# Power Electronics Implementation of Dynamic Thermal Inertia to Offset Stochastic Solar Resources in Low-Energy Buildings

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# Background – Low-energy and net-zero energy buildings

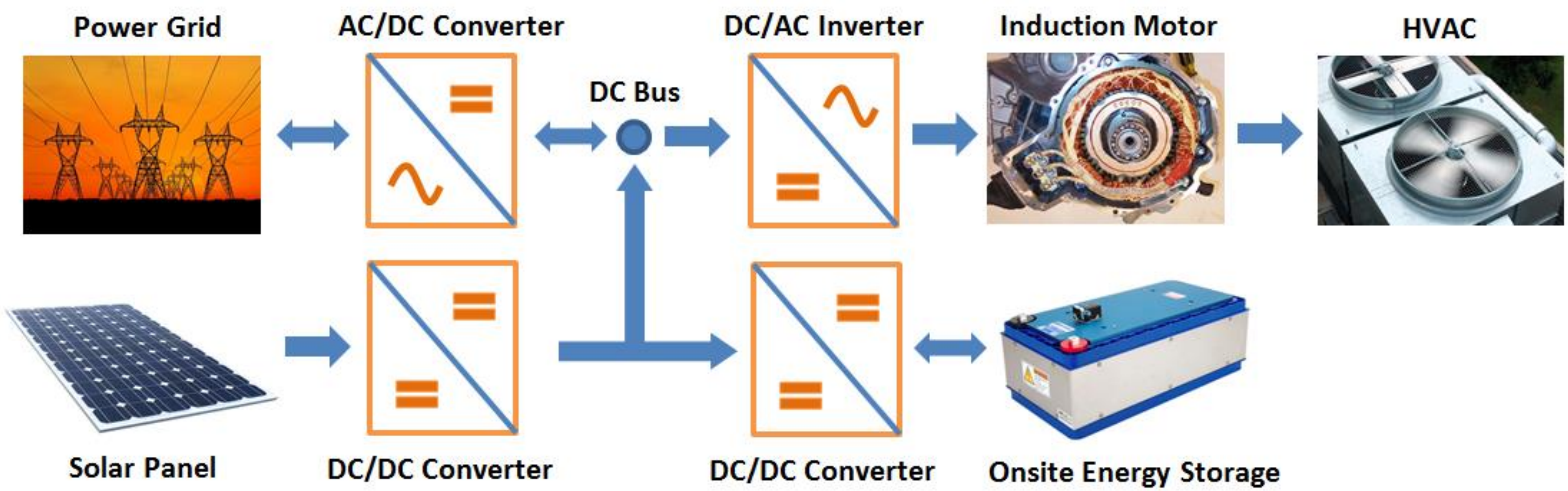
- Onsite renewable energy, such as solar power, supports building consumption and sends excess power to electricity grid
- Net-zero buildings provide all their own energy on average over a full year
- Multi-disciplinary challenges: Improved construction materials, lighting systems, air conditioning, and thermal insulation
- Low-energy buildings are integrated systems of renewable energy generation, advanced space conditioning, EV charging, and storage

Research Support Facility at the National Renewable Energy Laboratory (source: nrel.gov)

Upcoming Apple headquarters (source: news.sky.com)

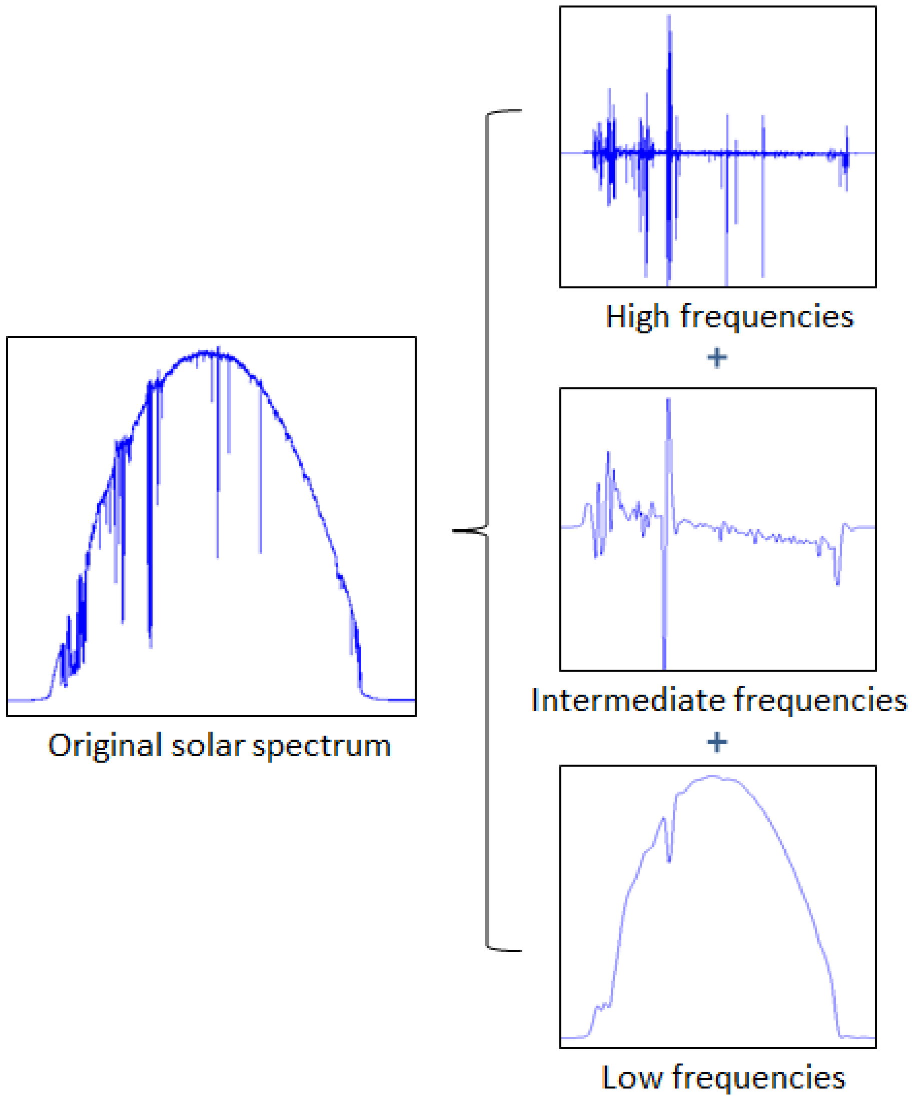
# Background – Energy elements in low-energy buildings

- Solar panels are the typical renewable energy source
- Grid connection is retained
- Onsite energy storage, such as batteries or supercapacitors
- Hot and cold water: water heating ~6% energy usage in buildings.
- Heating, ventilation, and air conditioning (HVAC) uses 40-60% of energy in a typical large building
- Energy converted and controlled via power electronics



