OVERVIEW OF U.S. ELECTRICITY MARKETS

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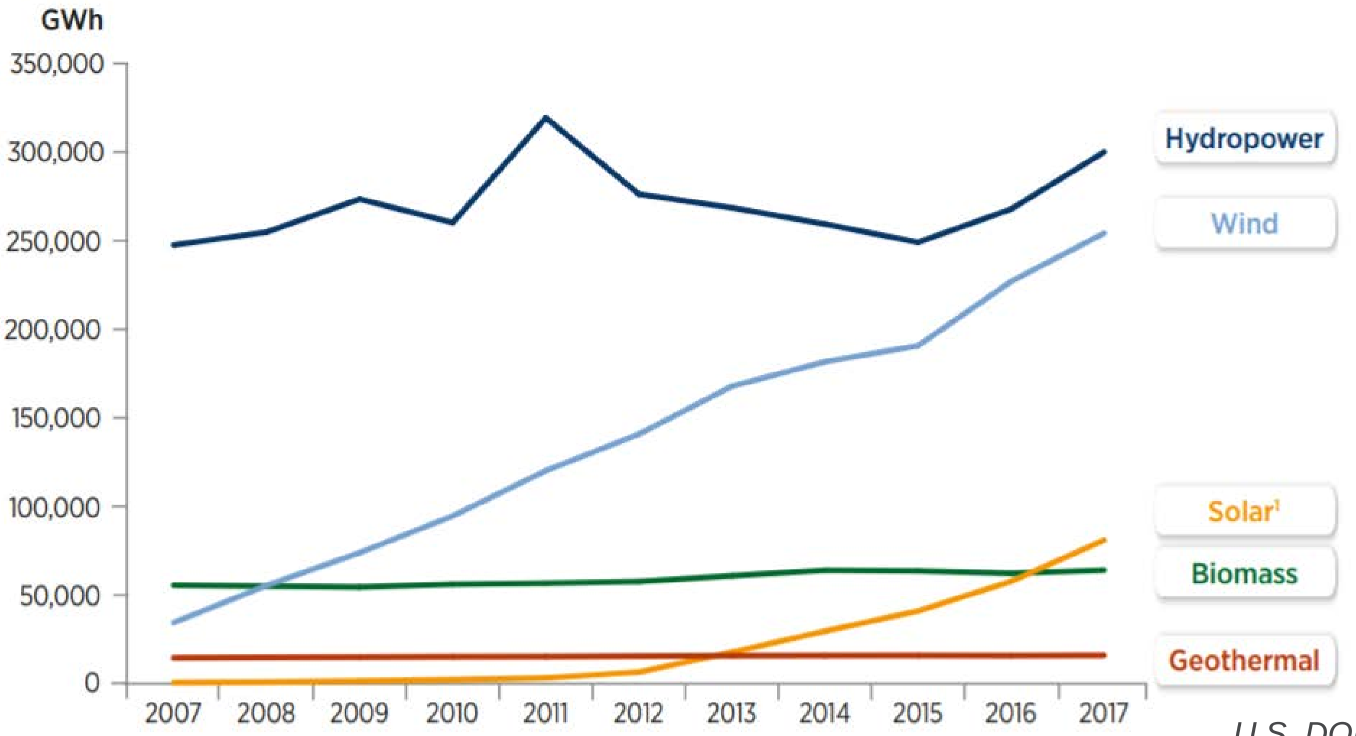
U.S. ELECTRICITY GENERATION BY SOURCE

	Coal	Petroleum Liquids	Petroleum Coke	Natural Gas	Other Gases	Nuclear	Renewables[1]	Other	Total Generation (GWh)
2007	48.4%	1.2%	0.4%	21.5%	0.3%	19.4%	8.5%	0.3%	4,163,642
2008	48.1%	0.8%	0.3%	21.4%	0.3%	19.5%	9.2%	0.3%	4,125,675
2009	44.4%	0.7%	0.3%	23.3%	0.3%	20.2%	10.6%	0.3%	3,955,540
2010	44.7%	0.6%	0.3%	23.9%	0.3%	19.5%	10.4%	0.3%	4,131,520
2011	42.2%	0.4%	0.3%	24.7%	0.3%	19.2%	12.5%	0.3%	4,107,981
2012	37.3%	0.3%	0.2%	30.2%	0.3%	19.0%	12.3%	0.3%	4,054,880
2013	38.8%	0.3%	0.3%	27.6%	0.3%	19.3%	13.0%	0.3%	4,079,349
2014	38.5%	0.4%	0.3%	27.4%	0.3%	19.4%	13.4%	0.3%	4,111,724
2015	33.0%	0.4%	0.3%	32.5%	0.3%	19.4%	13.7%	0.3%	4,098,815
2016	30.2%	0.3%	0.6%	33.6%	0.3%	19.6%	15.4%	0.3%	4,104,518
2017	29.8%	0.3%	0.5%	31.4%	0.3%	19.9%	17.7%	0.3%	4,049,365

