New flexibility resources:
the role of hybrid pumped hydropower
14th May 2021

The role of energy storage in the frequency control of power systems

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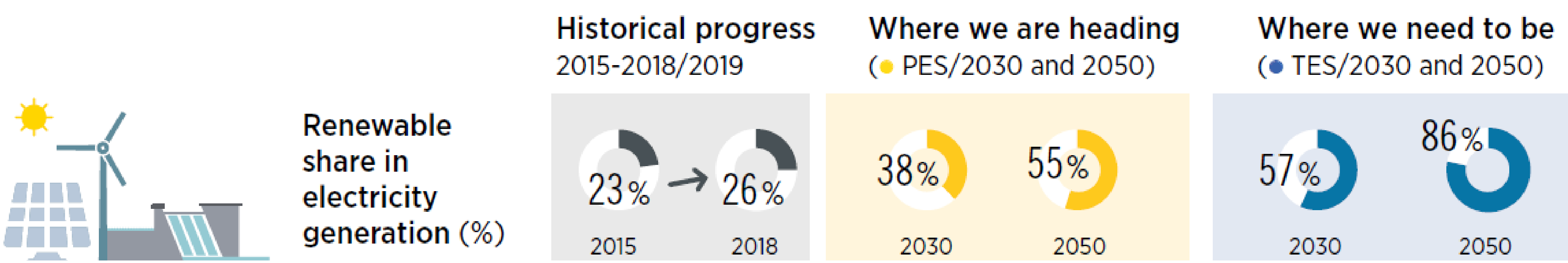
1. Renewable generation targets

In the European Union (EU), the Directive (EU) 2018/2001 establishes a binding target of 32 % for the share of renewable energy consumed in the EU by 2030, which translates into a rather higher share target when referred to the electricity consumption.

According to the International Renewable Energy Agency (IRENA), the share of renewable energy in the electricity production will reach between 41 % and 50 % by 2030 in the EU.

Not only the EU has initiated a firm transition to a fully renewable electric power system but also other regions of the world.

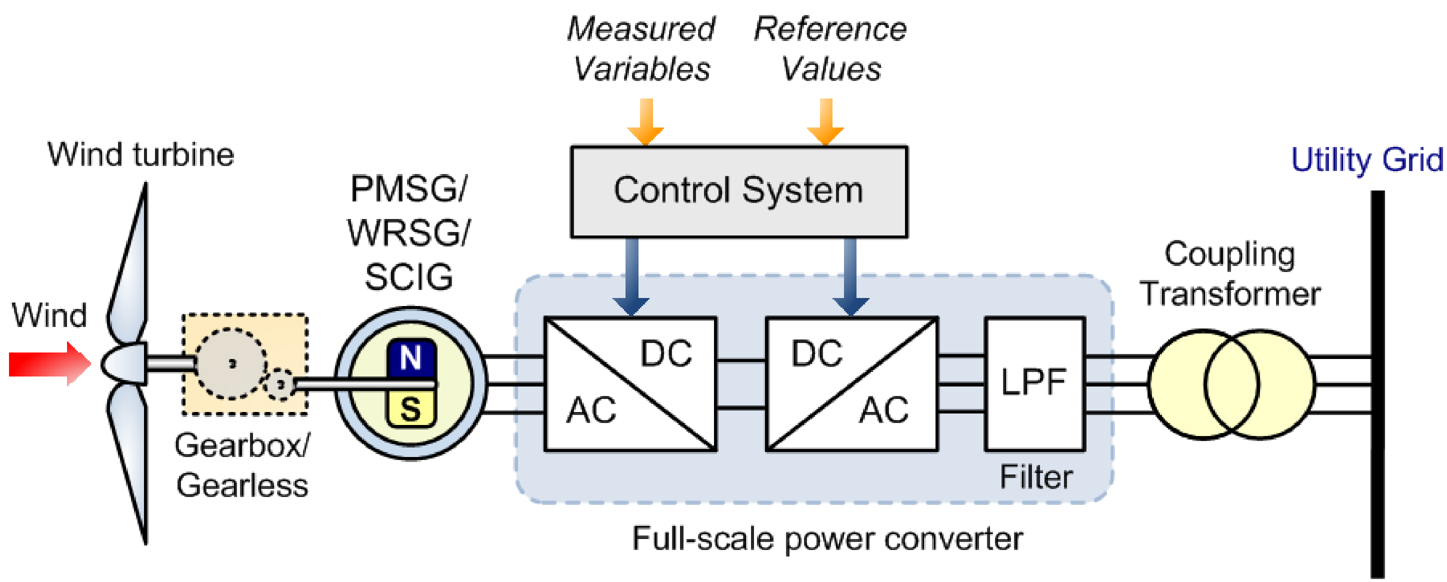


Taken from IRENA, Global Renewables Outlook, 2020.

2. Impact of converter-interfaced RG on the system's frequency

The impacts of wind and solar PV generation on the power system's frequency are mostly due to:

- Variability
- Unpredictability
- Most wind and solar PV generation units are connected to the grid through power electronics devices



Taken from Molina and Giménez (2011).

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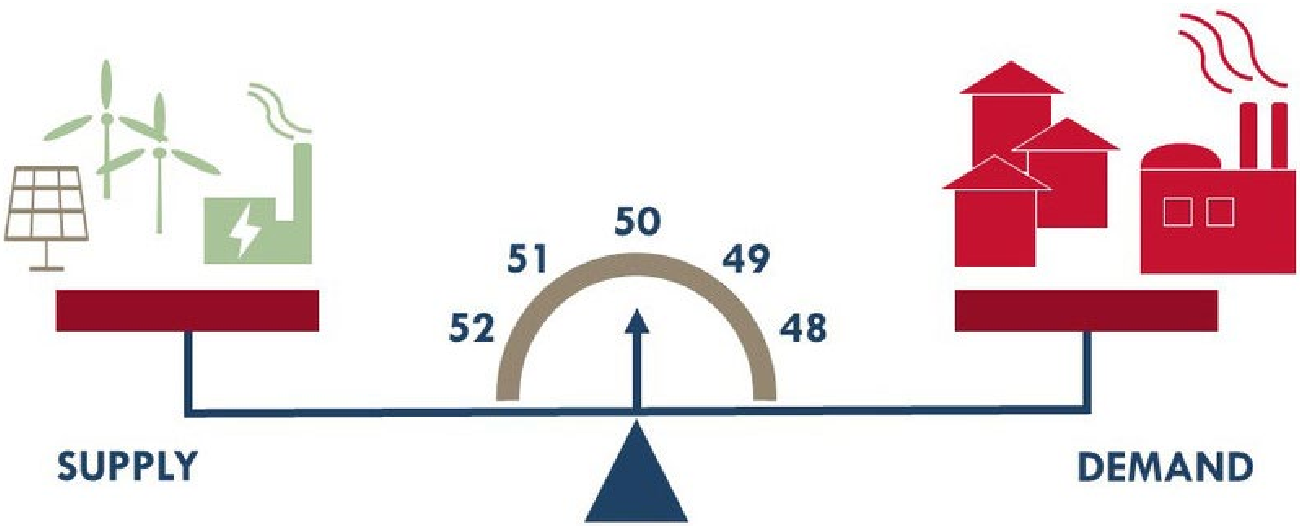

2. Impact of converter-interfaced RG on the system's frequency

The system's frequency must remain within strict limits established by the Commission Regulation (EU) 2017/1485 establishing a guideline on electricity transmission system operation

Data item	CE	GB	IE/NI	Nordic
Standard frequency range	± 50 mHz	± 200 mHz	± 200 mHz	± 100 mHz
Maximum instantaneous frequency deviation	800 mHz	800 mHz	1000 mHz	1000 mHz
Maximum steady-state frequency deviation	200 mHz	500 mHz	500 mHz	500 mHz
Time to recover frequency	Not used	1 minute	1 minute	Not used
Frequency recovery range	Not used	± 500 mHz	± 500 mHz	Not used
Time to restore frequency	15 minutes	15 minutes	15 minutes	15 minutes
Frequency restoration range	Not used	± 200 mHz	± 200 mHz	± 100 mHz
Alert state trigger time	5 minutes	10 minutes	10 minutes	5 minutes

Frequency quality defining parameters of synchronous areas. Taken from ENTSOE (2020), Load Frequency Control Annual Report 2019.