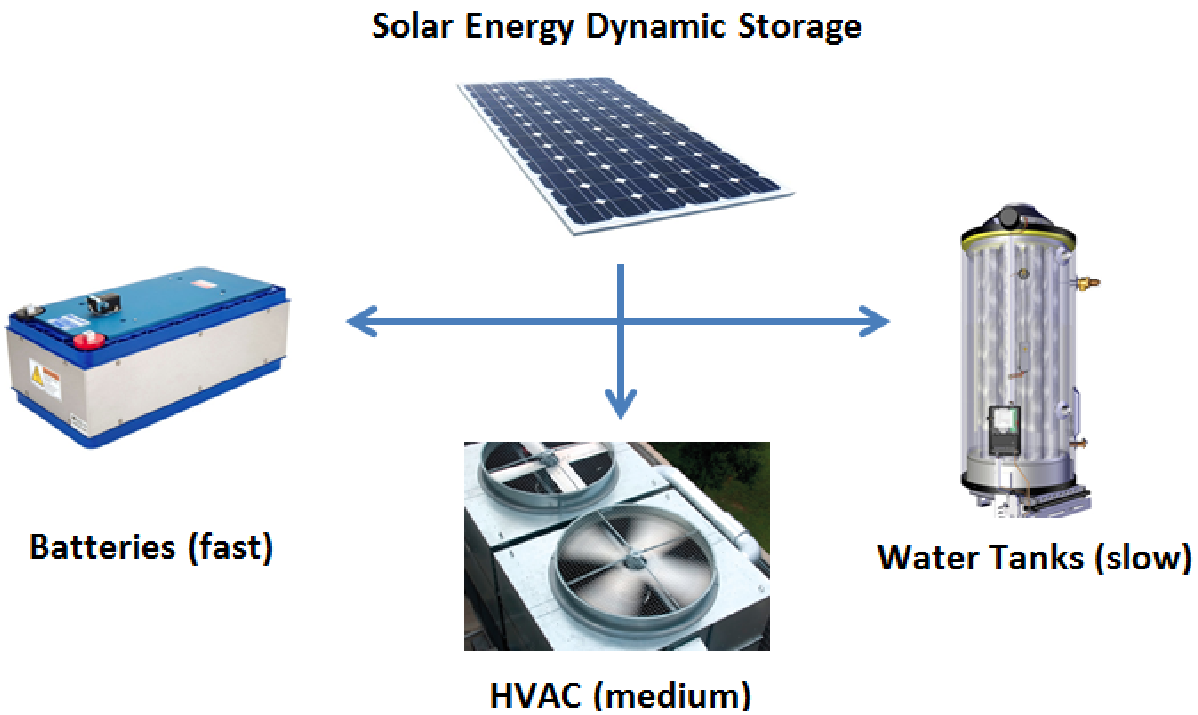
# Challenges with varying solar power

- Solar panel power varies rapidly due to clouds and other factors
- Solar spectrum contains high frequency (sub-sec to sec), medium frequency (min), and low frequency (min to hour) components
- Unpredictable fast changes challenge the grid
- Utilities suggest that new fast dynamic fossil capacity must be added as new solar resources are added



# Can fast solar changes be buffered locally?

- Batteries or supercapacitors can filter rapid power changes, but substantial size and costs are involved
- Water tanks can be used for thermal storage for minutes to hours
- Can HVAC systems "filter" the varying solar energy by using building thermal inertia as "virtual storage"?



# HVAC filtering concept formulation

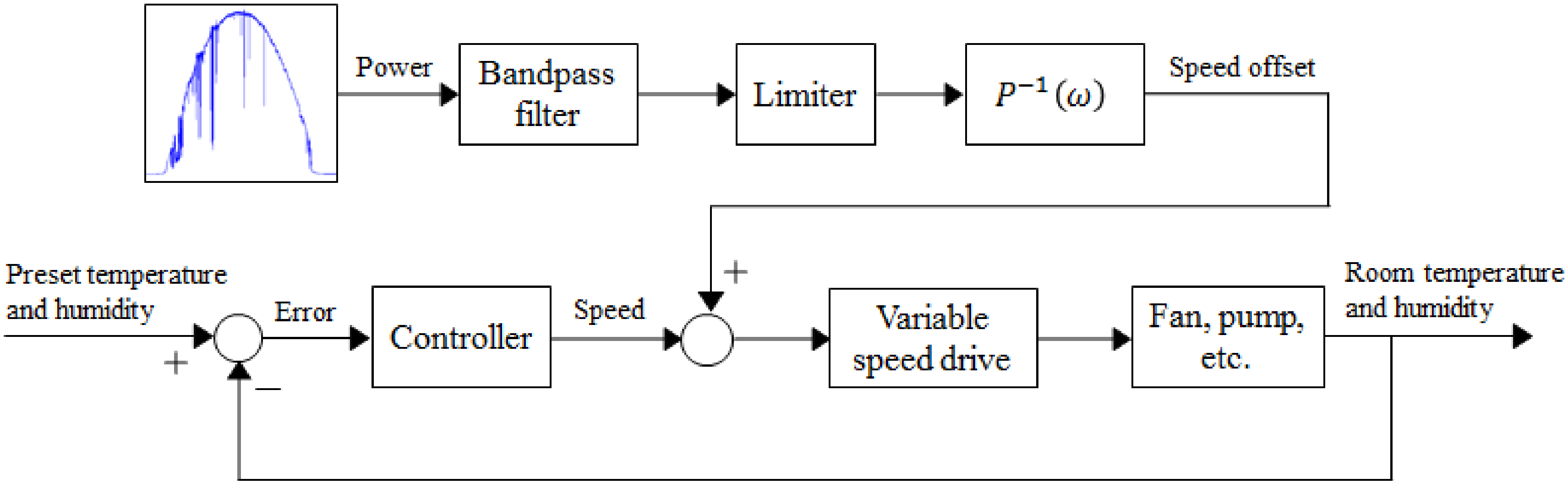
- HVAC energy filtering has upper and lower frequency limits, and amplitude limits
- Lower frequency limit: avoid impact on underlying HVAC control
  - Shield occupants from substantial temperature swings
  - Maintain all comfort targets
- Upper frequency limit: system reliability and operation
  - No undue wear and tear
  - No discomforting audible pitch or amplitude changes

Enthalpy wheel

- Rapid bang-bang control changes are ruled out

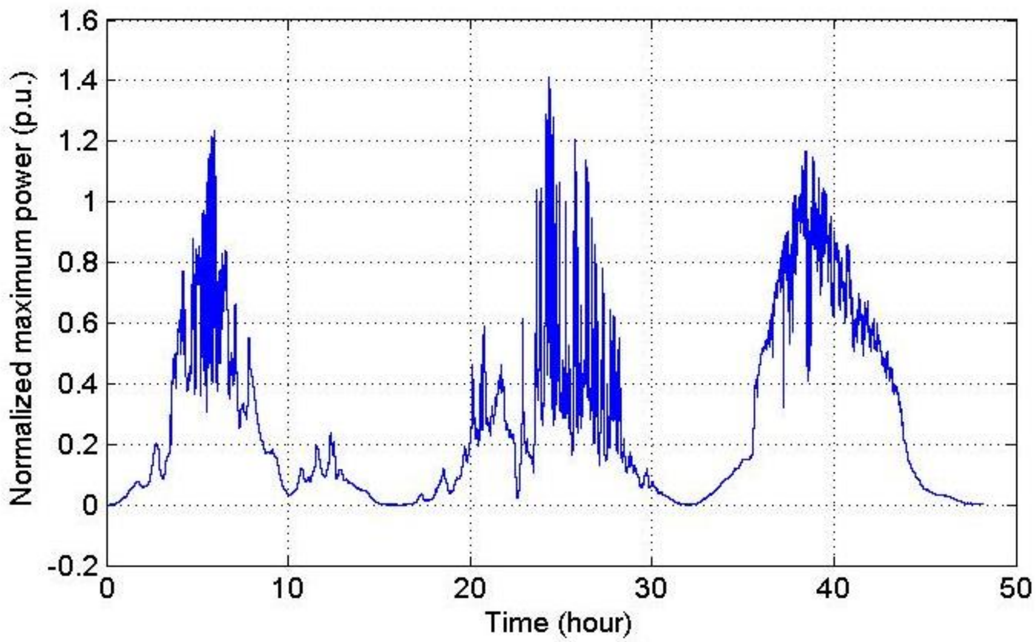
# Research contribution

- Employ power electronic HVAC drives as an effective electric swing bus
  - Determine bandwidth and amplitude limits of HVAC operation
  - Demonstrate effectiveness of the HVAC system for mitigating dynamic solar power changes
  - Quantify potential impacts on battery storage and grid regulation
- Demonstrate dynamic thermal storage implementation
  - "ac" feed-forward signal is injected into a fan drive to adjust power flow on fast time scales, while avoiding interference on slow time scales