U.S. DOE EERE (2019)

U.S. RENEWABLE ELECTRICITY GENERATION



U.S. DOE EERE (2019)

2018: Hydro/wind/solar 6.9%/6.5%/2.3% of total U.S. electricity generation

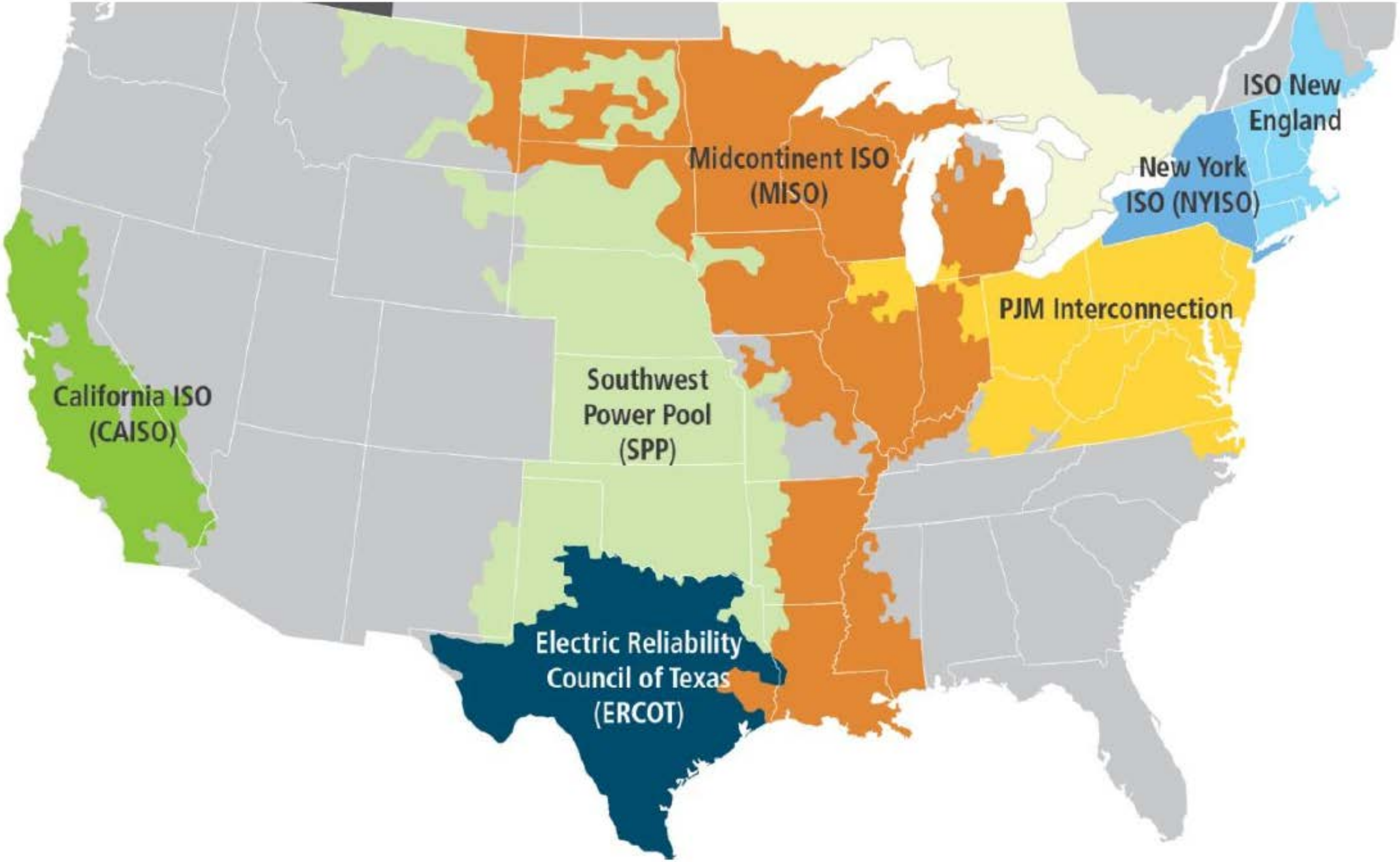
RENEWABLE ELECTRICITY IN U.S. AND EUROPE

