Data source: Iyer et al. 2017, GGCAM USA Analysis of U.S. Electric Power Sector Transitions (performed for the United States Mid-Century Strategy for Deep Decarbonization), Pacific Northwest National Laboratory; 2020 zero-carbon electricity supply from EIA Annual Energy Outlook 2019. For nuclear retirements: 8 GW of planned nuclear retirements through 2030, half of the fleet assumed to operate through 2050 (requiring 80 year licenses); 2040 a linear interpolation of 2030 and 2050.
NEW CLEAN ELECTRICITY NEEDED: WARREN (INSLEE) PLAN

NEW CLEAN ELECTRICITY NEEDED: SANDERS PLAN

Electrification Scenarios

Clean energy additions

- Mid: +33 avg GW/yr
- High: +26 avg GW/yr
- Low: +21 avg GW/yr

Terawatt-hours

Electricity: the Linchpin

Three Big Challenges

#1. The Race Between Declining Cost & Value
#2. Firm Low-Carbon Resources Needed
#3. Securing Social License
Wind and PV affect system reliability

System Stability
- High penetrations of inverter-based resources (IBR)
  - Frequency stability
  - Transient stability
  - Small-signal stability

System Balancing
- Wind and solar variability and uncertainty
- Diurnal mismatch of supply and demand
- Reducing curtailment
- Ramping needs

Resource Adequacy
- Seasonal mismatch of supply and demand
- Periods of low wind/solar/hydro
- 1 day in 10 years Loss of Load Expectation

100% Clean Energy is possible with today’s technology/know-how. The question is: Can we do this smarter, cheaper, and by 2050?
Moderate annual averages can cause high instantaneous penetrations

We’ll hit 100% instantaneous long before hitting 100% annual average

Source: Drake Bartlett, Xcel 2018
Illustrative difficulty of increasing variable renewables

Resource adequacy is challenging if we eliminate fuel-based resources.

Balancing challenges will get worse.

Transient/small-signal stability becomes difficult around ~75% instantaneous penetration for a pocket of the system.

Frequency stability is challenging if we try to operate with 100% inverters.
Potential solutions

- Grid-forming inverters/synchronous condensers
- Electrification, demand response and energy sector coupling
- Long-term storage or power-to-fuels
We need to integrate other energy sectors

Estimated U.S. Energy Consumption in 2017: 97.7 Quads

D. Lew, GE Energy Consulting, 2018
Monthly highest percentage of load served by RPS from January 2017 through October 2019

Percentage of Load Served by RPS
2017 --- 2019

RPS: wind, solar, biomass, biogas, geothermal and small hydro
Monthly highest percentage of load served by RPS from January 2017 through October 2019.

RPS: wind, solar, biomass, biogas, geothermal and small hydro