# Using DFT Decomposition to Size Energy Storage to Accommodate High Penetration of Renewable Resources in the WECC System


***On Behalf Of***

**Shuai Lu***
**Senior Research Engineer**

***Pacific Northwest National Laboratory**
****Energy Mark, Inc**

**Yuri Makarov*,**
**Michael Kintner-Meyer*,**
**Pengwei Du*,**
**Chunlian Jin*,**
**Howard Illian****



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# Outline

- Background: using energy storage to balance power system
- Basic concept and methodology to decompose balancing requirements
- Numerical results: applying to WECC system 2030 scenario
- Conclusion

# Using energy storage to balance power system

- Fast response from energy storage can improve frequency regulation performance;

- Potential to reduce $CO_2$ and other emissions by avoiding the dispatch of generators across a wide range of partial load at low efficiencies.

- Reduce generator maintenance costs.

How much energy storage will be necessary and where the optimal locations of the storage are will depend on many operational requirements and economic factors.

# Energy storage technologies and cycling period

| Full Power Duration of Storage | Application of Storage | Biomass | Hydrogen Electrolysis + Fuel Cell | Large Hydro | Compressed Air Energy Storage (CAES) | Heat or Cold Storage | Pumped Hydro | Redox Flow Cells | New and Old Battery Technologies | Flywheel | Superconducting Magnetic Energy Storage (SMES) | Supercapacitor |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 months | Annual smoothing of loads, wind and small hydro | √ | √ | √ | | | | | | | | |
| 3 weeks | Smoothing weather effects: load, PV, wind, small hydro | √ | √ | √ | | | | | | | | |
| 3 days | Weekly smoothing of loads and most weather variations | √ | √ | √ | √ | | √ | √ | | | | |
| 8 hours | Daily load cycle, PV, wind Transmission line repair | √ | √ | √ | √ | √ | √ | √ | √ | | | |
| 2 hours | Peak load lopping, standing reserve, wind power smoothing, minimization of trading penalties | √ | √ | √ | √ | √ | √ | √ | √ | | | |
| 20 minutes | Spinning reserve, wind power smoothing, clouds on PV | | √ | √ | √ | √ | √ | √ | √ | √ | | |
| 3 minutes | Spinning reserve, wind power smoothing of gusts | | √ | | | | √ | √ | √ | √ | √ | √ |

Source: Barton and Infield, 2004

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# Imbalance power

area control error (ACE)
$$-ACE = -(I_a - I_s) + 10B(F_a - F_s) \approx -(G_a - L_a) \to \min$$