# Frequency domain analysis of high frequency solar database

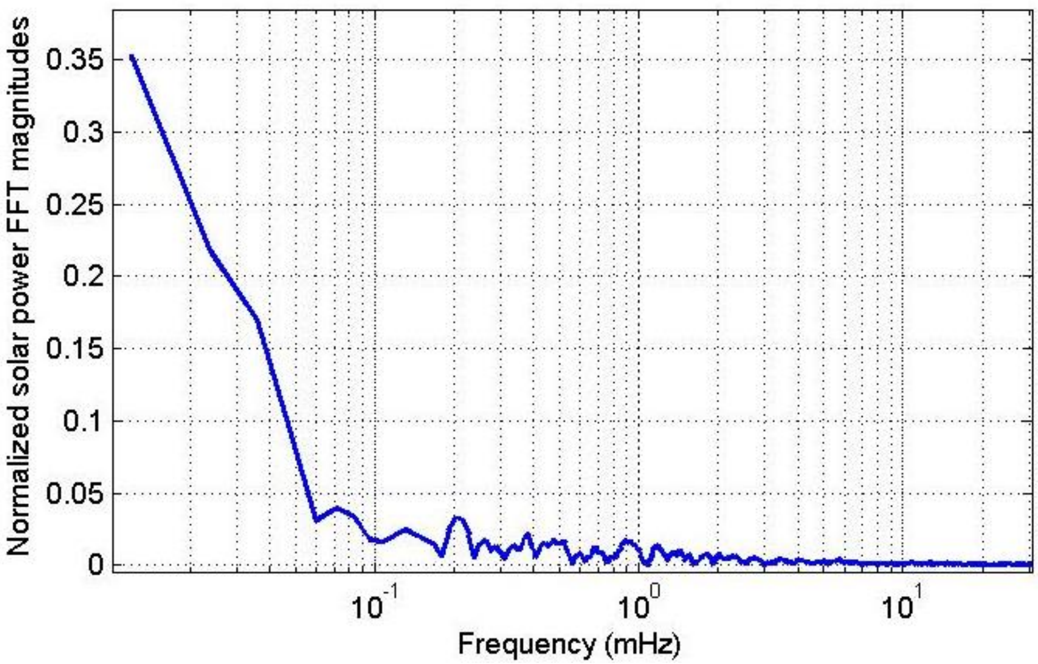
- 5 kHz (200 μs) solar data samples collected at University of Illinois from July 2012 through December 2013 (18 months)
- 50 Hz rate used, as higher frequency provides little info [4]
- Each day from 4 a.m. to 8 p.m. (16 hours)
- Random 100 days selected for analysis




Solar power profile from three sampled days (4 a.m. to 8 p.m. per day)

# Frequency domain analysis – Fourier transform (FT)

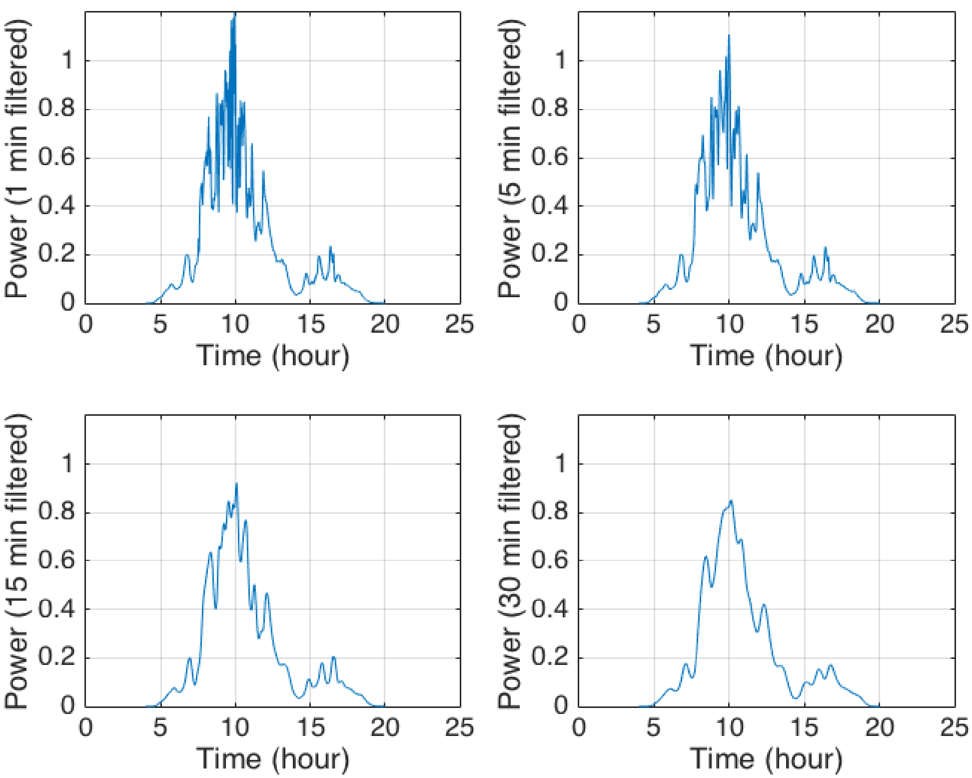
- Low frequency components: diurnal solar power changes and below
- Higher frequency components: dynamic cloud cover, etc.
- < 1 mHz (~15 min) associated with large FT magnitudes
- 1-20 mHz (~15 min to ~1 min) suitable for dynamic regulation
- > 20 mHz nearly absent



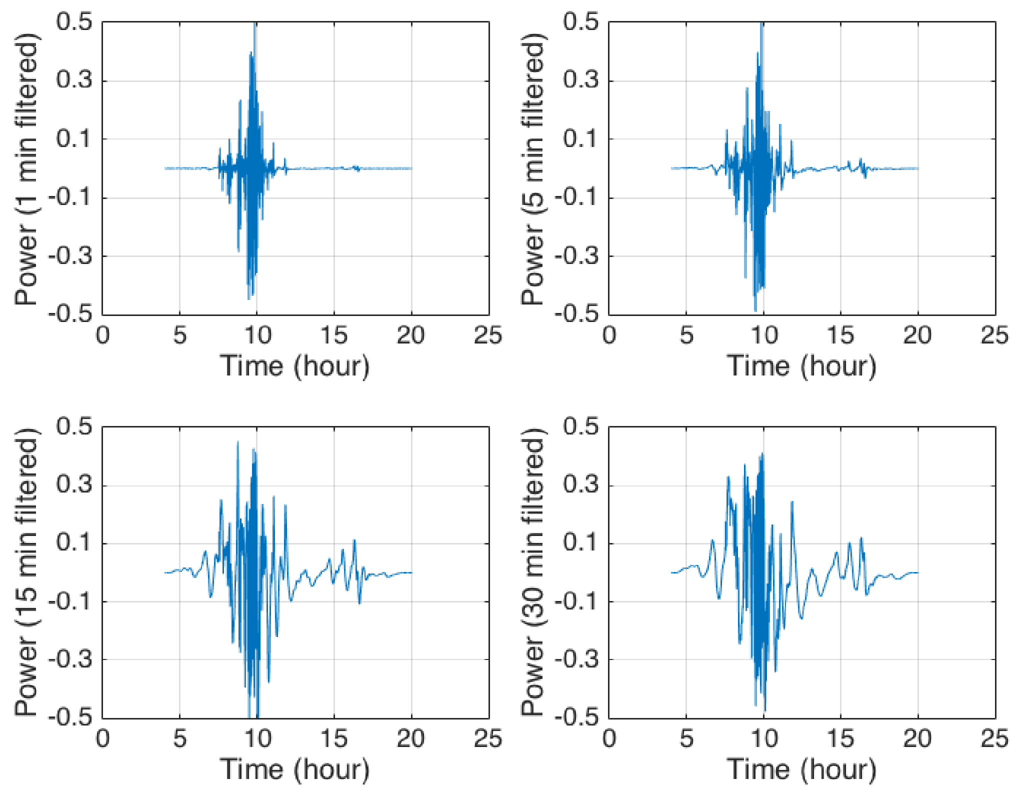

Solar power in frequency domain (semilog scale)

# Low pass filtering effects

- Solar energy variation faster than a defined frequency limit is filtered by the HVAC systems
- The band from 1 mHz to 33 mHz (1000 s to 30 s) appears to be of greatest interest for dynamic mitigation of solar resources