2. Impact of converter-interfaced RG on the system's frequency

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Synchronous area	Frequency range	Time period for operation
Continental Europe	47,5 Hz-48,5 Hz	To be specified by each TSO, but not less than 30 minutes
	48,5 Hz-49,0 Hz	To be specified by each TSO, but not less than the period for 47,5 Hz-48,5 Hz
	49,0 Hz-51,0 Hz	Unlimited
	51,0 Hz-51,5 Hz	30 minutes

Minimum time period for which a power-generating module has to be capable of operating on different frequencies , deviating from a nominal value, without disconnecting from the network. Taken from the Commission Regulation (EU) 2016/631 establishing a network code on requirements for grid connection of generators.

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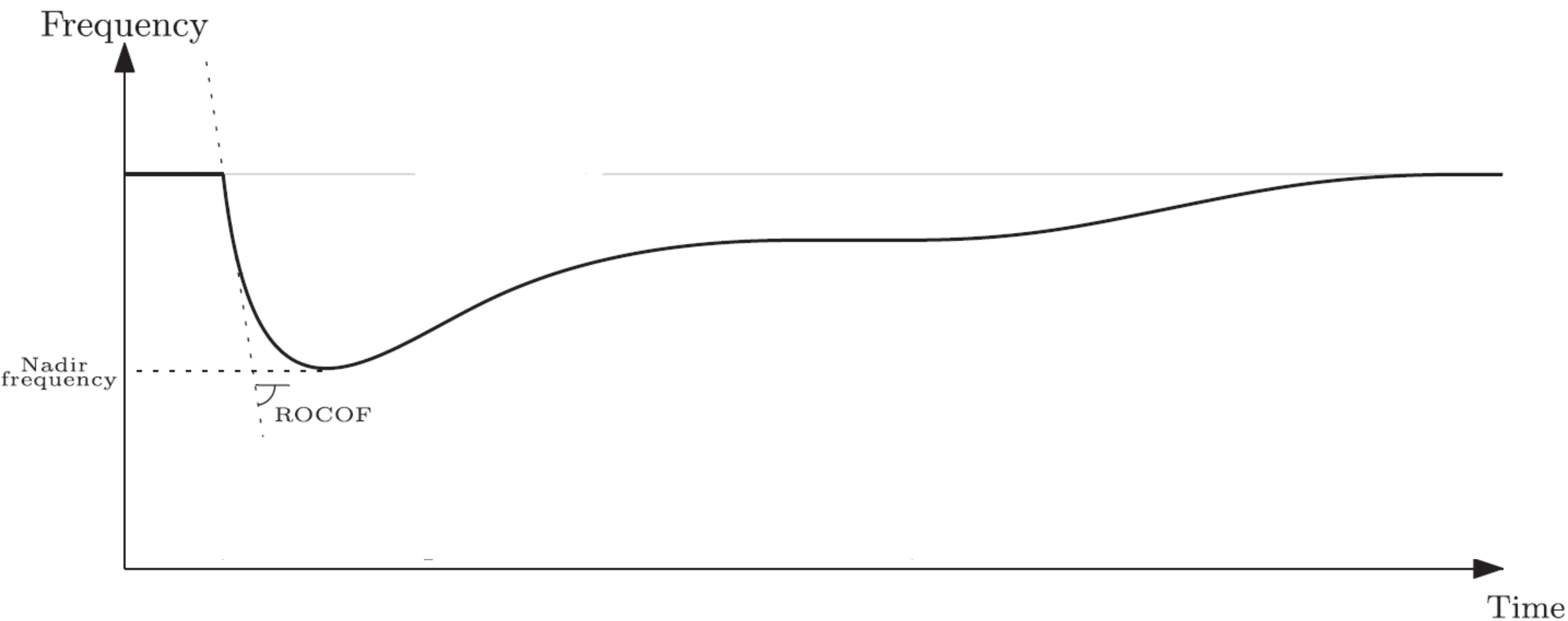

Theretical system's response after the trip of a large generator. Adapted from P. Tielens and D. Van Hertem, The relevance of inertia in power systems, Renewable and Sustainable Energy Reviews 55, 2016.

2. Impact of converter-interfaced RG on the system’s frequency

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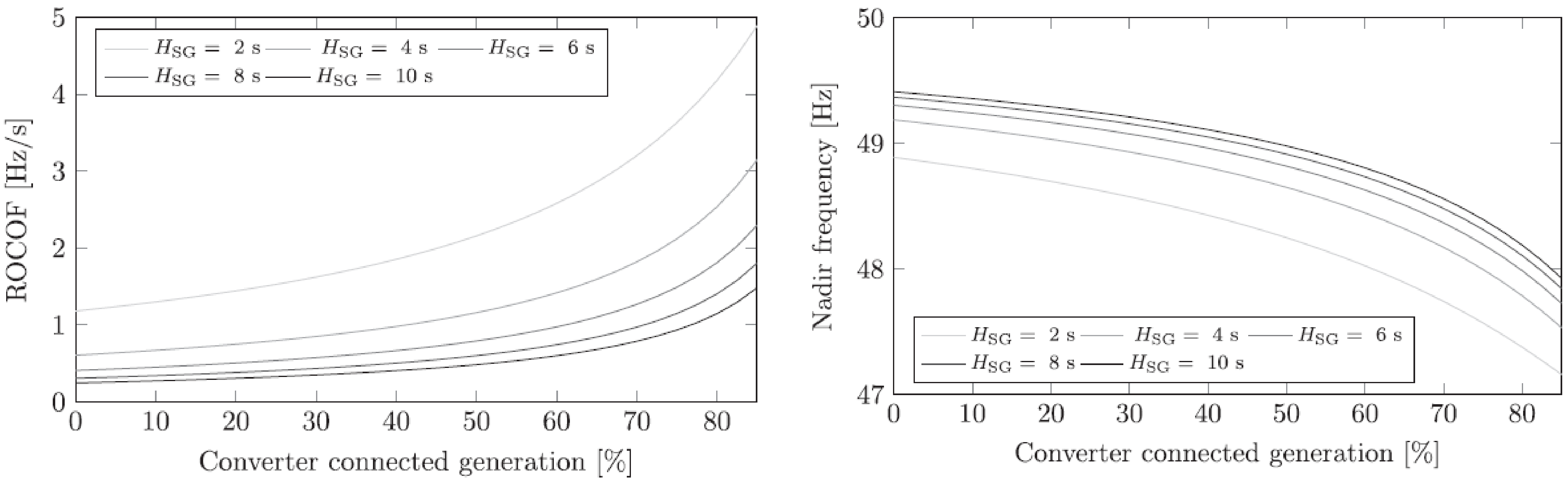
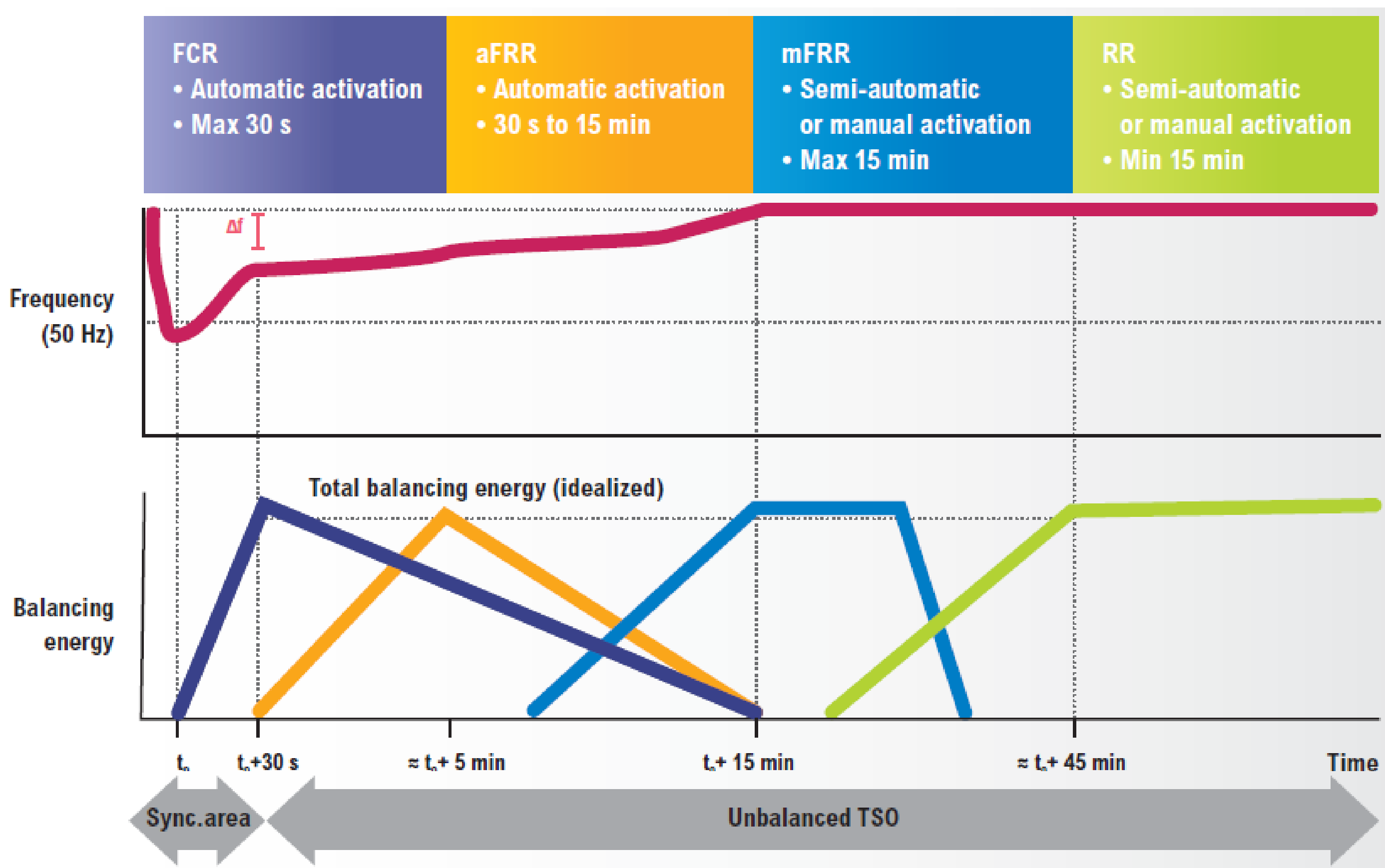