generation output
$$G_a = G_s + G_{dev}$$

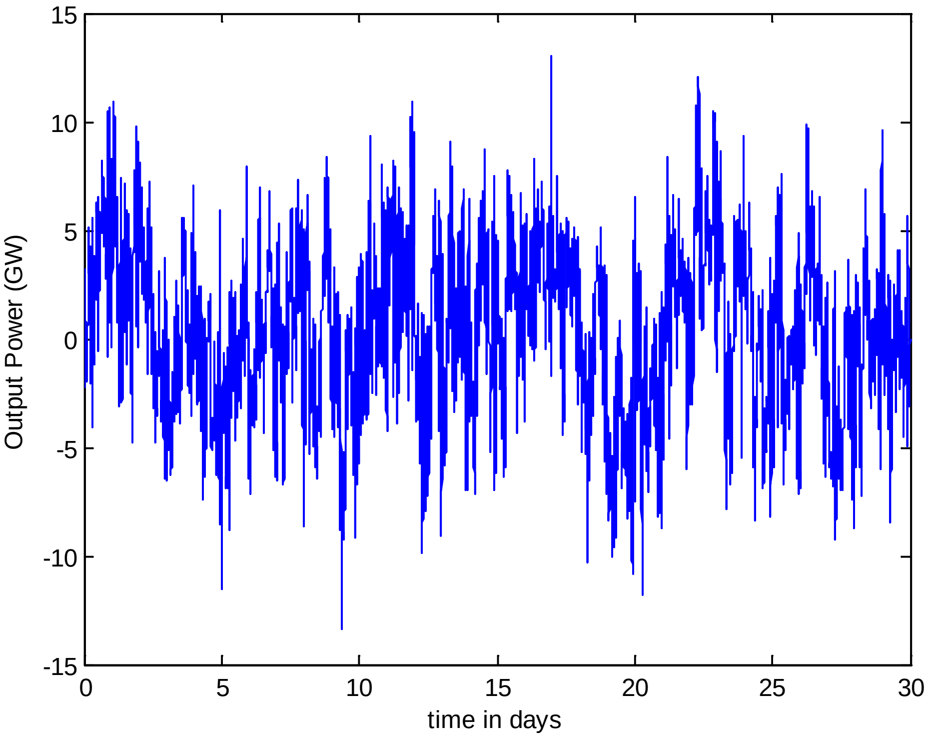
load
$$L_a = L_{f\_ha} + L_{dev}$$

based on the assumption that
$$G_s = L_{f\_ha}$$

load deviation
$$L_{dev} = L_a - G_s$$

load deviation with wind power
$$L_{dev} = (L_a - G_a^w) - G^s = L_a - L_{f\_ha} - (G_a^w - G_{f\_ha}^w)$$

This represents the gap between generation and load that causes fluctuations of the system frequency.




System **i**mbalance imposed by load and wind variability and forecast error for assumed 88 GW of installed wind capacity (WECC, Aug. 2030)

# DFT analysis procedures

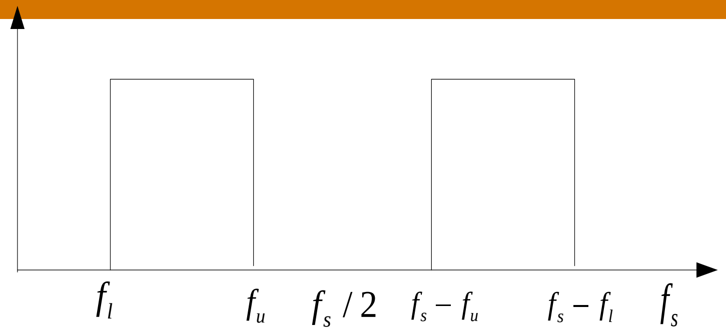
Analysis equation: $$X[k] = \sum_{n=0}^{N-1} x[n] W_N^{kn}$$

Synthesis equation: $$x[n] = \frac{1}{N} \sum_{k=0}^{N-1} X[k] W_N^{-kn}$$

The imbalance power can be broken down into the components spanning different frequency ranges using discrete Fourier transform (DFT).

This is attractive because each component of the periodic signal, except for the lowest frequency component which includes the average deviation from zero, represents energy that averages very close to zero over one operational cycle.