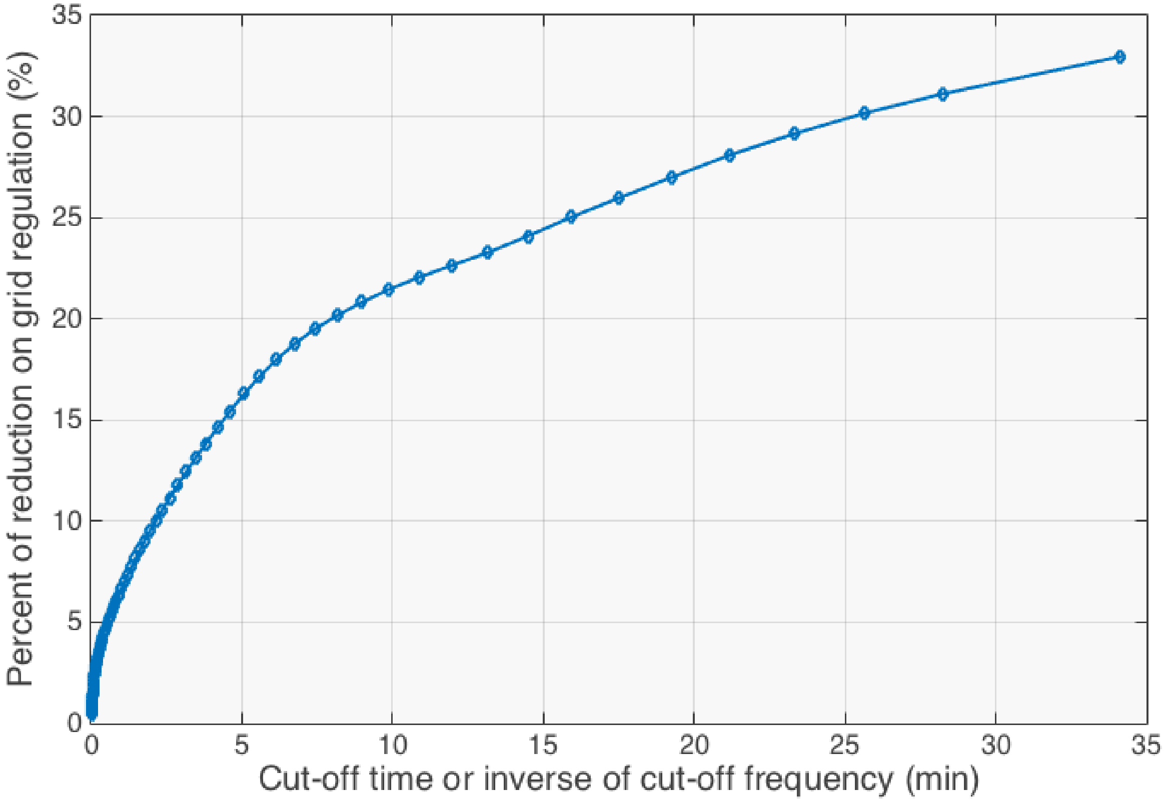

Solar power profile seen from the grid after HVAC filtering effect




Solar power to be filtered by the HVAC systems

# Grid regulation requirements can be reduced

- The reduction is about 5% for filtering that can achieve 1 min buffering, and 25% for 15 min buffering
- Average power and total energy demand from the grid are not altered – must maintain overall HVAC performance



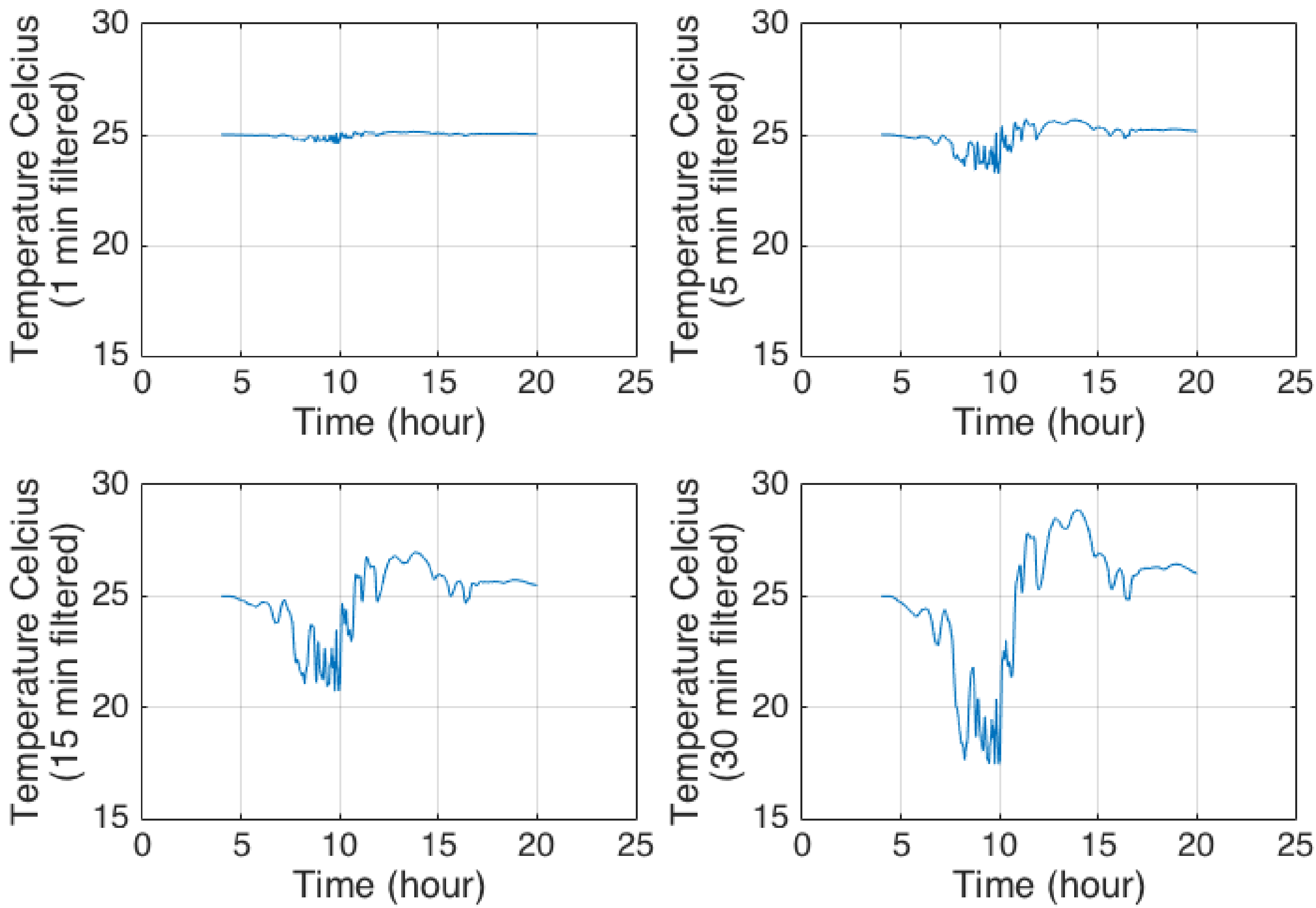

Percent of energy filtered for different cutoff intervals

# Electrical and thermal energy systems modeling

- First-order thermal model $$C\frac{dT(t)}{dt} = -\frac{1}{R_w}[T(t)-T_o(t)] + c_p\dot{m}(t)[T_l - T(t)] + Q_o$$
- Fan power, speed, air flow rate relationships

$$\dot{m}(t) = k_1\omega_{fan}(t)$$

$$P_{fan}(t) = k_2\omega_{fan}^3(t)$$




Room temperature profile for different filtering scenarios

# HVAC filtering lower frequency bound summary

- 1 mHz, the inverse of 15-minute intervals, is proposed to be an appropriate HVAC filtering lower frequency bound
- This bound coincides with existing electric grid 10-15 minute spinning reserve schedule