Frequency nadir and ROCOF after the trip of a large generator for different penetrations of converter-interfaced generation and different synchronous inertia constants (thermal and hydro units). Taken from P. Tielens and D. Van Hertem, The relevance of inertia in power systems, Renewable and Sustainable Energy Reviews 55, 2016.

3. Common frequency control services

Frequency control reserves are deployed in a hierarchical order as a function of the activation time and the time during which the control action keeps active.



Hierarchical deployment of frequency control reserves. Adapted from ENTSOE, Electricity Balancing in Europe, November 2018.

4. Overview of energy storage worldwide installed capacity

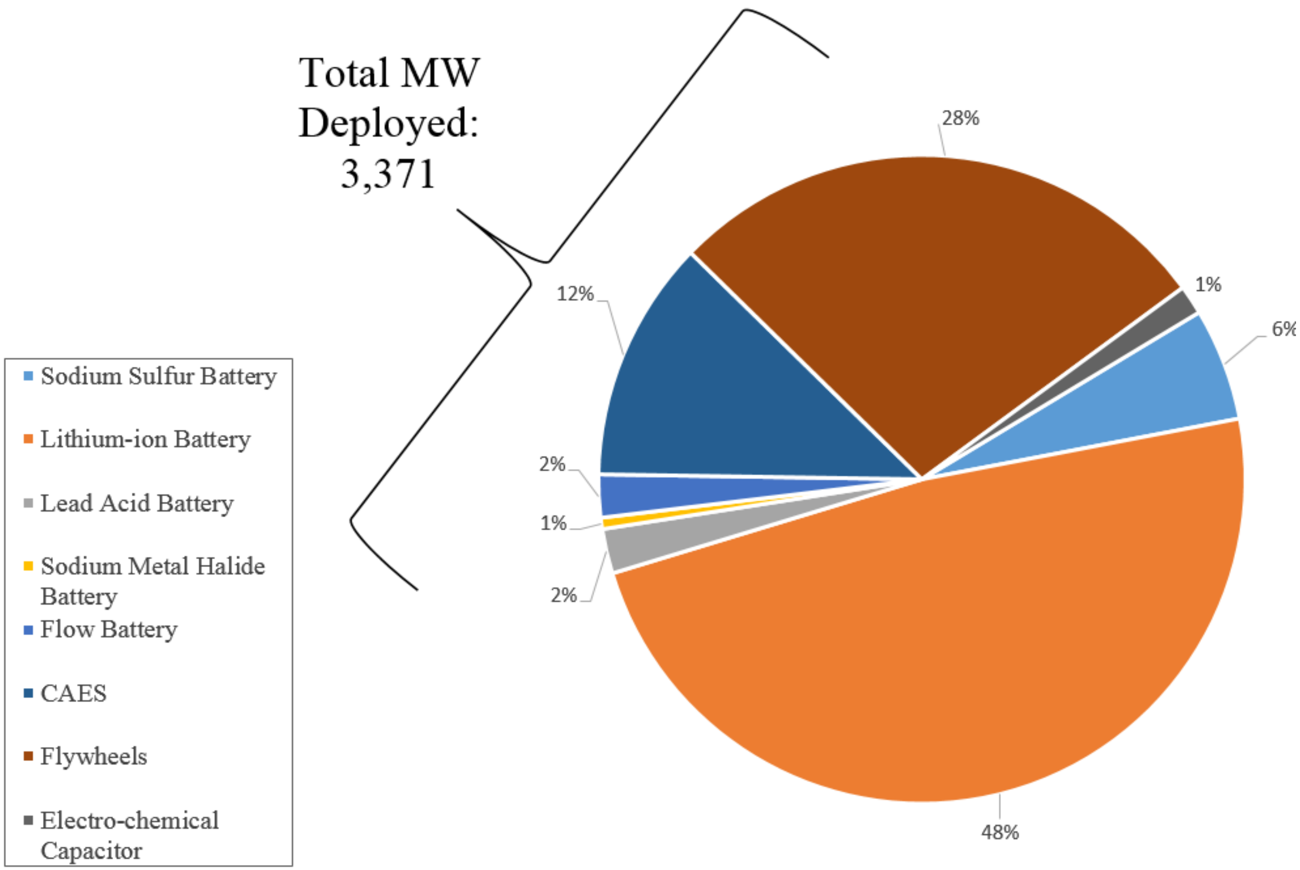
Pumped-storage represents 98 % of grid-connected energy storage worldwide installed capacity.

Technology	MW Deployed
Sodium sulfur	189
Lithium-ion	1,629
Lead acid	75
Sodium metal halide	19
Flow battery	72
PSH	169,557
CAES	407
Flywheels	931
Electrochemical capacitor	49
Total	172,928

Energy storage worldwide installed capacity in 2018. Taken from Mongird, K. et al., Energy Storage Technology and Cost Characterization Report, 2019.