# Band-pass filter applied to imbalance signal spectrum



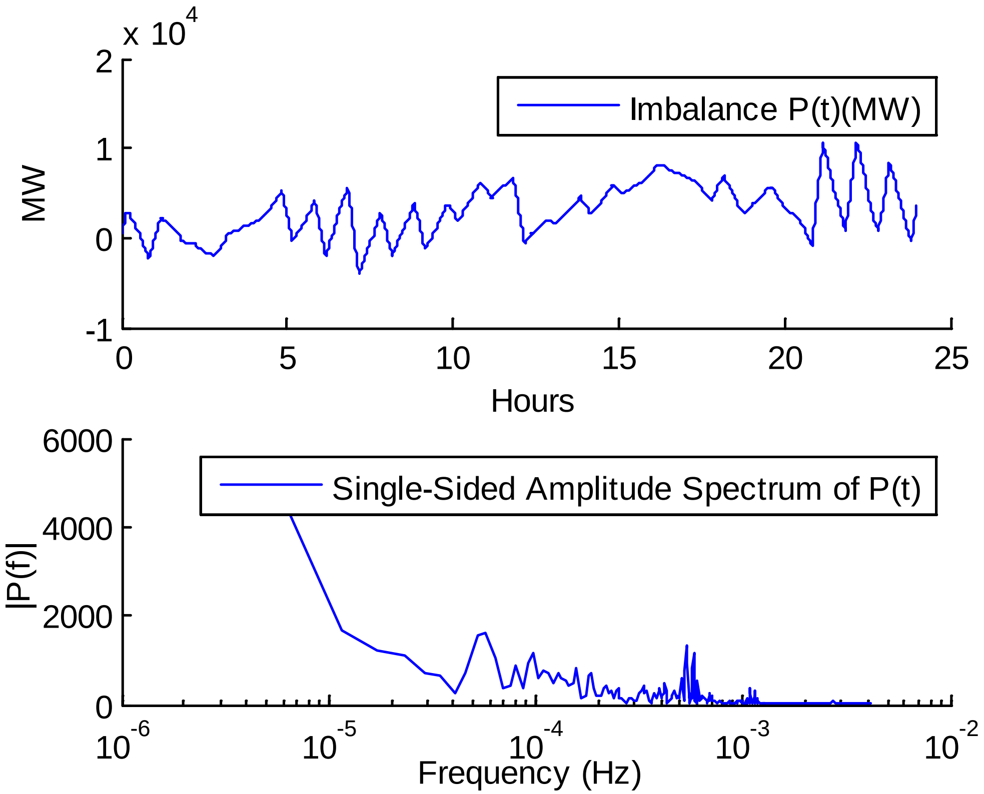

band-pass applied to spectrum

| No. | Component | $f_l$ (Hz) | $f_u$ (Hz) |
|---|---|---|---|
| 1 | Intra-week | 0 | 2.3148e-5 |
| 2 | Intra-day | 2.3148e-5 | 9.2593e-5 |
| 3 | Intra-hour | 9.2593e-5 | 0.0033 |
| 4 | Real-time | 0.0033 | 0.0083 |

Four different frequency ranges are selected, and the signal is decomposed into four categories: intra-week, intra-day, intra-hour and real-time components

The band-pass filter applied to the spectrum is a rectangular window with unit magnitude within the band and zero magnitude outside of the band

# Imbalance power for a selected day in August 2030 in WECC system




This figure shows the one-day time-domain signal (top) and the corresponding spectrum (bottom).

Majority of the energy is concentrated in the low and middle frequency band.

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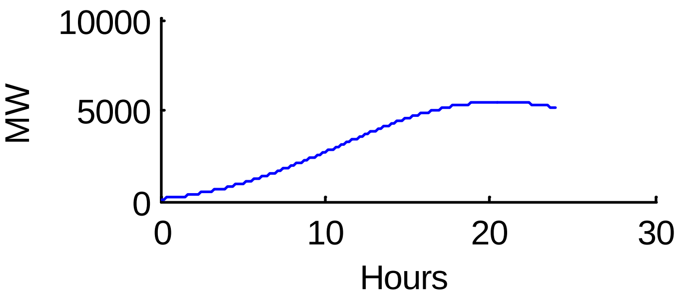
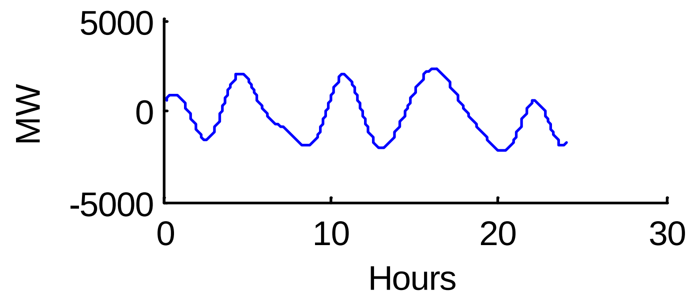
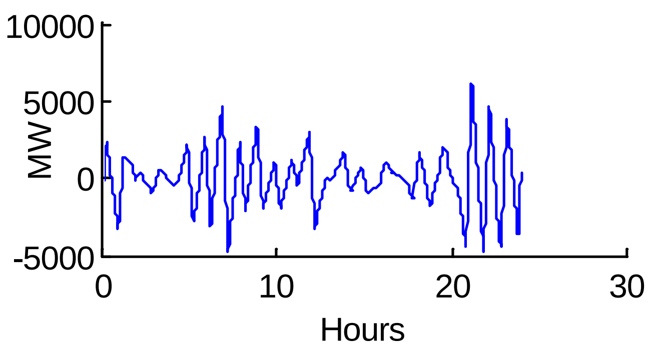
# Decomposition of imbalance signal for a selected day in August, 2030



