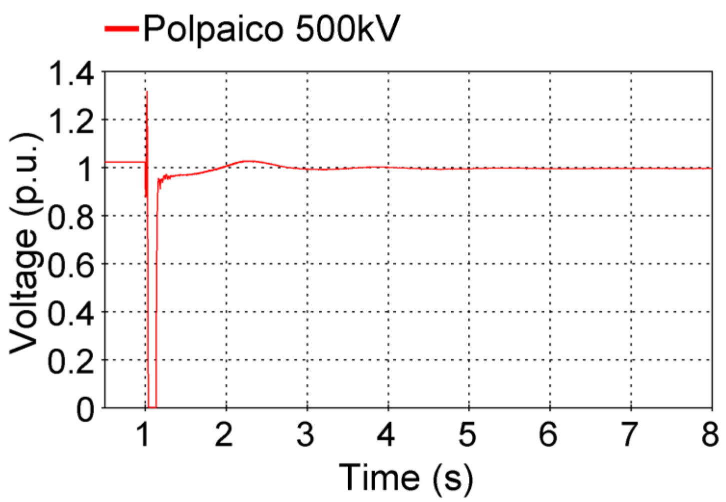


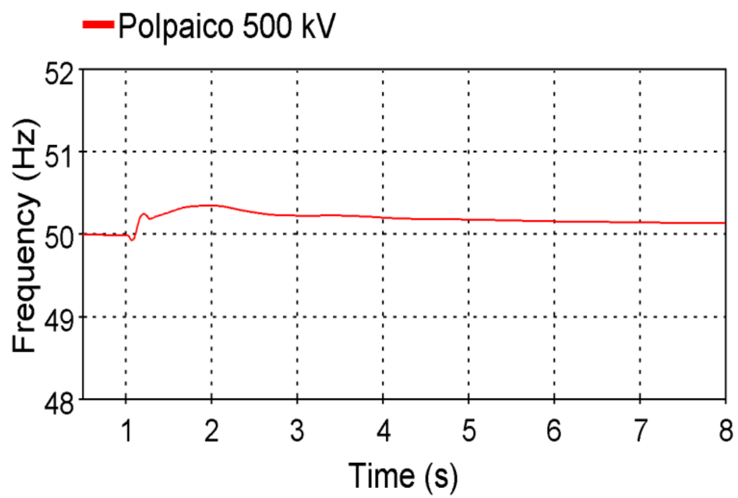


WIDE-AREA GFM IBRs ANALYSIS: results (2)

➢ Fault near Polpaico substation

- With synchronous condensers (1100 MVAr), no GFM IBRs
- System is stable due to synchronous condensers
    - High reactive current contribution during faults
    - Improved dynamic voltage response
    - ESCR in the grid increases
- Frequency recovers slowly





WIDE-AREA GFM IBRs ANALYSIS: results (3)

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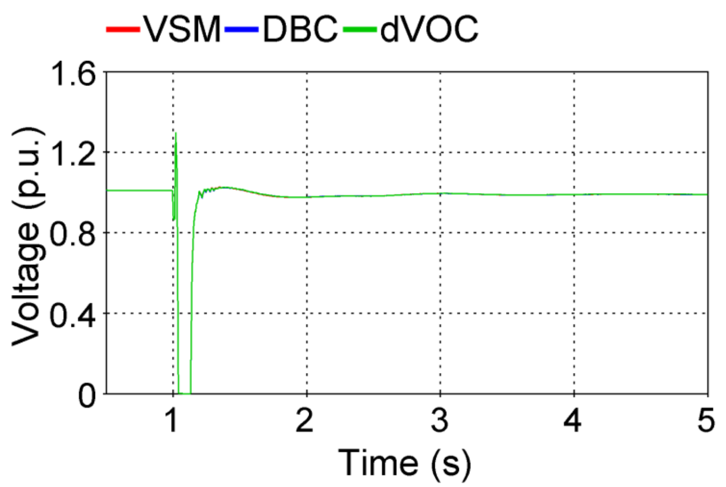
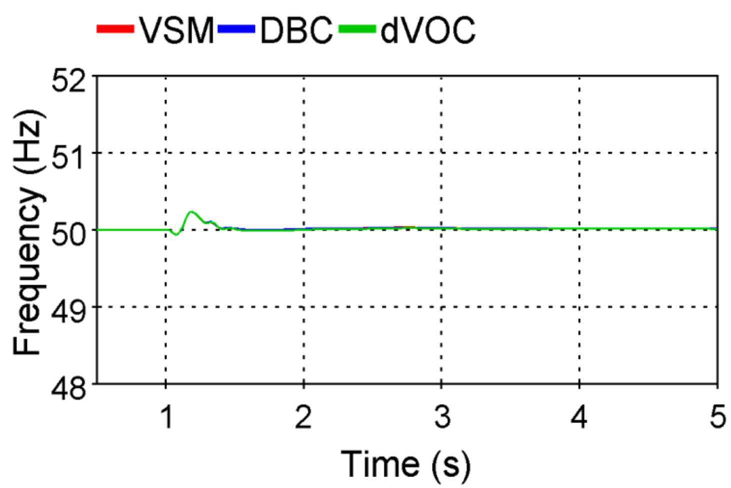
➢Fault near Polpaico substation