4. Overview of energy storage worldwide installed capacity

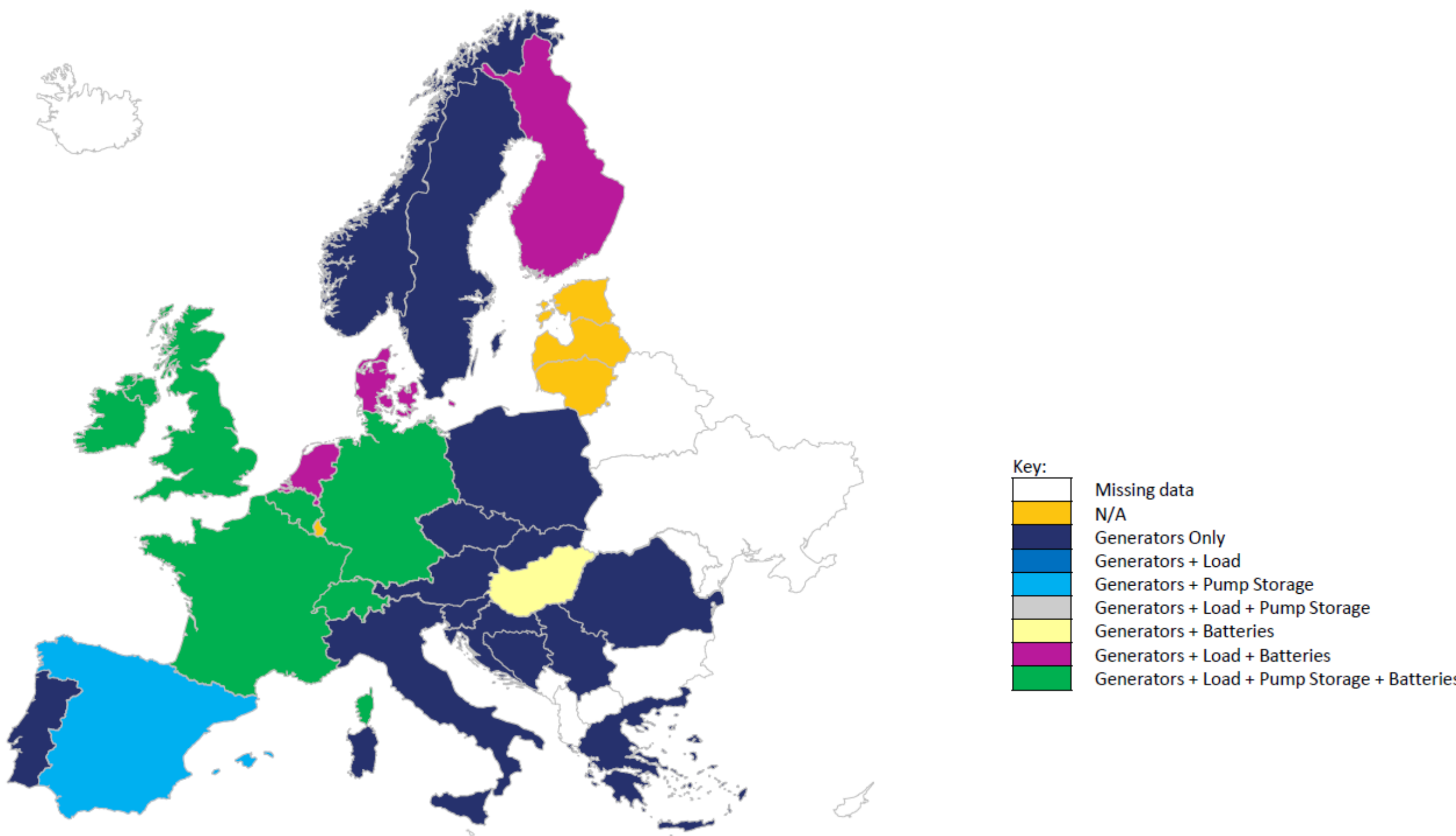
The installed capacity in energy storage technologies other than pumped-storage amounted to 3,371 MW in 2018.



Percentage of installed capacity of energy storage technologies other tan pumped-storage in 2018. Taken from Mongird, K. et al., Energy Storage Technology and Cost Characterization Report, 2019.

5. Provision of frequency control services by energy storage

Since the entry into force of the Commission Regulation (EU) 2017/2195 establishing a guideline on electricity balancing, National Regulatory Authorities are implementing profound regulatory changes so as to facilitate the participation of energy storage in the frequency control services.



Technologies allowed to provide FCR (capacity) in 2019. Taken from ENTSO-E Working Group on Ancillary Services, Survey on ancillary services procurement, Balancing market design 2019, 2020.

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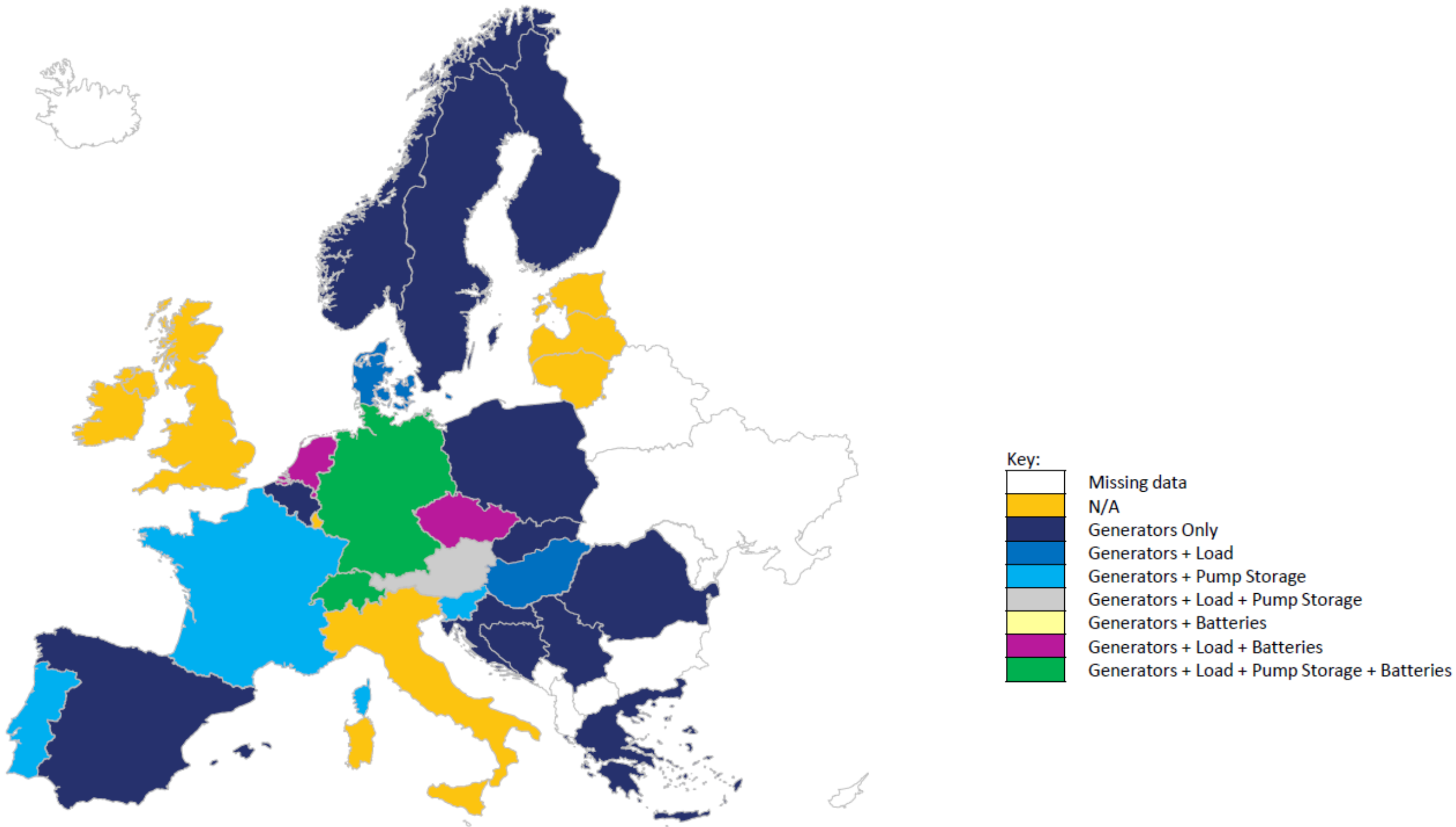
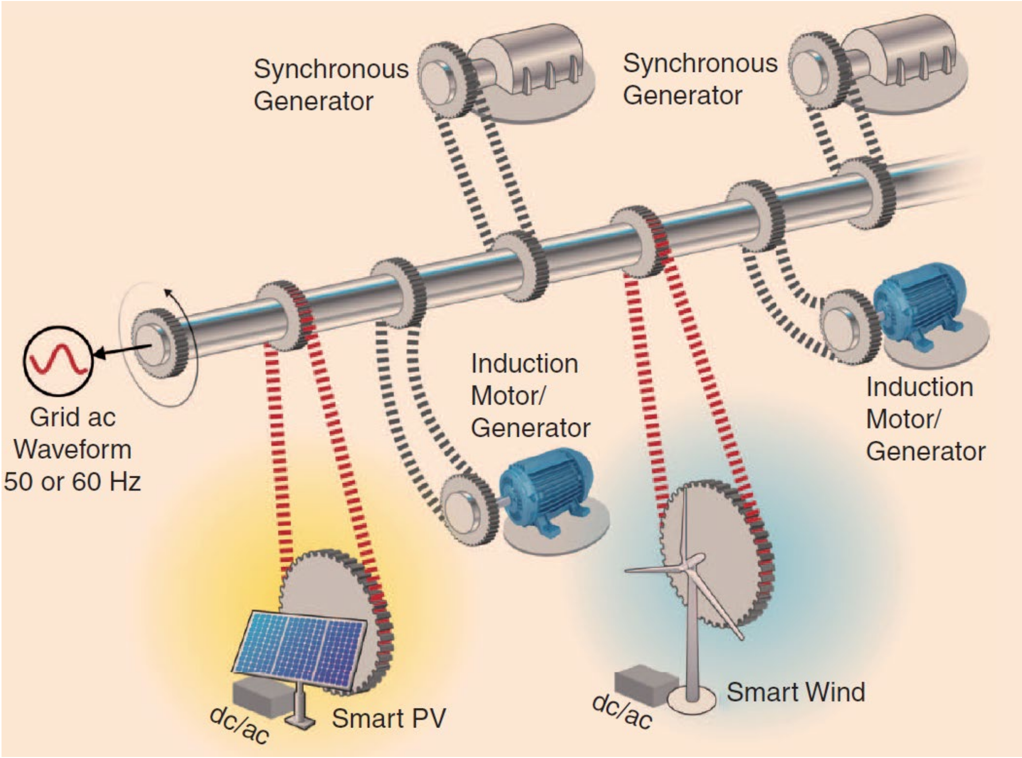


Technologies allowed to provide aFRR (capacity) in 2019. Taken from ENTSO-E Working Group on Ancillary Services, Survey on ancillary services procurement, Balancing market design 2019, 2020.