# Scaled fan drive experiment

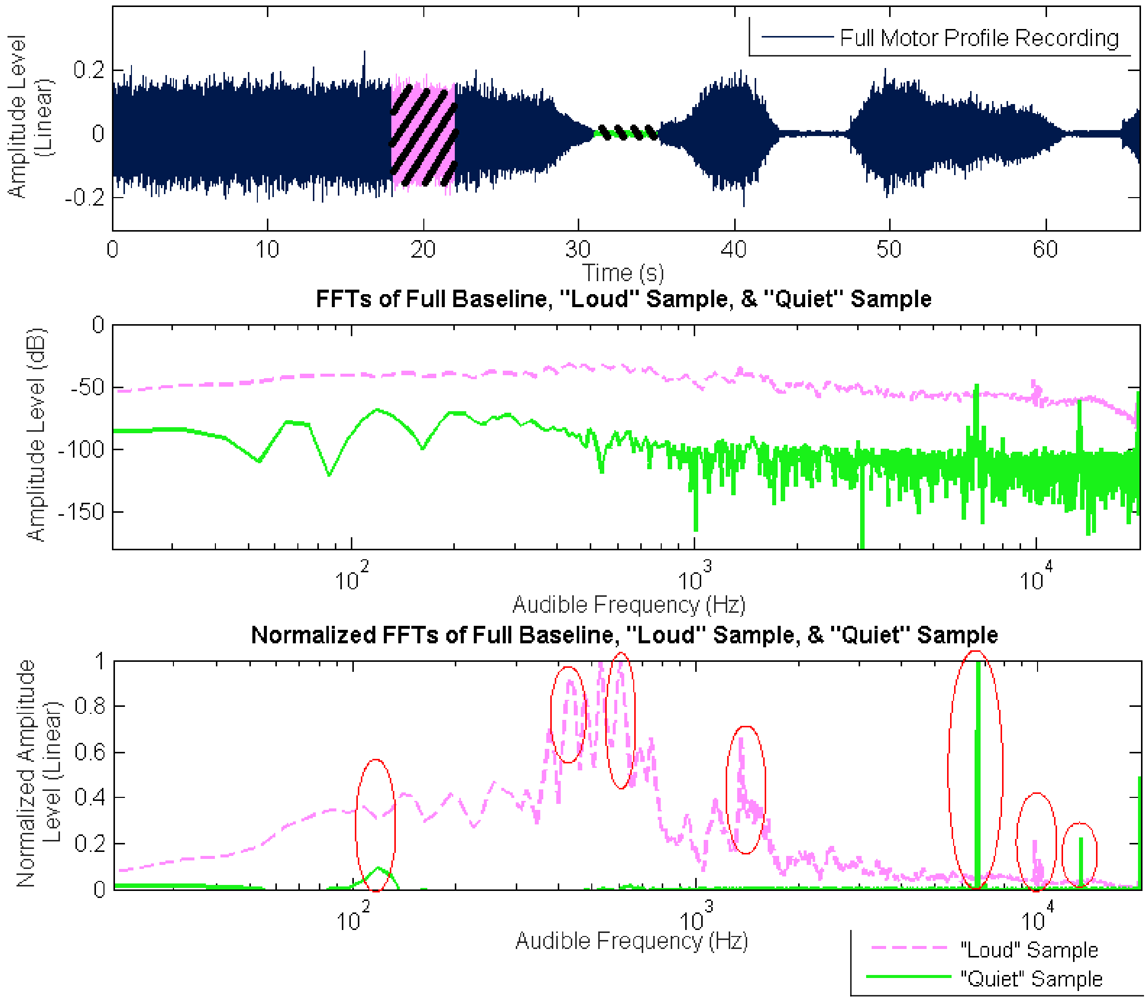
- Hardware capabilities, including motors and drives, in addition to physical structures such as ducts and vents, determine in part the HVAC filtering upper frequency bound
- 3-phase 480 V Yaskawa Z1000 commercial drive used to control fan speed
- A fan drive was characterized, and a 1/2 HP, three-phase, four-pole, induction machine was coupled with a squirrel-cage fan tied to a 4 m duct

$$P(\omega) = 1.152\times10^{-5}\omega^3 + 5.205\times10^{-4}\omega^2 + 1.224\times10^{-2}\omega + 6.538$$

- Fan drive digitally controlled via serial communication
- Microphone and sound recording

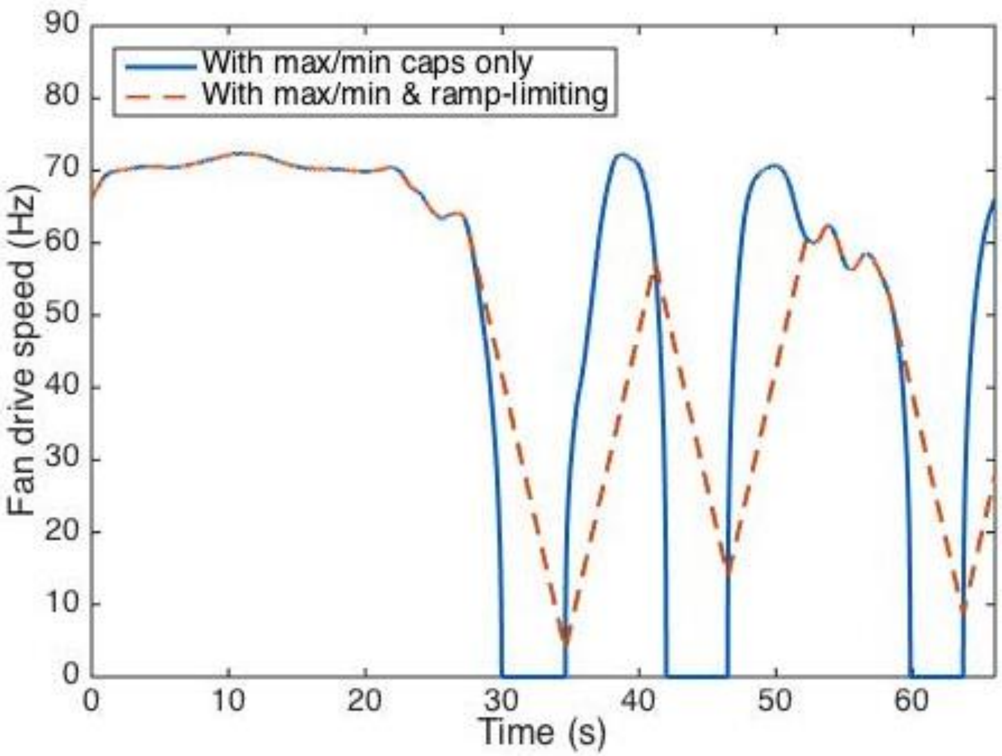
# Importance of acoustics concerns

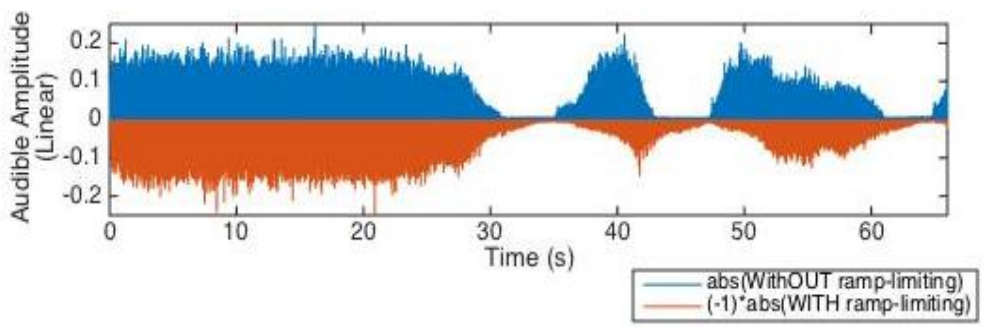
- Address two main characteristics of sound: pitch (frequency) and loudness (amplitude)



# Fan drive ramp-rate limitation

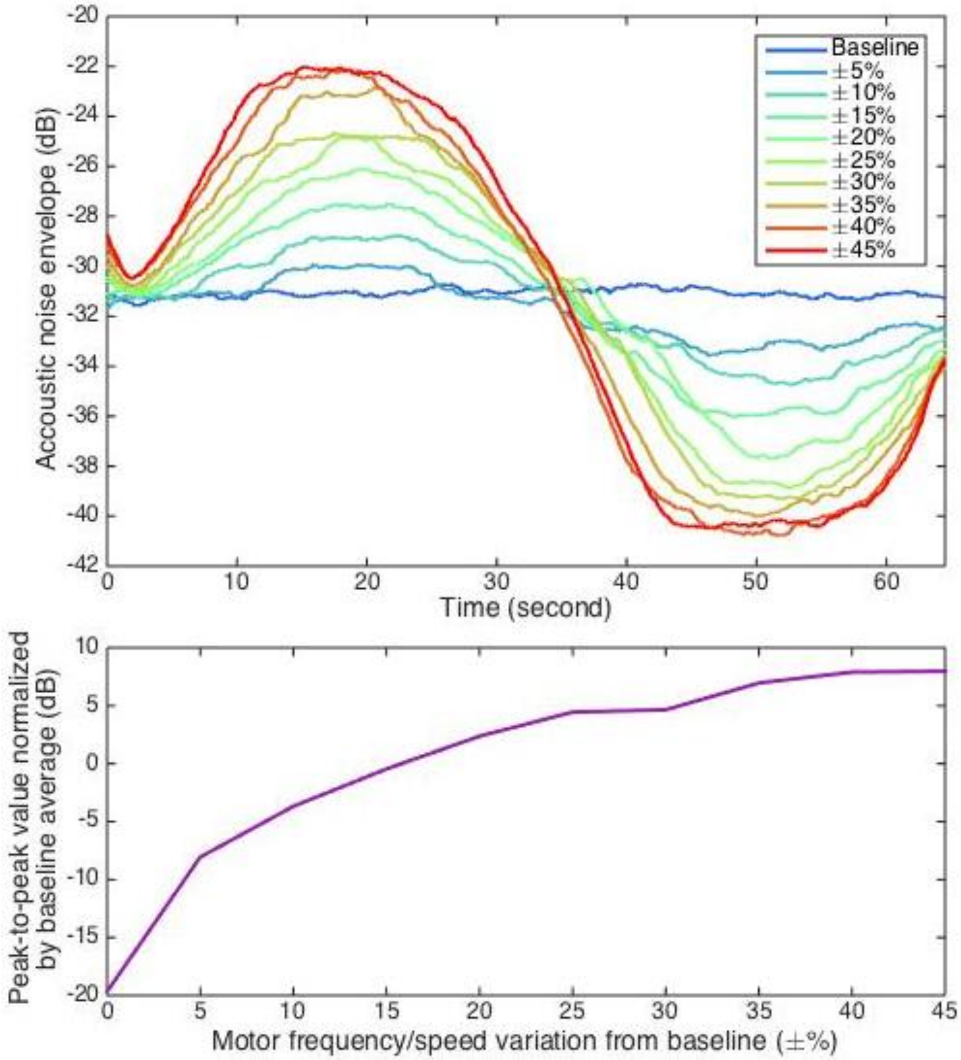
- Avoid obvious pitch (frequency) shifts in fans
- Absolute max and min of fan speeds, 0-150%, or 0-90 Hz
- Ramp-rate: how fast the fan can increase or decrease
- Ramp rate limit was determined to be 9 Hz/s, or 90 Hz in 10 s