- With GFM IBRs (4 x 150 MW), no synchronous condensers
- System is stable with all control methods
  - GPCM generates an independent voltage magnitude and phase reference
  - Fast frequency response supplied by the energy stored in the BESS units
  - Fast voltage control through the injection of reactive current during faults
  - Dynamic response of the grid is significantly improved
- Frequency recovers fast





WIDE-AREA GFM IBRs ANALYSIS: results (4)

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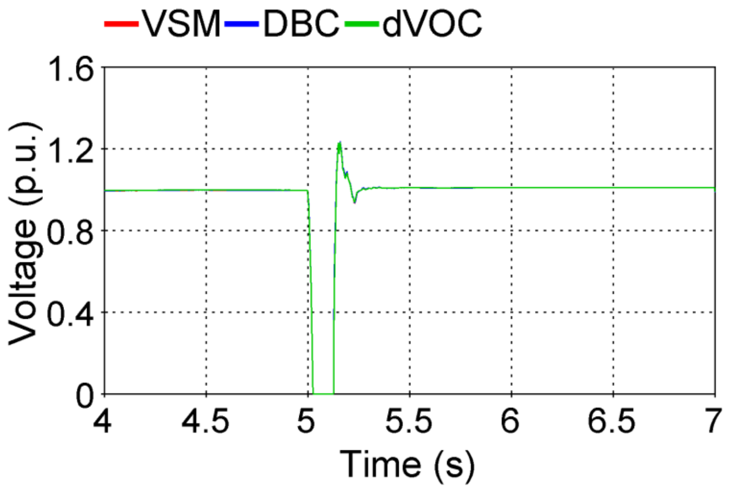
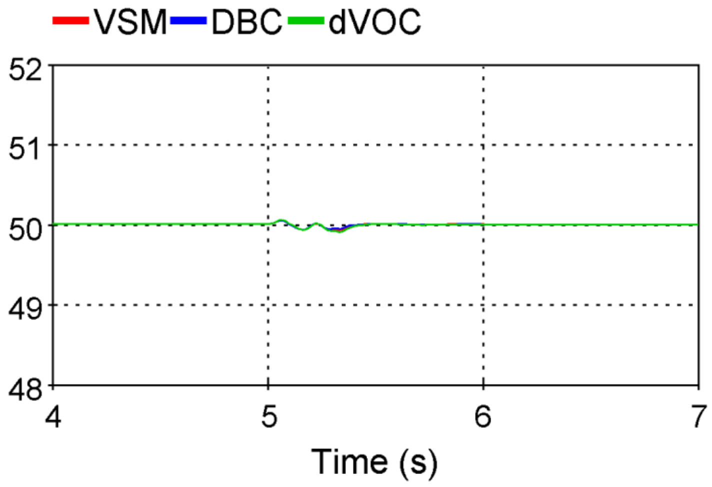
➢Islanding

- LLG fault at Parinas 500 kV substation => trip after 120 ms of 2 x 500 kV lines => 2 islands
- Northern island:
  - 2782 MW of GFL VRE generation
  - 300 MW of GFM BESS (3 x 150 MVA remains in the northern island)
  - 50 MW SG (last and only SG unit)
- All control methods (VSM, DBC, dVOC) keep northern island stable
  - Voltage and frequency at Parinas 500 kV substation:

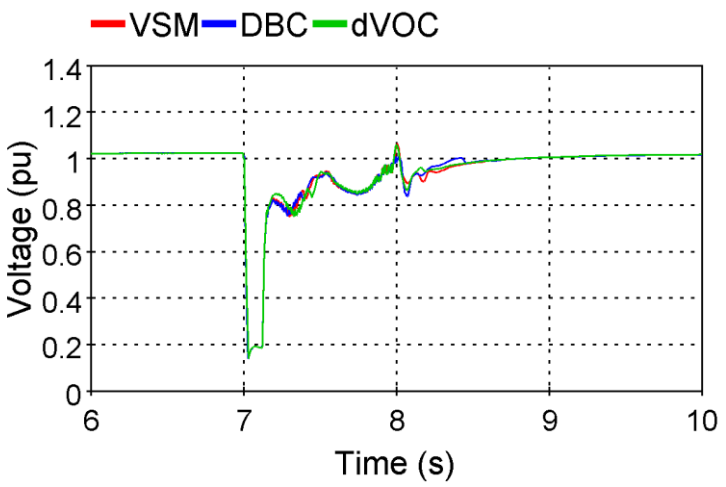


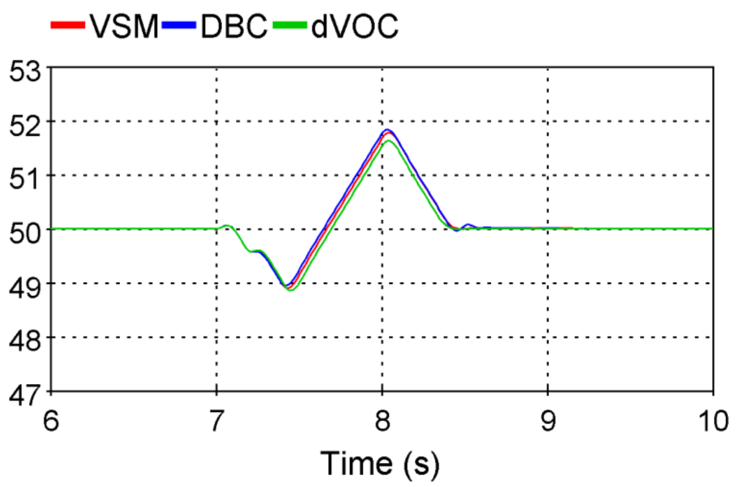


WIDE-AREA GFM IBRs ANALYSIS: results (5)

➢Loss of the Last SG

- LLG fault at the last SG bus in the northern island, last SG (50 MW) trips
  - 2782 MW of GFL VRE generation
  - 300 MW of GFM BESS (3 x 150 MVA capacity available in the northern island)
- All control methods (VSM, DBC, dVOC) keep northern island stable
  - Significant frequency deviation
  - Slow voltage recovery
  - Behavior differs depending on the control method
  - Voltage and frequency at Kimal 500 kV substation:

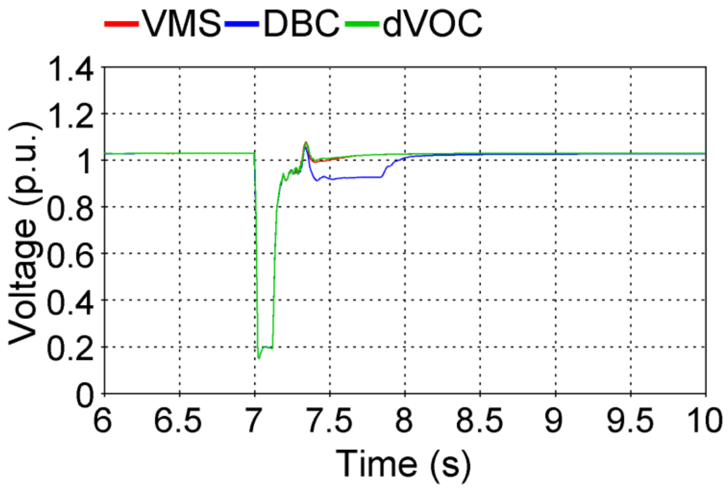


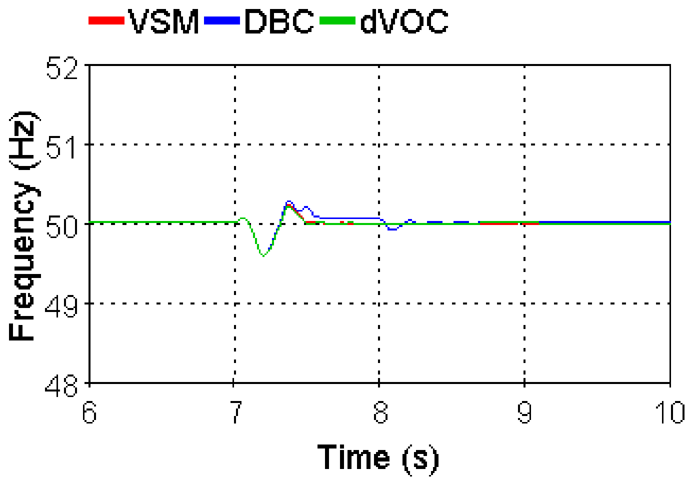


WIDE-AREA GFM IBRs ANALYSIS: results (6)

➢Loss of the Last SG with larger GFM capacity

- LLG fault at the last SG bus in the northern island, last SG (50 MW) trips
  - 2782 MW of GFL VRE generation
  - 300 MW of GFM BESS (**3 x ~~150~~ 200 MVA** capacity available in the northern island ≈ 15%)
- All control methods (VSM, DBC, dVOC) keep northern island stable
  - More stable response
  - Voltage recovers more slowly with DBC method
  - Voltage and frequency at Kimal 500 kV substation:





CONCLUSIONS

- GFM can positively impact the dynamic behavior and stability of a grid with high VRE resources
- Minimum share of GFM to keep the grid stable under extreme events
  - Around 15%
- Enabling technologies (FACTS, GET, BESS, SCs, GFM, etc.) are critical to accelerate the energy transition in Chile
- Advanced EMT tools are essential to assess the dynamic and transient behavior of grids dominated by power electronic IBRs

NEXT STEPS (At CEN)

- Further research to test additional capabilities in large grids
  - Short-term current contribution
  - Protection coordination
  - Black-start capabilities
- Validate results with vendor's specific GFM models
- Test GFM behavior with even higher shares of VRE (80-90%)
- Elaborate technical requirements and specification for GFM technologies