5. Provision of frequency control services by energy storage

Energy storage systems connected using synchronous generators, such as pumped-storage and compressed air, provide synchronous inertia and frequency control reserves in the same way as a conventional generator*.

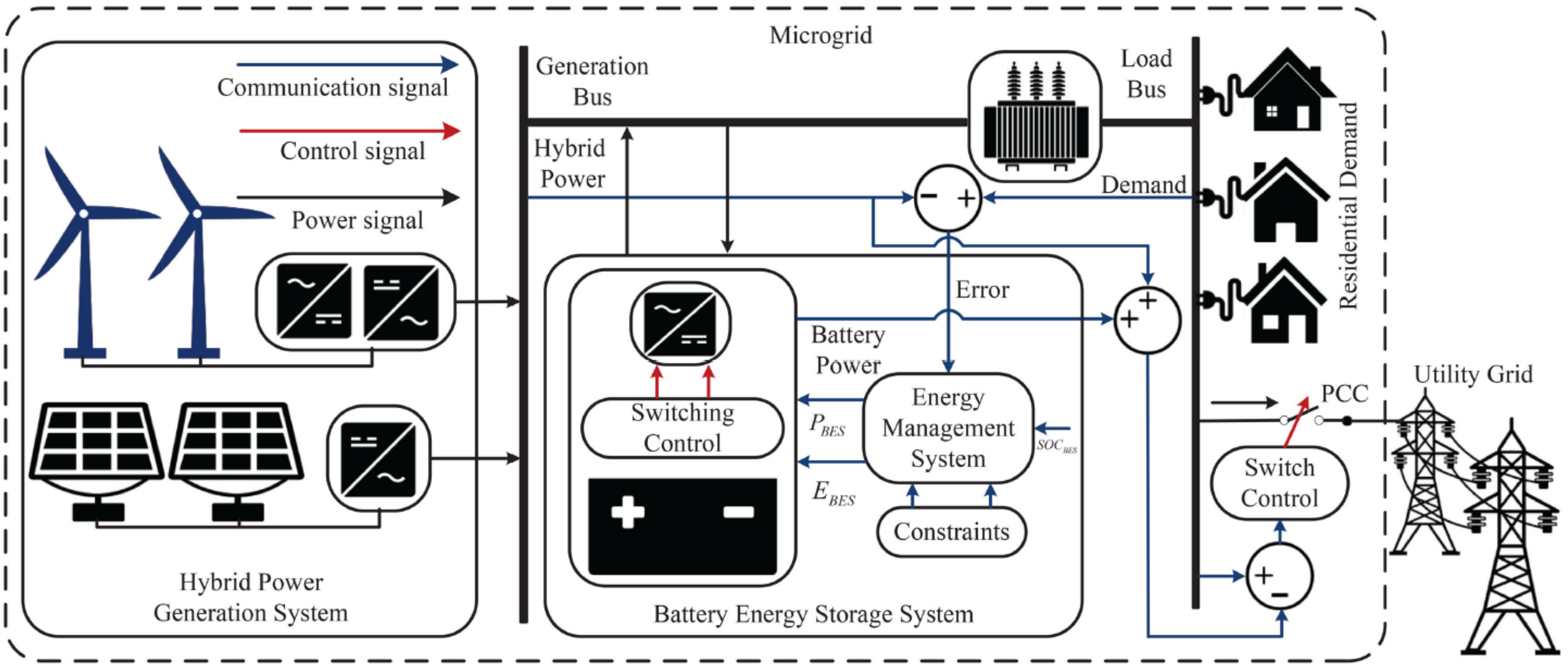


Synchronous (rigid) coupling between the grid and synchronous generators. Taken from B. Kroposki et al., Achieving a 100 % Renewable Grid, Operating Power Systems with Extremely High Levels of Variable Renewable Energy, IEEE Power & Energy Magazine, March/April 2017.

* Conventional pumped-storage cannot vary its power input in pump mode.

5. Provision of frequency control services by energy storage

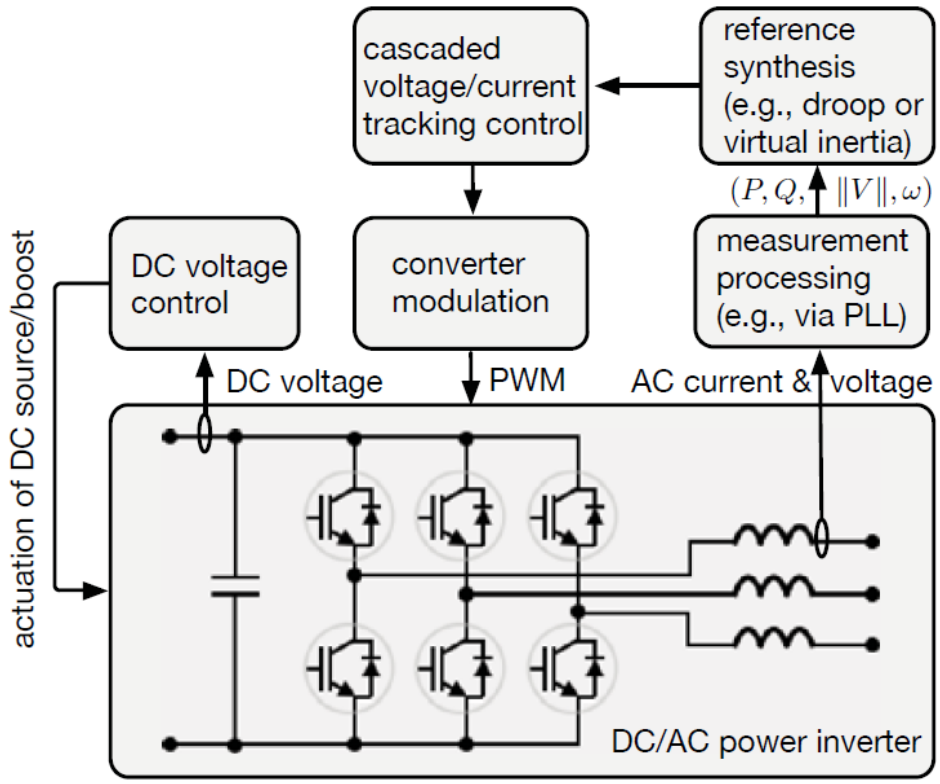
Converter-interfaced energy storage systems CIESS can provide frequency control services by the use of a proper Energy Management System (EMS)



Grid-connected microgrid system with a Battery Energy Storage System operated through a suitable EMS. Taken from Akram et al., Optimal sizing of a wind/solar/battery hybrid grid-connected microgrid system, IET Renewable Power Generation, 12 (1), 2018.