Technology	United States		Europe (EU-28)	
	2005	2016	2005	2016
Hydro [%]	6.7	6.5	10.4	10.8
Wind [%]	0.4	5.5	2.1	9.6
Solar [%]	0.0	1.7	0.0	3.4
Biomass [%]	1.3	1.5	1.3	2.8
Other [%]	0.4	0.4	1.0	3.0
Total [%]	**8.8**	**15.6**	**14.8**	**29.6**
Total [TWh]	358.2	640.3	490.3	959.4

Sources: U.S. DOE (2018) and Eurostat (2018).

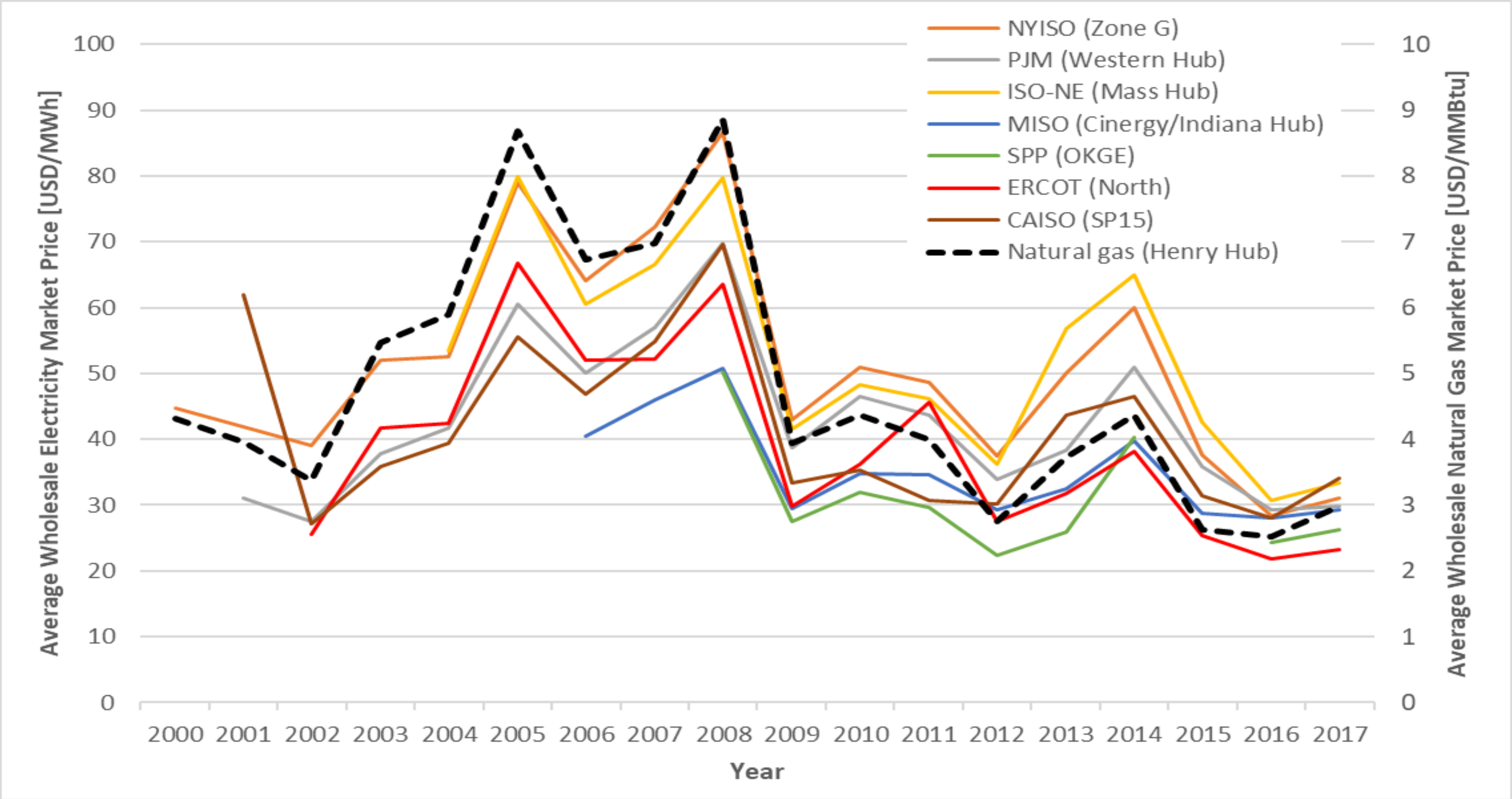
- About twice as much renewables in Europe compared to U.S.; similar growth rates
- Hydropower still the largest renewable electricity resource, followed by wind power