# Acoustic amplitude limitation

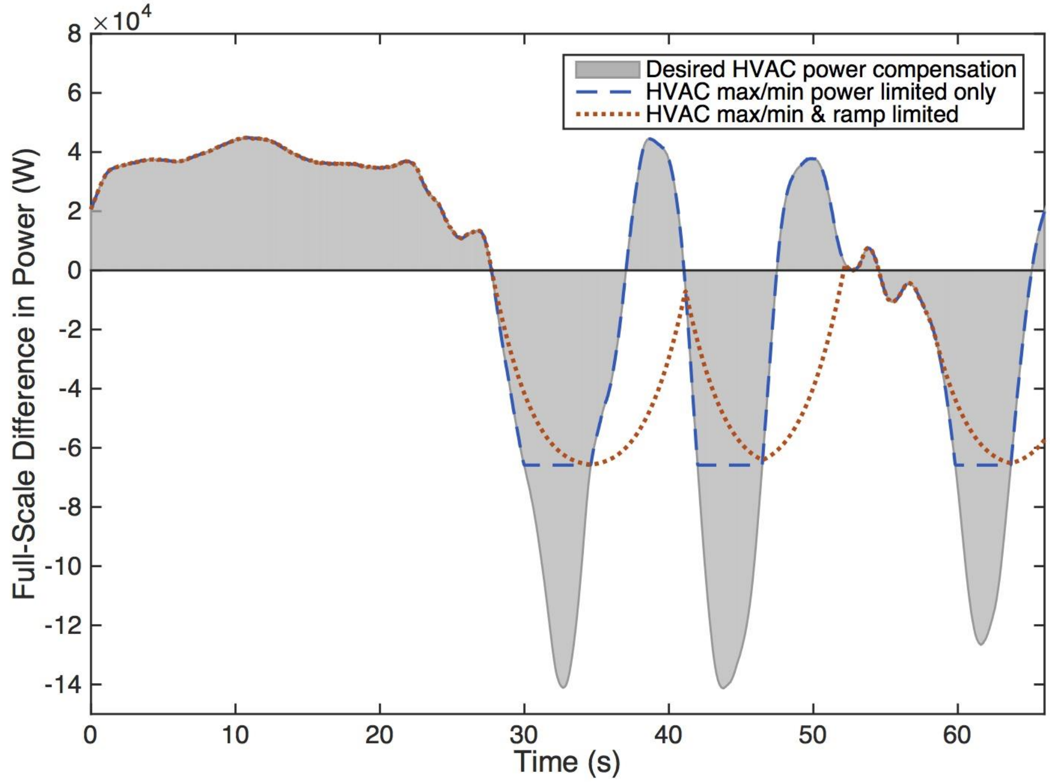
- Avoid obvious loudness (amplitude) shifts in fans
- Taking 60 Hz as a baseline speed, the speed amplitudes varied ±5%, ±10%, …, ±45%, with 90 Hz as the absolute maximum speed
- Peak-to-peak change equal to the baseline magnitude, ±16%, found to be imperceptible
- Amplitude limits using absolute fan speed changes of ±10 Hz are implemented



# HVAC filtering capability

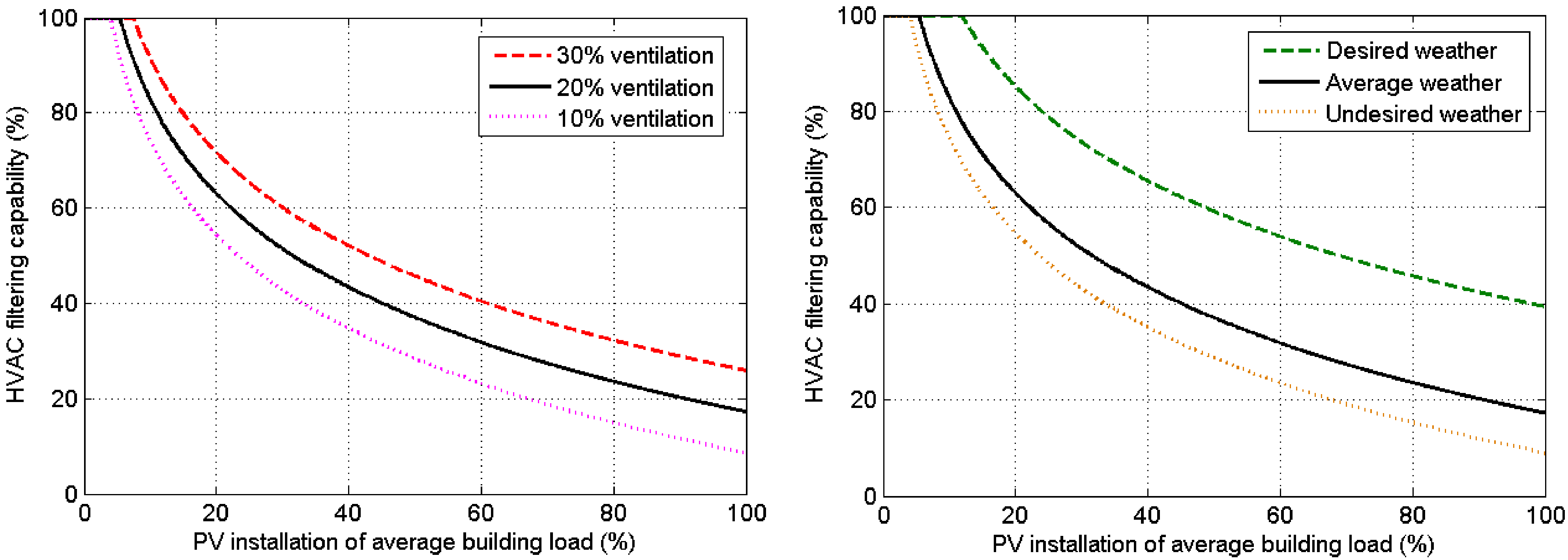
- Integrating the area under the dashed curve and under the gray region and then finding the ratio between the two
- There are times during which the HVAC filter is potentially counterproductive because of acoustic-based slew limits

Desired power compensation requested from full-scale HVAC systems with and without speed clamps and ramp limiting



# Filtering capability under constraints

- Depends on solar installation percent of the total building loads
- Depends on percent of HVAC energy used in total building loads
  Ventilation, for example, is part of the HVAC loads
- Building's regional weather pattern affects the HVAC filtering capability