5. Provision of frequency control services by energy storage

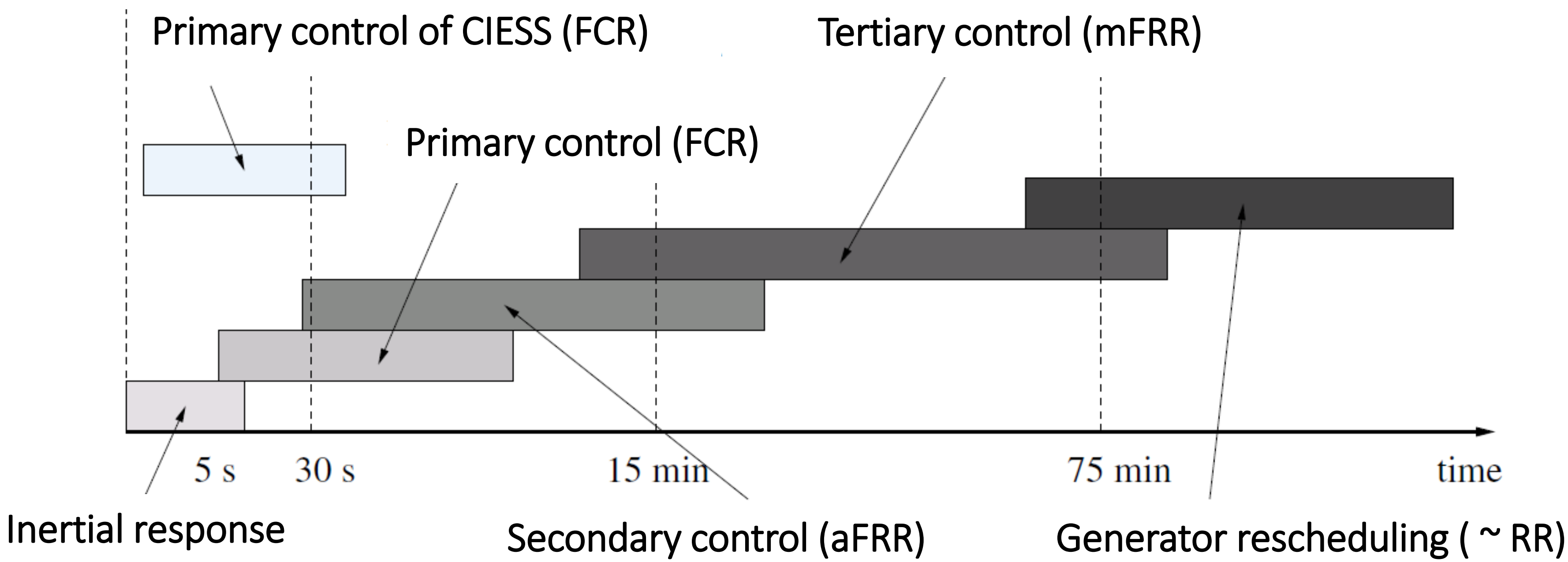
CIESS does not use the rotor speed as frequency measurement but rather utilize the Phase-Locked Loop (PLL) to estimate the local bus frequency.



Prototypical device-level implementation of virtual inertia. Taken from Milano et al. Foundations and Challenges of Low-Inertia Systems, in Proc. 2018 PSCC.

5. Provision of frequency control services by energy storage

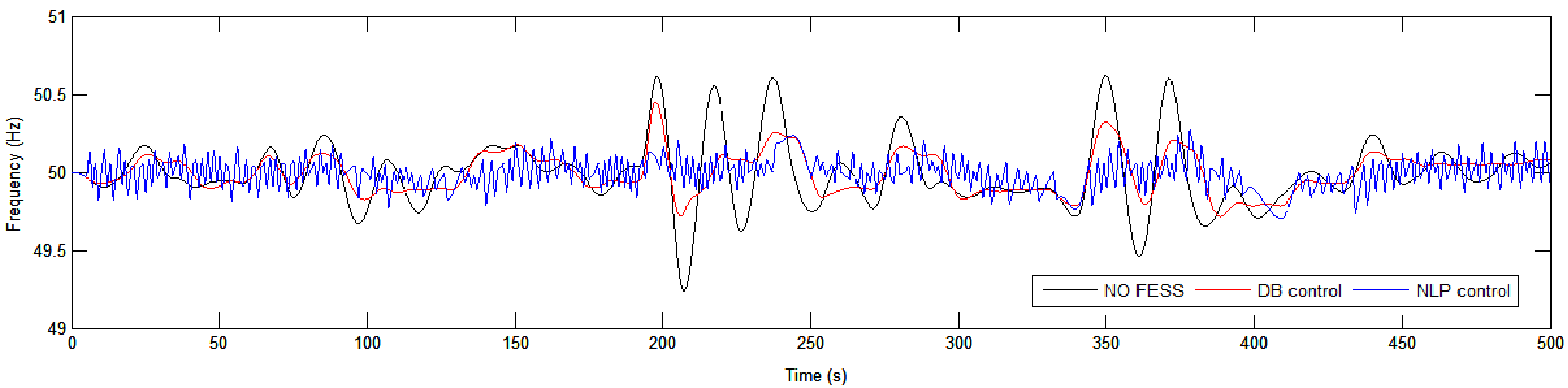
With a suitable EMS, CIESS can provide frequency control reserves with a much higher response speed than synchronous generators.



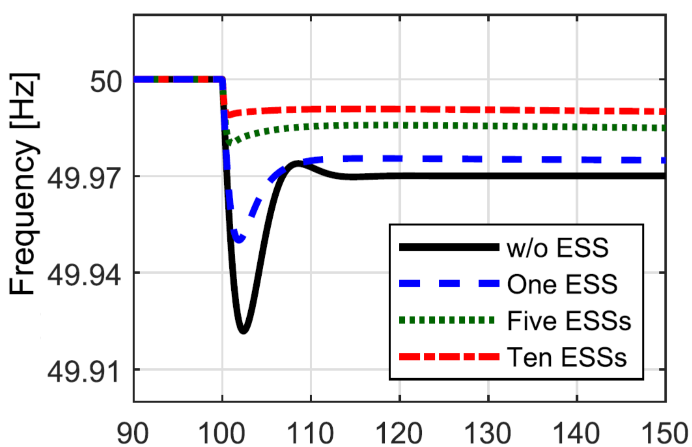
Typical time scales of frequency-related dynamics in conventional power systems as well as typical time scale of frequency control that can be provided through. Adapted from Milano et al. Foundations and Challenges of Low-Inertia Systems, in Proc. 2018 PSCC.

5. Provision of frequency control services by energy storage

There are tens of articles and projects where the benefits of the provision of fast frequency control by CIESS has been demonstrated.



Frequency in El-Hierro power system with and without a Flywheel-based ESS considering different control strategies in the EMS. Taken from Torres et al., Control strategy and sizing of a flywheel energy storage plant for the frequency control of an isolated wind-hydro power system. 15 th Wind Integration Workshop, November 2016.



Hypothetical frequency response in a power system with and without battery-based ESS, considering different numbers of ESSs. Taken from Shim et al., On Droop Control of Energy-Constrained Battery Energy Storage Systems for Grid Frequency Regulation, IEEE Access, vol. 7, 2019.