U.S. REGIONAL ELECTRICITY MARKETS



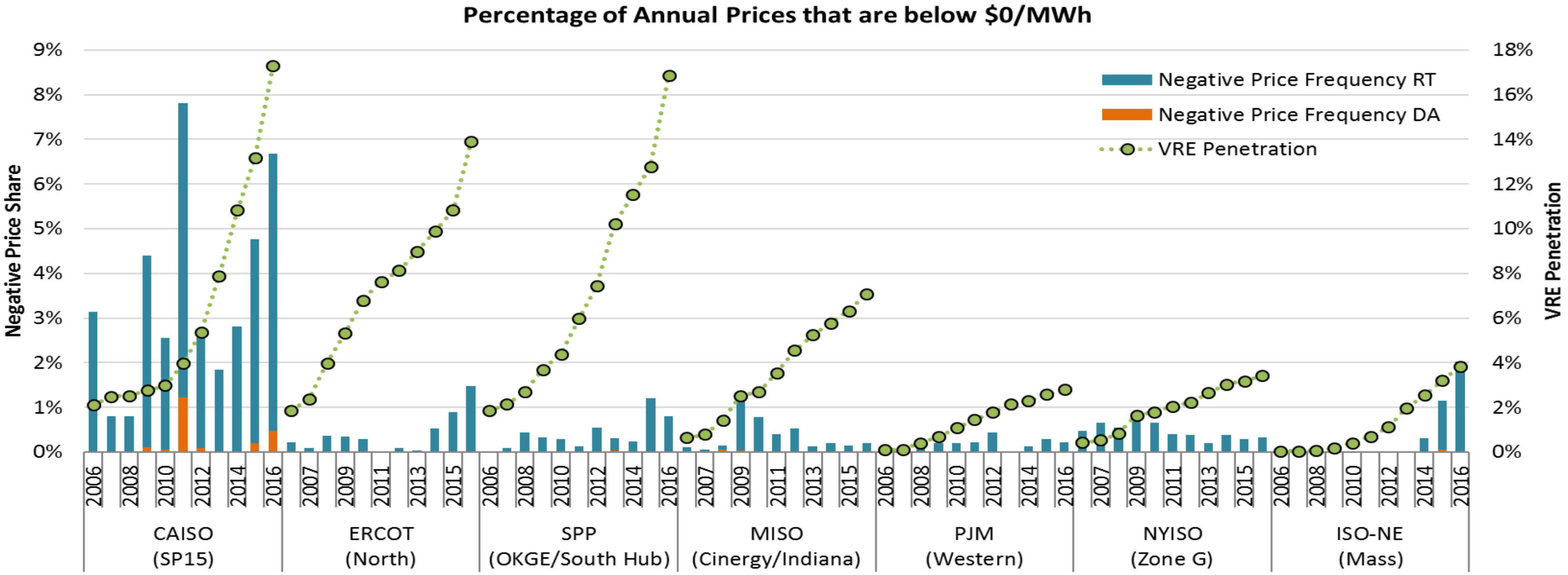
ISO/RTO Council

ELECTRICITY AND NATURAL GAS PRICES IN U.S.



VARIABLE RENEWABLES INFLUENCE MARKET PRICES

- The merit order effect reduces electricity prices
  - Empirical literature indicates a larger effect in Europe than the U.S.
  - Lower natural gas price main reason for lower electricity prices in U.S.
- The occurrence of negative prices has increased with higher VRE penetration



Wiser et al. , LBNL/ANL Report, Nov. 2017.