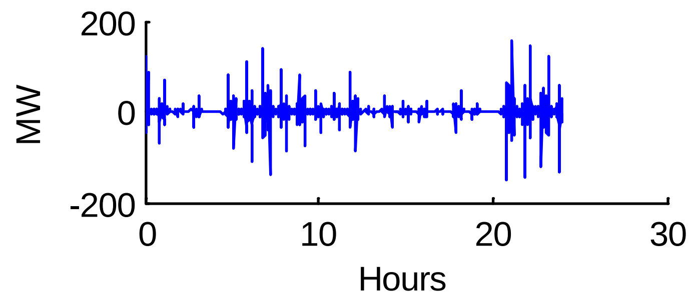

(a)Intra-week component




(b) Intra-days component



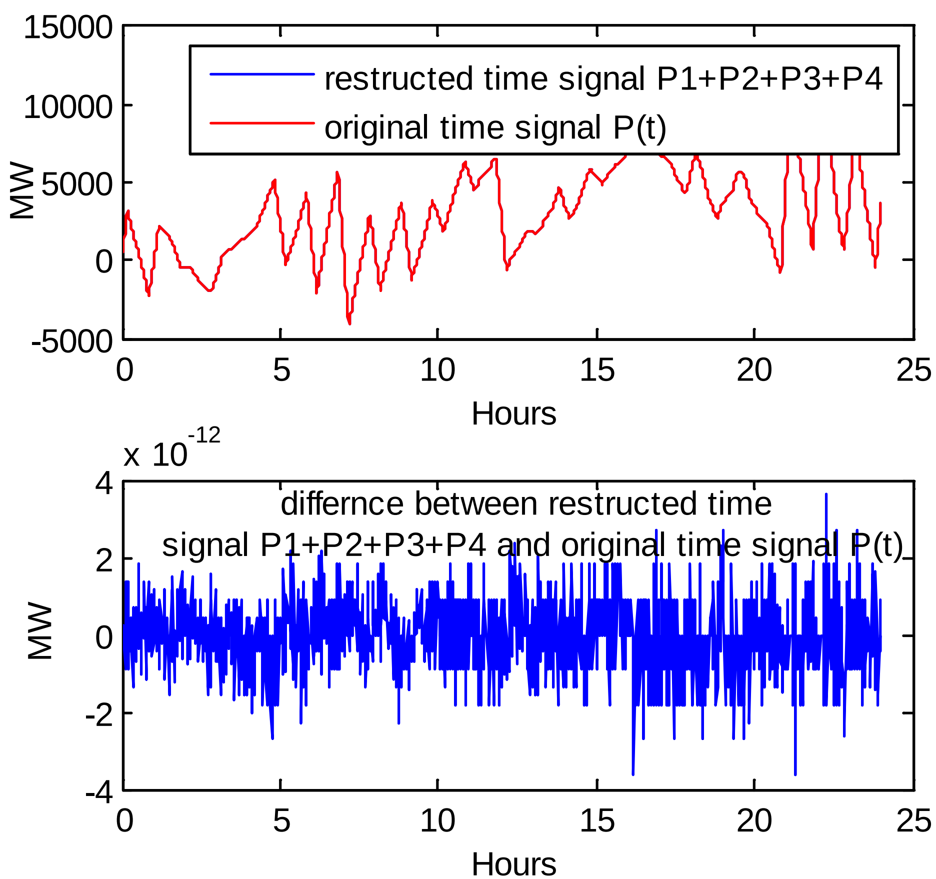

(c) Intra-hour component




(d) Real-time component

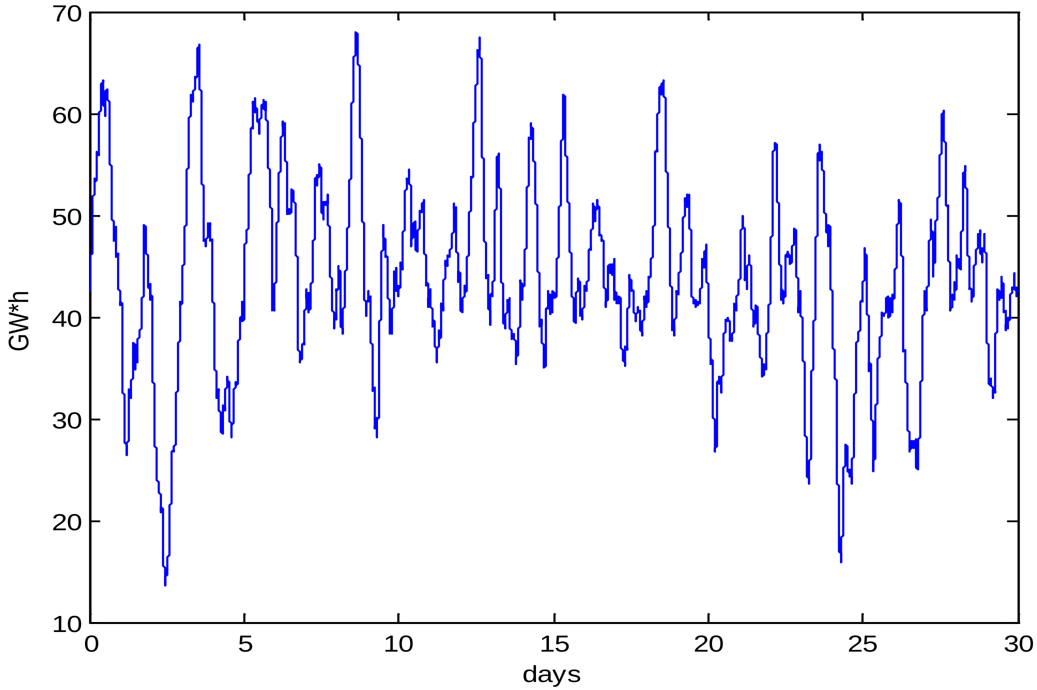
The imbalance power, *P*(t), is decomposed into four components, *P*1(t), *P*2(t), *P*3(t) and *P*4(t)

# Comparison between original and re-constructed signal for the selected day




The reconstructed signal matches well with the original signal

# State of charge profile for energy storage (Storage size=68.05 GWh) (Aug 2030 WECC)




Assumption: Minimum state of charge for the energy storage is 80%

Significant energy storage (68.05 GWh) is required without DFT decomposition.