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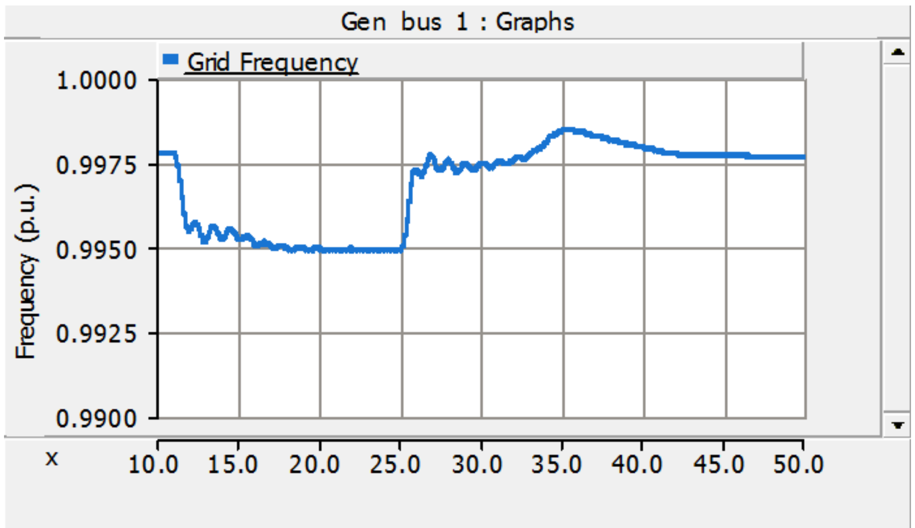
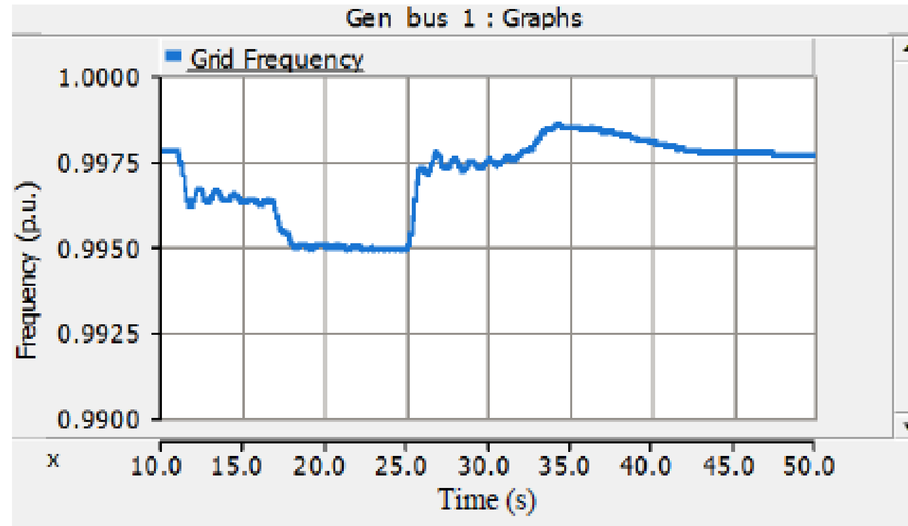
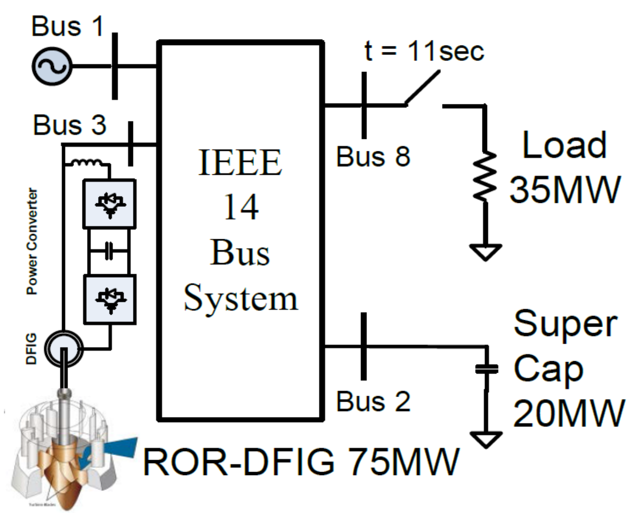






Frequency in a test case (lower figure) with a supercapacitor-based ESS providing inertial response (upper right figure) and without the ESS (upper left fiigure). Taken from Gevorgian et al., Supercapacitor to provide ancillary services. 2017 IEEE Energy Conversion Congress and Exposition.

5. Provision of frequency control services by energy storage

There are tens of CIESS currently in operation all over the world.

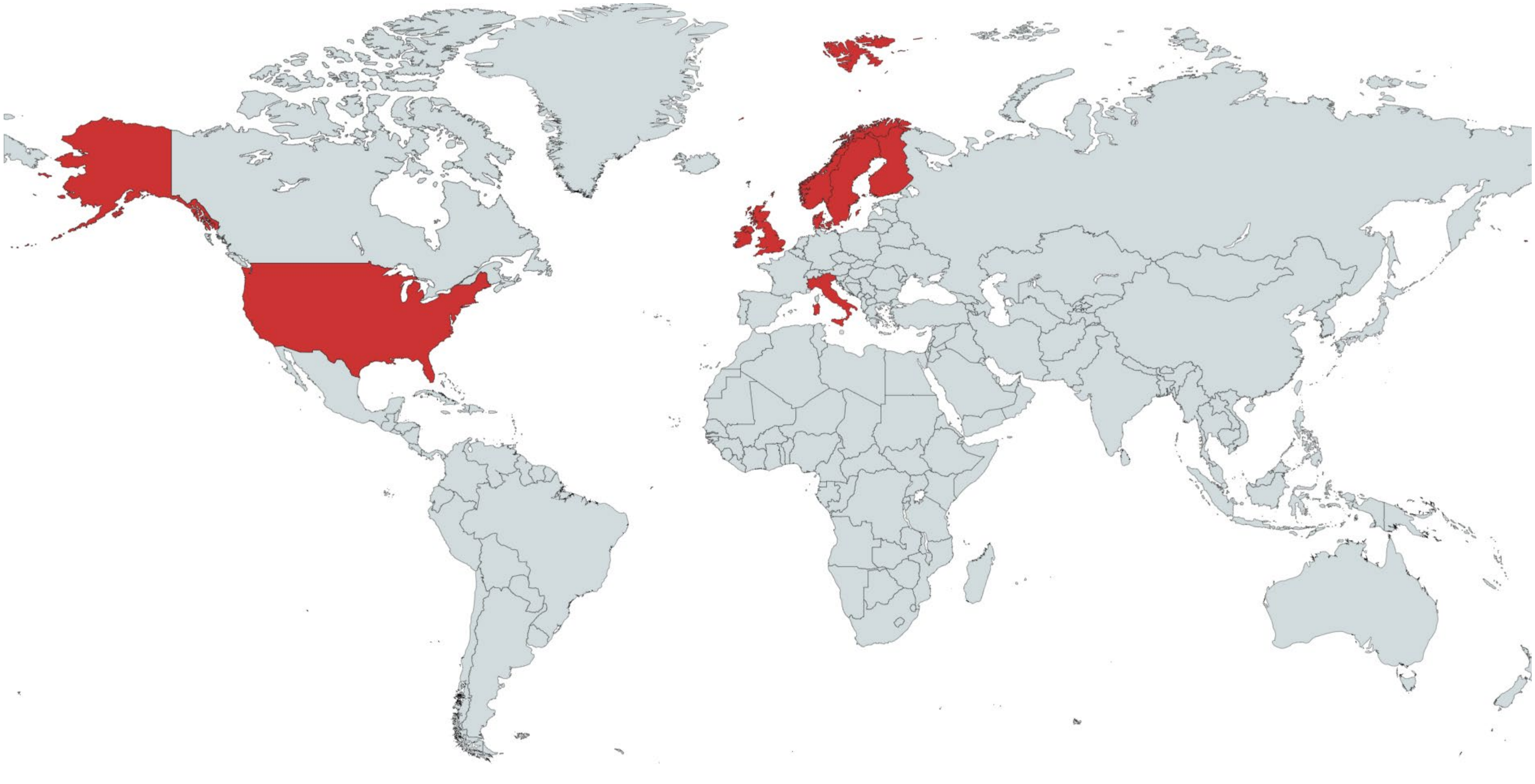
4-MW/5-s supercapacitor ESS installed in La Palma island, Spain. Taken from P. Fontela et al., Canary Islands Benefit from Enhanced Grids, T&D World, 2015.

150-MW/189-MWh battery ESS installed in Hornsdale, Australia. Taken from S. Tomevska, Tesla battery in South Australia expanded by 50 per cent energy minister lauds benefits, ABC News, 2020.

20 MW/15-min. flywheel ESS installed in Stephentown Supercapacitor installed in Stephentown, NY, USA. Taken from https://beaconpower.com/.