ELECTRICITY MARKET OPERATIONS: U.S. VS. EUROPE

- **United States**
  - Build into existing system operators (ISOs)
    - Short-term system operation
    - ISOs do not own transmission system
    - ***Emphasize physics of the power system***
  - Short-term market operations
    - Day-ahead market (ISO - hourly)
    - ***Real-time market (ISO - 5 min)***
    - Complex bids/ISO UC
    - ***Locational marginal prices***
    - Co-optimization of energy and operating reserves
    - ***More centralized control through ISO***
  - Variable renewable energy
    - Intermittent policy support
    - Tax credits, renewable portfolio standards
    - ***“Dispatchable” VRE***
  - Retail competition
    - Retail choice in some states

- **Europe**
  - Introduced new power exchanges (PXs)
    - Include long-term contracts
    - TSOs typically own transmission system
    - ***Emphasize markets and economics***
  - Short-term market operations
    - Day-ahead and intraday markets (PX)
    - Real-time balancing markets (TSO)
    - Simple bids/generator UC
    - ***Zonal pricing/market coupling***
    - Sequential reserve and energy markets
    - ***Market based, decentralized balancing through balance responsible parties***
  - Variable renewable energy
    - Strong policy support
    - Feed-in tariffs - premiums, tenders/auctions
    - ***VRE as “must-take”***
  - Retail competition
    - Retail choice in all countries

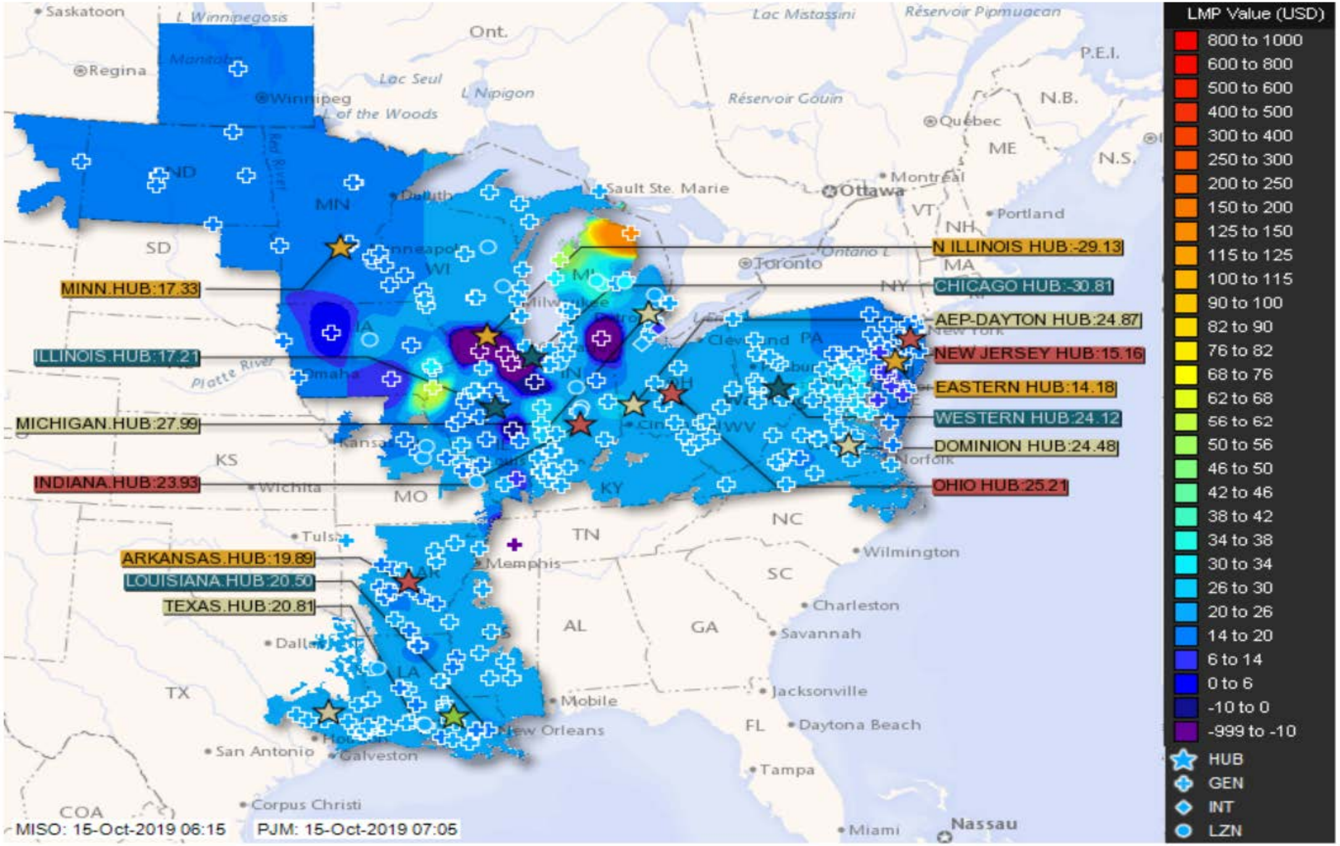
Botterud and Auer, EEEP, 20(2), 2020.