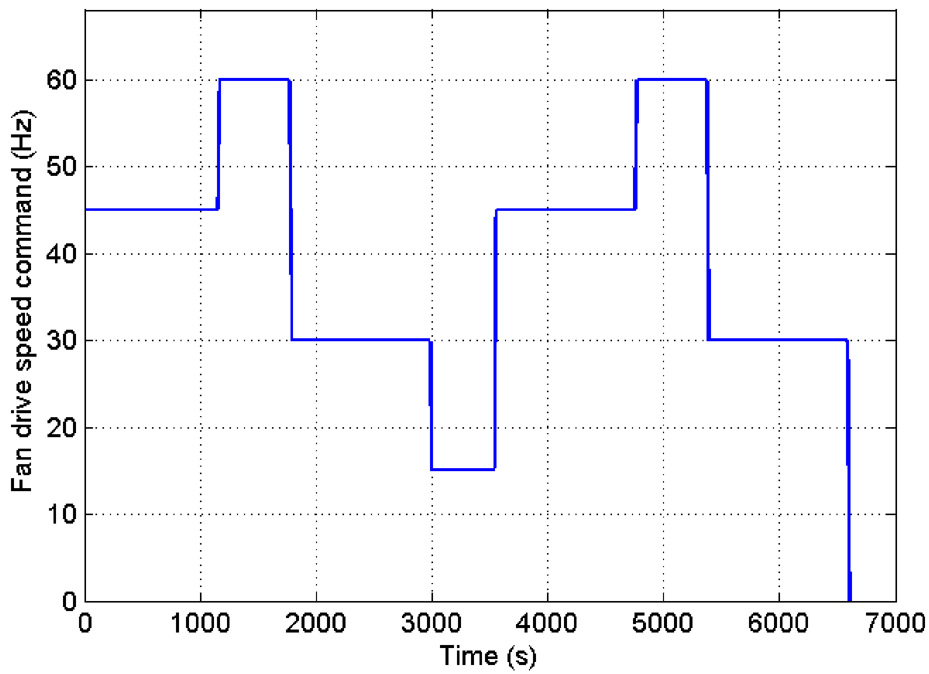


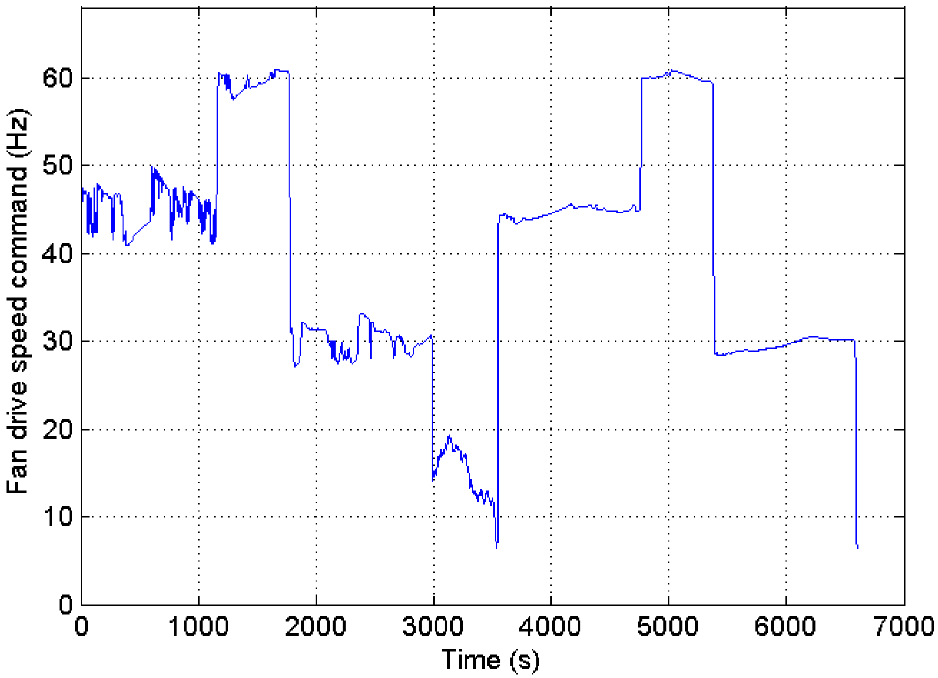
# HVAC filtering upper frequency bound summary

- 0.1 Hz, or inverse of 10 s interval, to be a plausible upper frequency bound
- Acoustic frequency changes and amplitude limits impose extra constraints on the control of the fan drive operation

# Case study demonstration (small scale)

- A small fan drive first used to follow scaled responses to various band-limited solar power profiles
- Z1000 drive with motor and duct fed with two speed command profiles for approximately two hours
- The second speed profile implements the ac signal injected control