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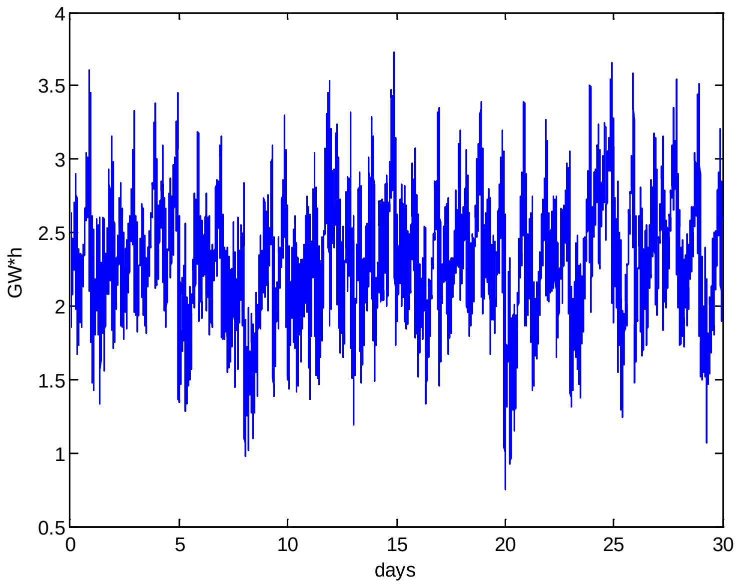
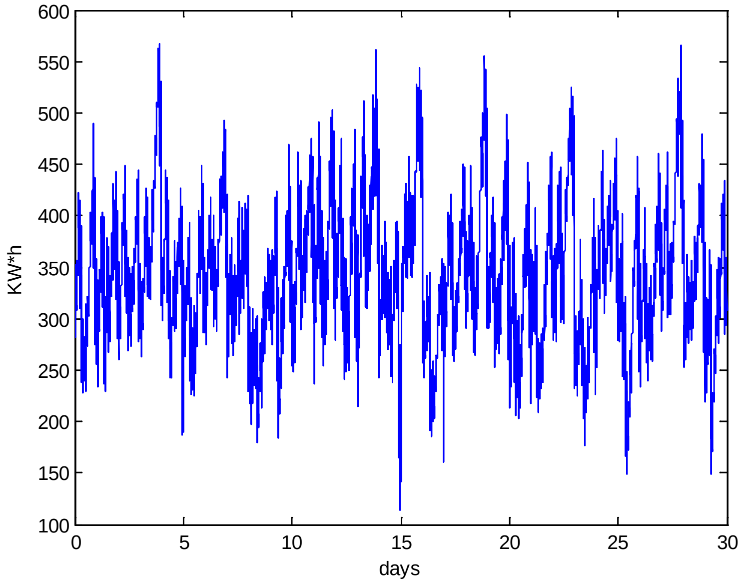
# State of charge profile for intra-hour and real-time components (Aug 2030 WECC)




(a) Intra-hour component (Storage size=3.73 GWh)




(b) Real-time component (Storage size=568 kWh)

The compensation of the individual components, i.e., intra-week, intra-day, intra-hour or real-time one, requires different sizes of energy storage.

The size of the energy storage requirement is 3.73 GWh for the intra-hour component and 568 kWh for real-time component

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# Summary of benefits of partial balance using DFT decomposition

| | Fully Balance[1] | Partial Balance[2] | Reduction of fast energy storage |
|---|---|---|---|
| Power (GW) | 13.4 | 7.38 | 45% |
| Energy (GWh) | 68.05 | 3.73 | 94.5% |

[1] Full balance: energy storage compensates all the imbalance power
[2] Partial balance: energy storage compensates only intra-hour and real-time components

This has significant impact on the power and energy capacity for ancillary service providers (generators or energy storage) because the intra-week and intra-day components can be provided using slow, less expensive options.

# Conclusions and future work

**Conclusion**: introduction of a cycling period decomposition (intra-week, intra-day, intra-hour, intra-minute or real-time) on system imbalance signal offers a new way to:

Evaluate the size of certain energy storage technologies for balancing services;

Characterize future balancing requirements for a large interconnect or balancing area.

**Future work**: uncertainty analysis and geographic effect of energy storage would be the subjects of the future work.

# Questions?

Contact information: pengwei.du@pnl.gov 509-3724678