LOCATIONAL MARGINAL PRICES (LMPS)

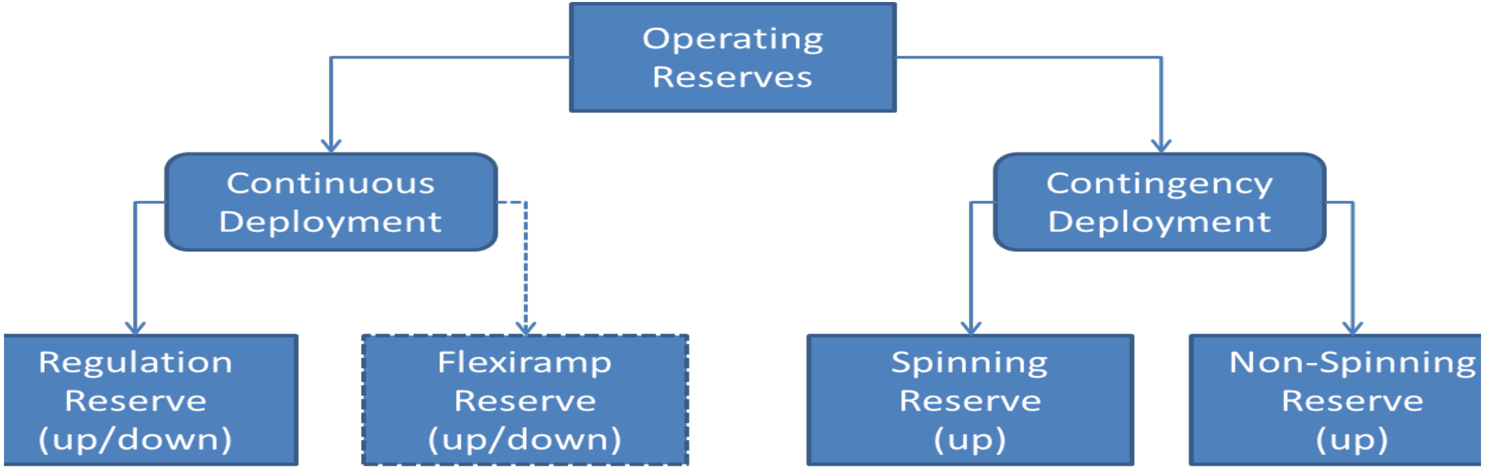
Real-time prices (Oct 15, 2019, 7:05):

PJM (11,600 price nodes)

MISO (2,200 price nodes)