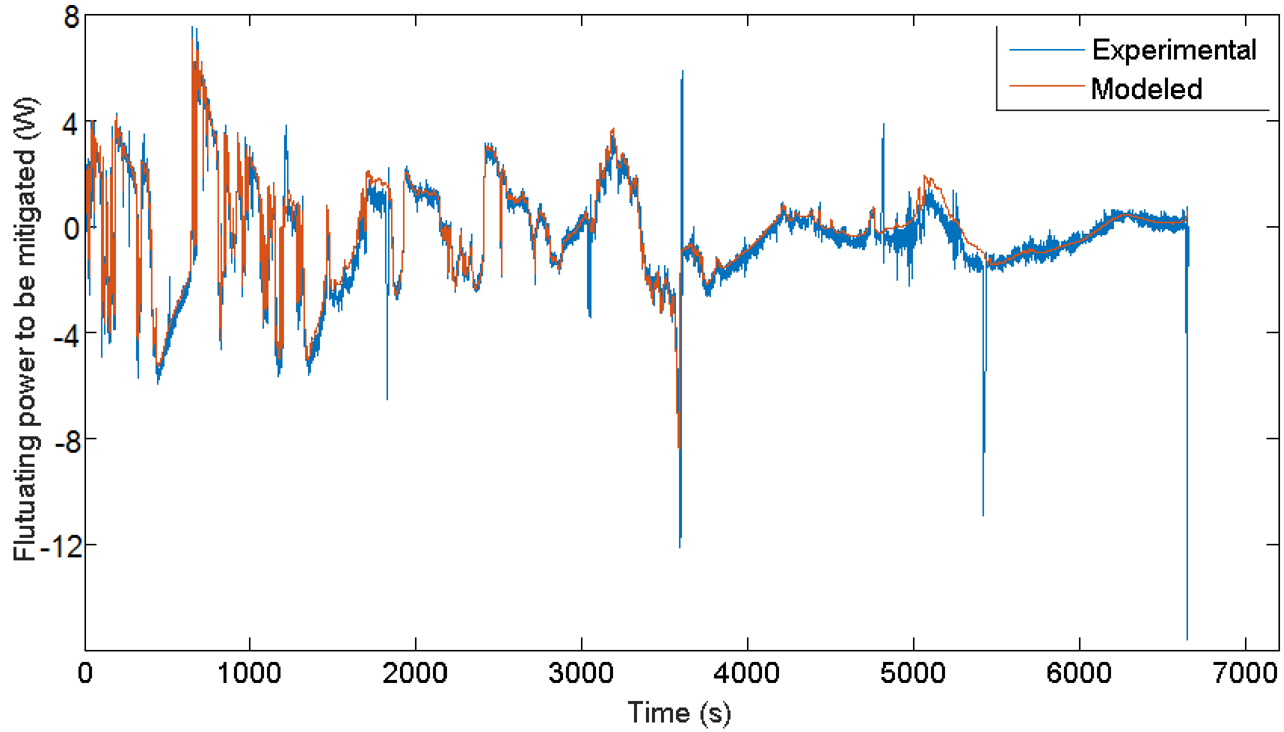



Fan drive speed profile without (a) and with (b) dynamic HVAC filtering

# Case study demonstration (small scale)

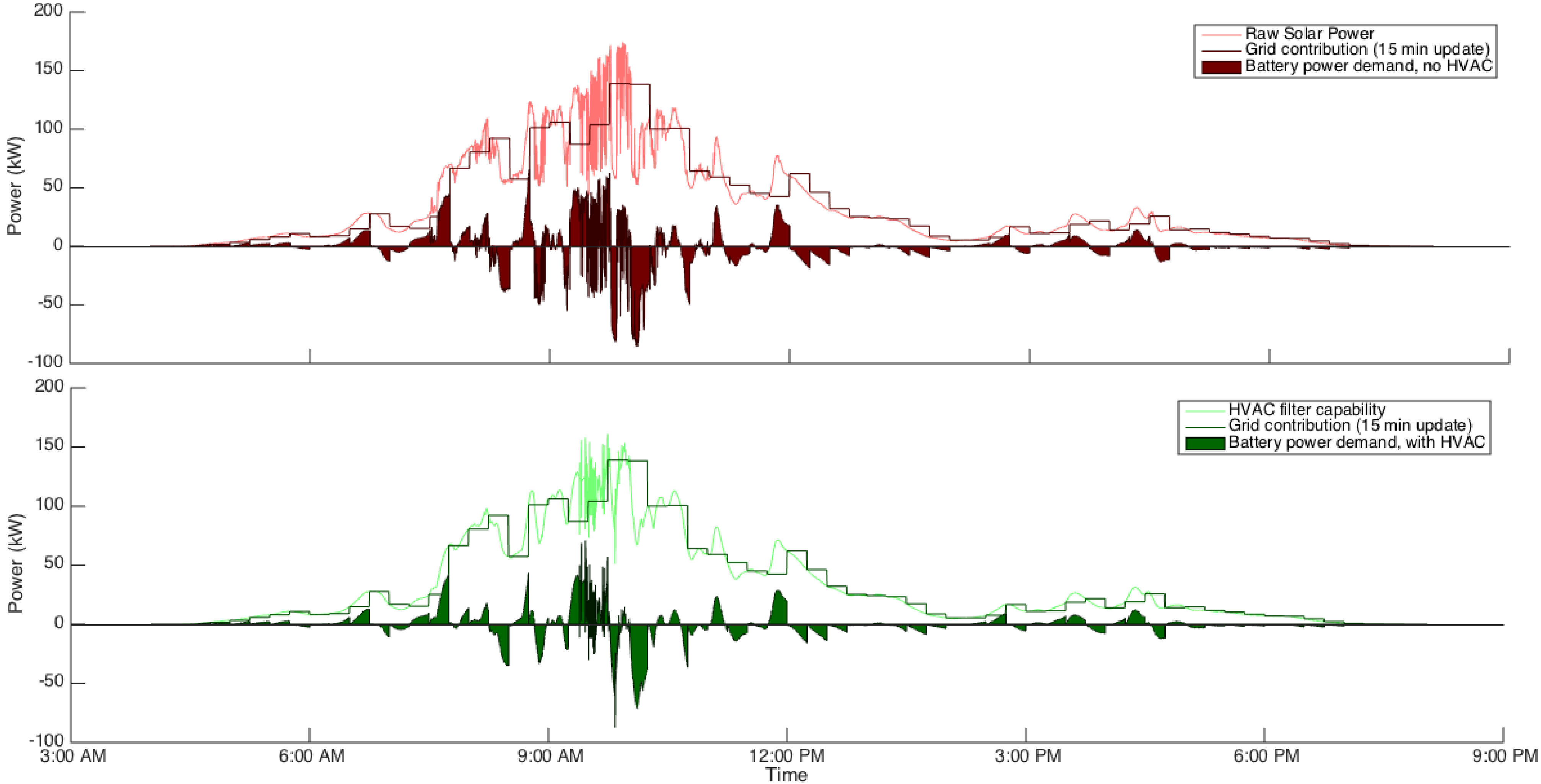
- Experiments collected two sets of power consumed by the fan system and measured the difference, which represents the fluctuating power to be mitigated.
- The modeled curve follows the experimental curve closely, providing an accurate basis for a large scale multiple-day simulation.




Power difference consumed by the fan drive between the two speed profiles.

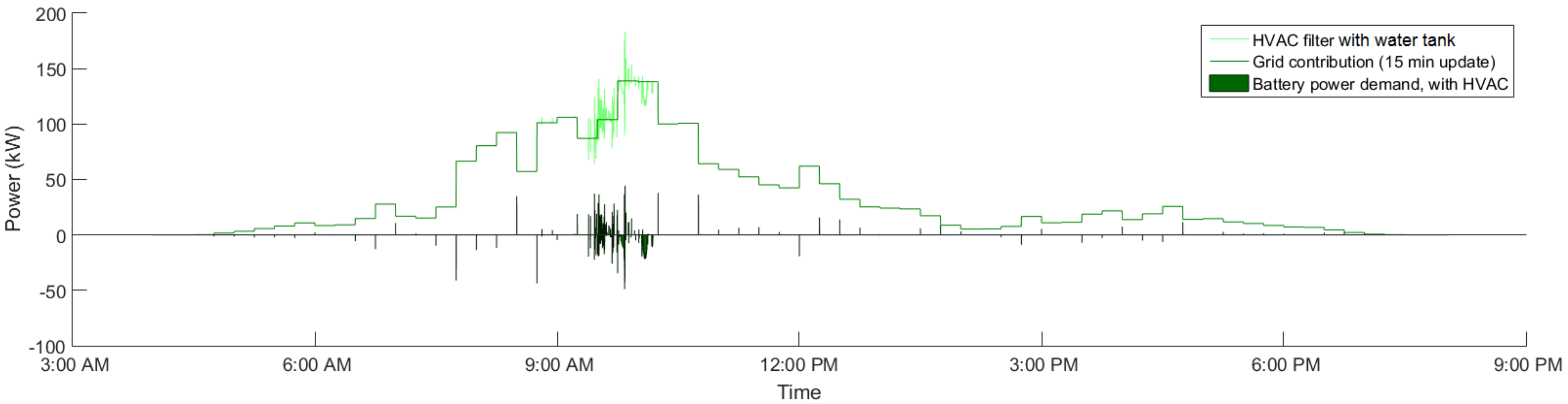
# Case study demonstration (full scale)

- Assume an energy efficient building with solar installation at peak 300 kW and an HVAC system at 150 kW capacity



# Case study demonstration (full scale)

- Of 10 days simulation, 53.0 kWh battery energy is required for grid support when filtering is not engaged
- With HVAC only, 39.1 kWh battery; with HVAC and water tank, 2.68 kWh battery
- Energy entering and exiting the battery also drastically reduced (34.80 kWh and 120.12 kWh for the two scenarios), avoiding power electronics converter losses



# Implementation notes

- HVAC filtering lower and upper frequency bounds and amplitude limits can be relaxed for some buildings used for unmanned environments, such as data centers or product warehouses.
- Neighboring non-solar buildings can be retrofitted to contribute their thermal inertia to assist in the same fashion

# Conclusion

- HVAC systems can employ relatively fast dynamics to use building thermal inertia as virtual storage
- Dynamic thermal storage can mitigate solar power variation
- 10 s to 15 min band can be usable without causing occupant discomfort in temperature and acoustics
- Filtering capability varies with installed solar capacity, regional weather patterns, building functionality, and dynamic building usage
- Significant grid-side and storage-side benefits demonstrated by case study

# Acknowledgements


- Grainger Center for Electric Machinery and Electromechanics (CEME) at the University of Illinois – Urbana-Champaign
- Prof. R.C.N. Pilawa-Podgurski and his group obtained the long-term fast solar data
- Prof. S. Meyn (Univ. of Florida) has explored this concept on a larger scale for grid regulation


# Selected references


[1] Y. Cao, J. A. Magerko, T. Navidi, and P. T. Krein, "Power electronics implementation of dynamic thermal inertia to offset stochastic solar resources in low-energy buildings," submitted to *IEEE Journal of Emerging and Selected Topics in Power Electronics (JESTPE) -Special Issue on Energy Efficient Buildings*, 2016.

[2] Y. Cao, J. A. Magerko, T. Navidi, and P. T. Krein, "Dynamic filtering stochastic solar resources using HVAC drive control - A determination of feasible bandwidth," in *Proc. IEEE Energy Conversion Congress and Expo (ECCE)*, 2015, pp. 3127-3134.

[3] Y. Cao, J. A. Magerko, T. Navidi, and P. T. Krein, "Dynamic energy management needs in low-energy buildings imposed by stochastic solar resources," in *Proc. International Conf. Complex Systems Engineering (ICCSE)*, 2015, invited paper.

[4] J. A. Magerko, Y. Cao, and P. T. Krein, "Quantifying photovoltaic fluctuation with 5 kHz data: implications for energy loss via maximum power point trackers," in *Proc. IEEE Power and Energy Conference at Illinois (PECI)*, 2016.

# Implementation notes and impacts on other storage

- HVAC adjustment for virtual dynamic thermal storage is relatively easy to implement
  - Conventional building energy management systems implement slow control loops
  - HVAC adjustment injects ac feedforward signals on fast time scales
  - Average performance of the HVAC system remains intact, and fast adjustment is invisible to users
- Once a mitigation level of 10 min to 15 min is achieved, more conventional grid dispatch methods can be used