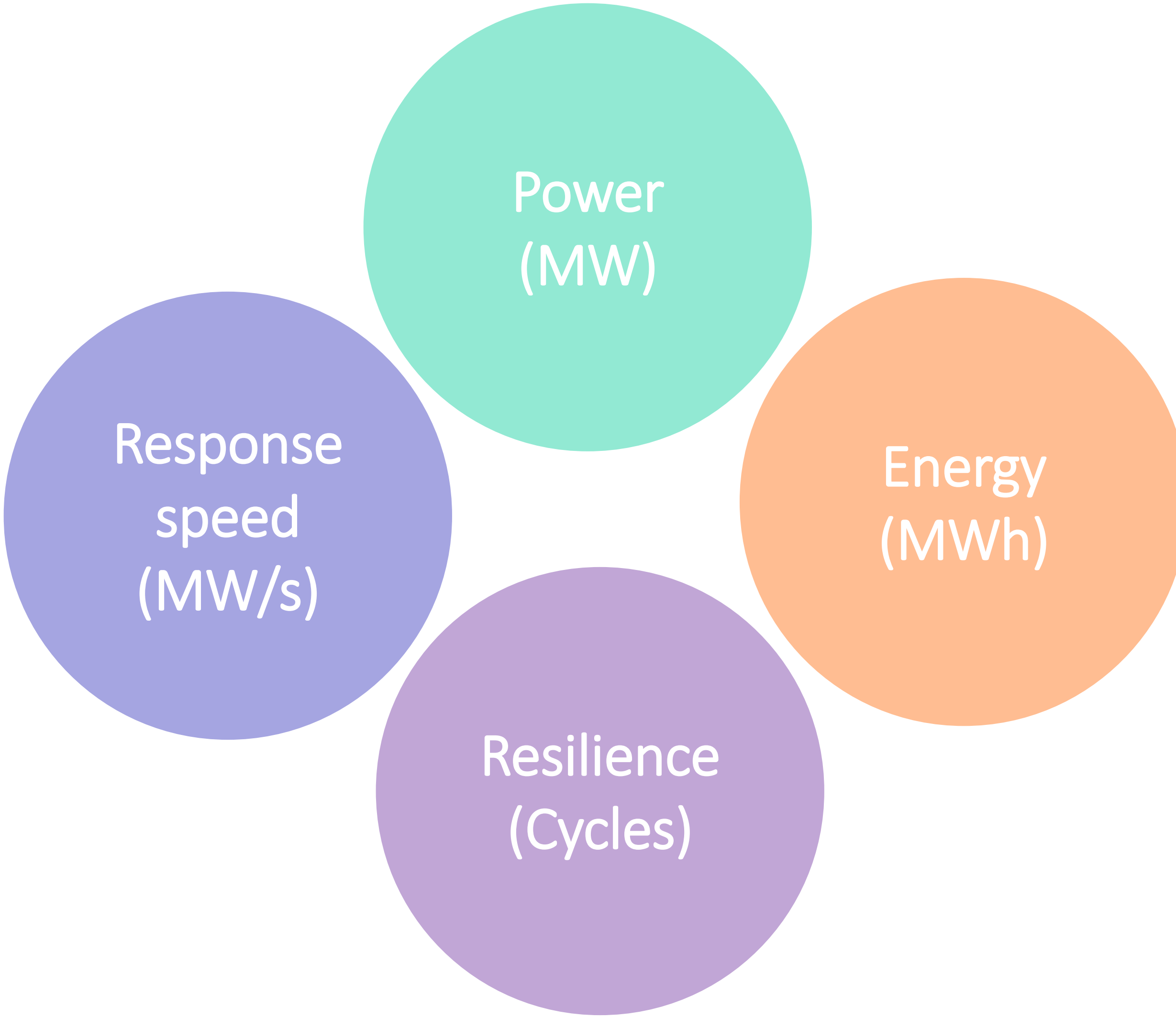
6. Novel frequency control services

In last decade, a few countries/TSOs have implemented or are planning to implement novel frequency control services which value the response speed of the service provider, or that can only be provided by CIESS or GIG.



7. Overview of performance characteristics of ES technologies

The suitability of each ES technology to provide each frequency control service depends on various technical features



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Technology	Power range (MW)	Discharge (hours)	Cycle life (# cycles)	Response time (seconds)
Pumped hydro	10-5,000 [7]	1-24 [7]	20,000-50,000 [7]	> 10 [7]
Compressed air	5-400 [7]	1-24 [7]	>13,000 [7]	> 10 [7]
Flywheel	0.01-20 [8]	< 0.5[7]	20,000-225,000 [1,7]	< 10 [7]
Lead-acid	0.005-100 [1]	0.25-10 [1]	< 5,500 [1]	< 10 [7]
Lithium-ion	0.001-35 [9]	0.25-5 [1]	2,000-3,500 [9]	< 10 [7]
Sodium-sulphur	0.05-50 [7,9]	0.0167-8 [1,9]	2,500-4,500 [9]	< 10 [10]
Redox-flow	0.02-50 [1]	0.0167-10 [7]	5,000-13,000 [7,9]	< 10 [7]
Hydrogen	0.3-500 [7]	0.0167-24 [7]	<20,000 [7]	< 10 [7]
Supercapacitor	<4 [11]	<1 [11]	>100,000 [7]	< 10 [7]

Performance characteristics of different energy storage technologies. Taken from O. Schmidt et al., Projecting the Future Levelized Cost of Electricity Storage Technologies, Joule 3(1), 2019.

8. Conclusion

The optimal solution is HYBRID

Hybrid pumped-storage+Li-ion batteries ESS in Pfreimd hydropower system, Germany. Taken from https://www.engie-deutschland.de/ and https://blog-tractebel.lahmeyer.de/

Hybrid flywheel+lead-acid batteres ESS in Rhode, Ireland. Taken from https://schwungrad-energie.com/

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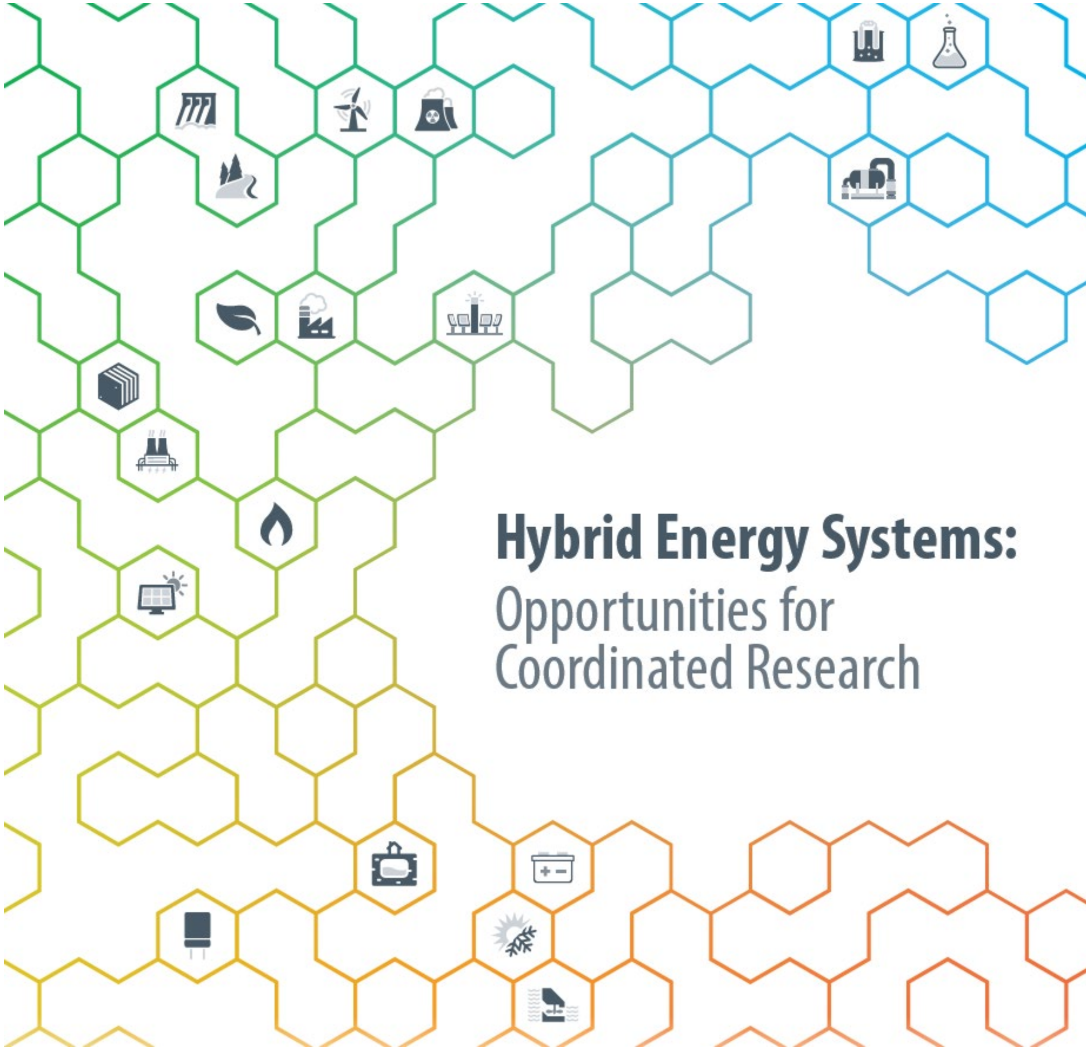

Cover of U.S. Department of Energy (DOE). 2021. Hybrid Energy Systems: Opportunities for Coordinated Research. Golden, CO: National Renewable Energy Laboratory. DOE/GO-102021-5447.

THANK YOU!

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