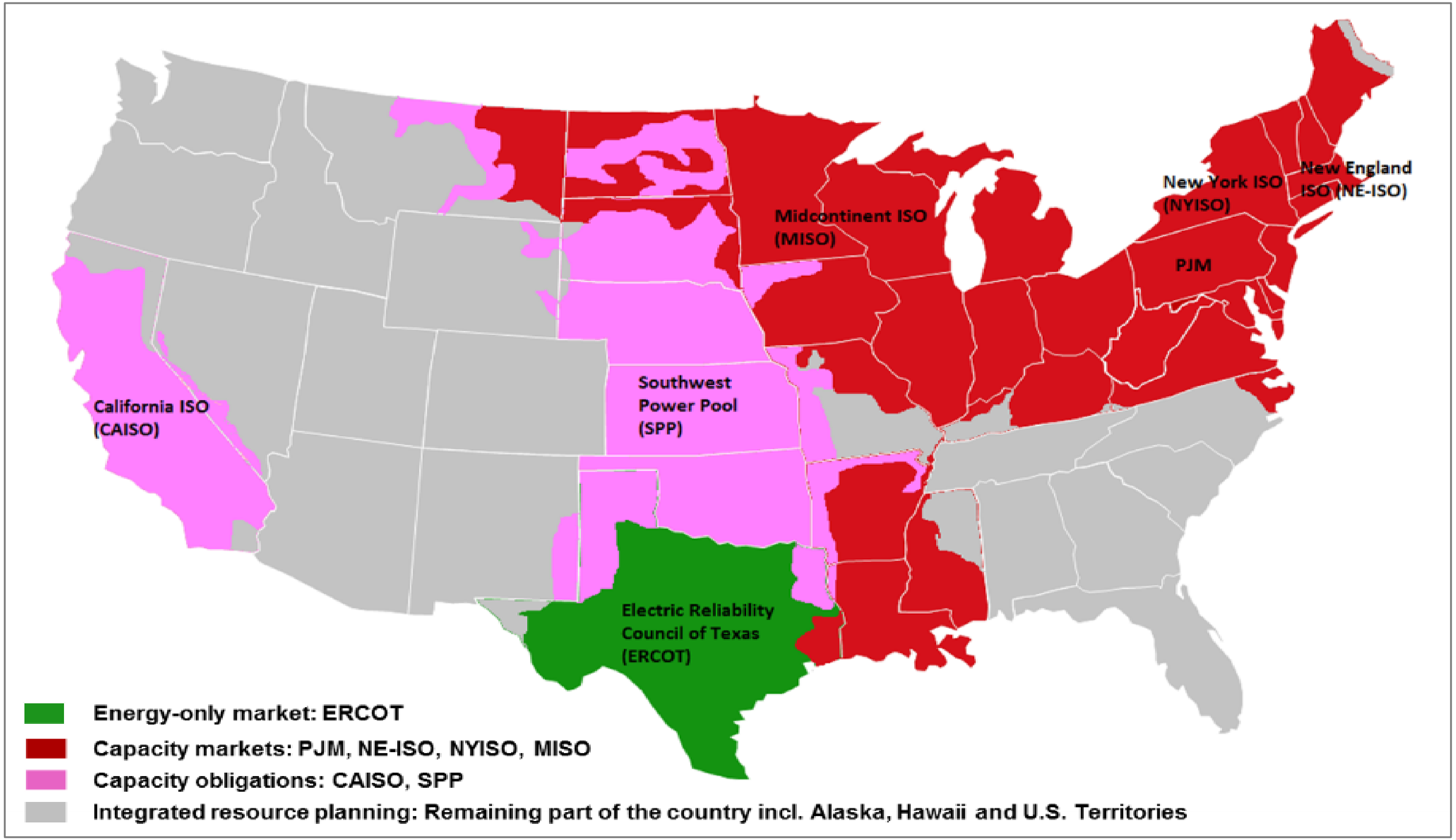


EVOLVING ANCILLARY SERVICES MARKETS



- Recent developments
  - More dynamic assessment of reserve requirements
  - Regulation reserve: Pay for performance incentives
  - “Flexi-ramp reserves” to ensure sufficient ramping capability available in real-time
    - California ISO (CAISO)
    - Midcontinent ISO (MISO)
- No compensation for primary frequency response

CAPACITY REMUNERATION MECHANISMS IN U.S.



Botterud and Auer, EEEP, 20(2), 2020.

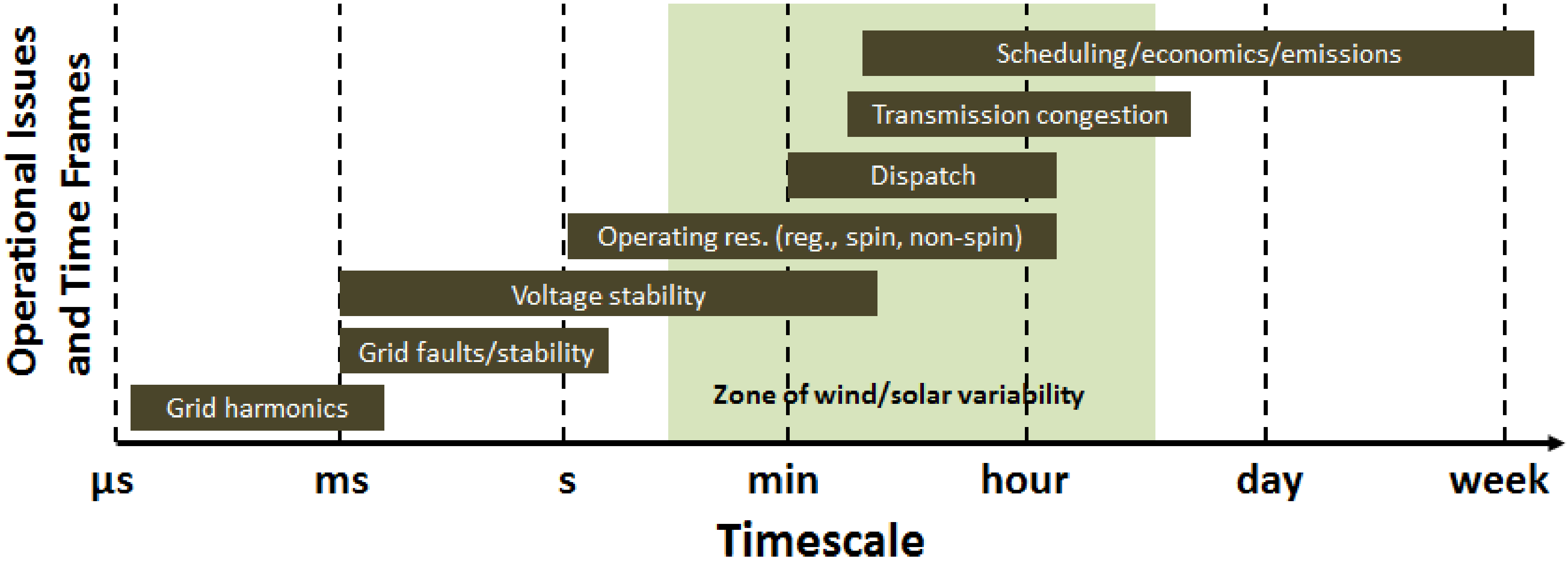
MARKET ACCESS FOR PUMPED STORAGE HYDRO

ISO/RTO	Participation Model	Capacity	Energy	Regulation	Operating reserves
CAISO	Pumped storage hydro	N/A	Yes	Yes	Yes
ISO-NE	Dispatchable-asset-related demand pump	Yes	Yes	Yes	Yes
MISO	Long-term storage resource	Yes	Yes	Yes	Yes
NYISO	Energy limited resource	Yes	Yes	Yes	Yes
PJM	Pumped hydro	Yes	Yes	Yes	Yes
SPP	-	N/A	Yes	Yes	Yes

Kwon and Botterud, forthcoming.

Other energy storage technologies use different market participation models that do not necessarily provide access to all relevant markets (FERC Order 841)

OPERATING THE POWER GRID IS COMPLEX



Adapted from Fisher et al. 2012

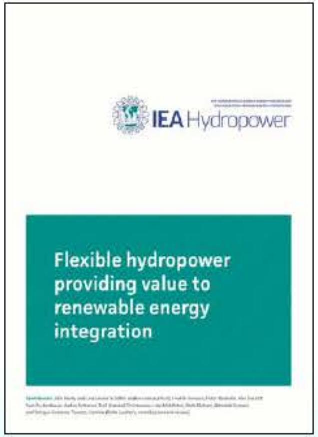
Handling uncertainty and variability in a cost-effective manner is a key challenge.

IEA Hydropower

THE INTERNATIONAL ENERGY AGENCY TECHNOLOGY COLLABORATION PROGRAMME ON HYDROPOWER

Presentation of White Paper no 1

Flexible hydropower providing value to renewable energy integration


IEA Hydropower

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White Paper no 1 - October 2019

CONCLUSIONS

- U.S electricity markets
  - Evolving resource mix
  - Market design reflects the physics of the power grid
  - High precision pricing (high-resolution LMPs) do incentivize flexibility
  - Challenges include adequate compensation for all grid services
- Hydropower in electricity markets
  - Large-scale provider of flexibility at different timescales
  - Enabler of variable renewable energy
  - Important to assess operational flexibility, including constraints and costs
- Research interests
  - Operations and planning under uncertainty
  - Electricity markets for the future power grid
  - Flexibility provisions: software vs. hardware solutions
  - Energy systems integration

REFERENCES

Kwon J., Botterud A., “Participation Models for Pumped Storage Hydropower in Electricity Markets,” White Paper, DOE HydroWires, forthcoming.

Botterud A. and Auer H., “Resource Adequacy with Increasing Shares of Wind and Solar Power: A Comparison of European and U.S. Electricity Market Designs,” *Economics of Energy & Environmental Policy*, Vol. 9, No. 2, 2020. (Also: MIT CEEPR Working Paper 2018-08).

Harby A. et al., “Flexible hydropower providing value to renewable energy generation,” white paper, IEA Hydro Annex IX, Oct. 2019.

U.S. Dept. of Energy, Office of Energy Efficiency and Renewable Energy, “2017 Renewable Energy Data Book,” 2019.

Uría-Martínez R., Johnson M.M., O’Connor P.W., “2017 Hydropower Market Report,” U.S. DOE WPTO, April 2018.

Koritarov V. et al., “Modeling and Analysis of Value of Advanced Pumped Storage Hydropower in the United States,” Argonne National Laboratory Report ANL/DIS-14/7, Argonne, IL, June 2014.

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