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Wind Technology for Enhancing Power System Flexibility toward Energy Transition

17 September, 2019.

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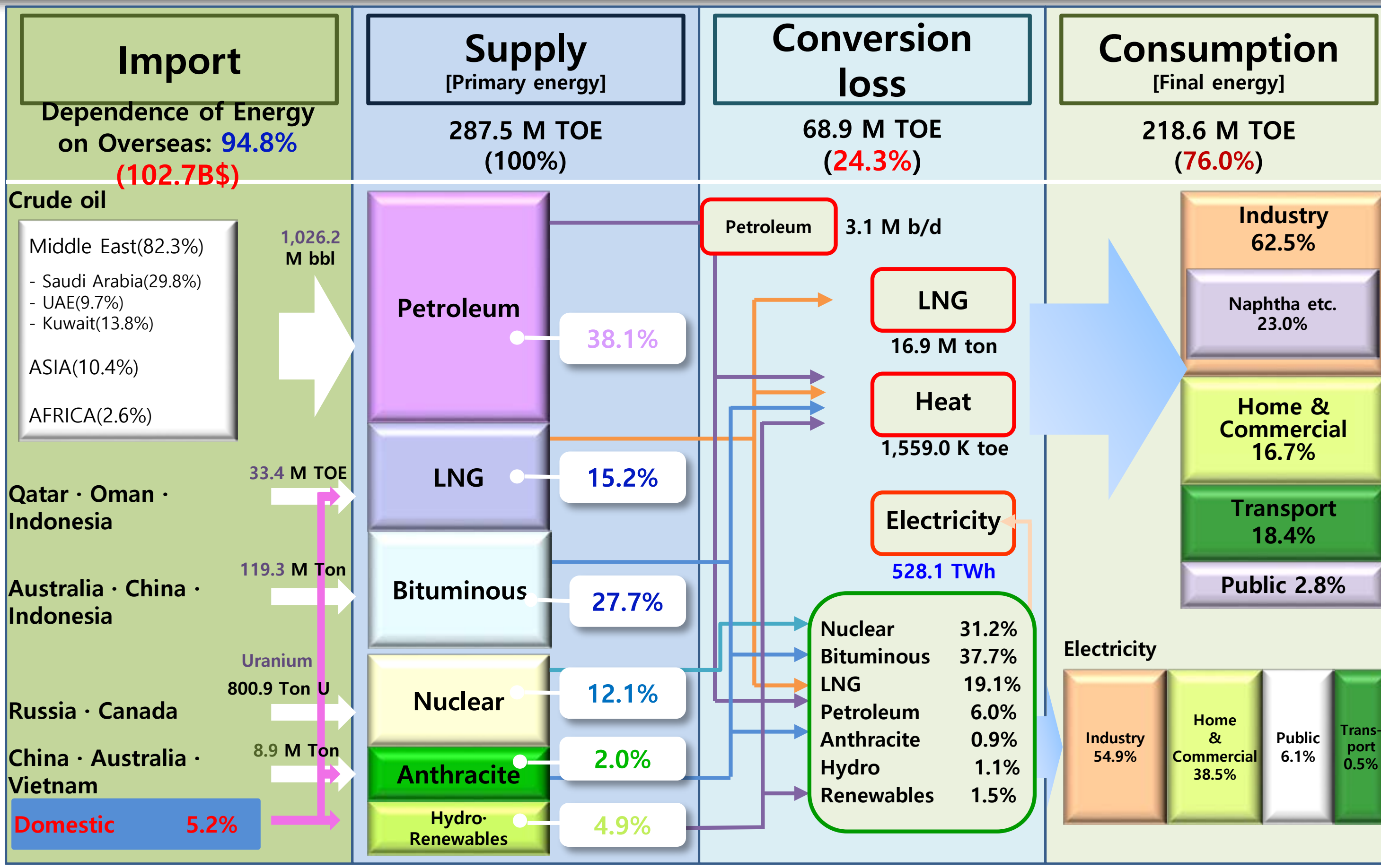
2015 Energy balance flow in Korea



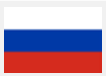
- Average import for energy (5 yrs): 144 B$
- Average import for electricity (5 yrs): 47 B$
- GDP: $82/day/capita
- Import of energy: $8/day/capita

What does 3020 RE plan mean to Korea?

Saves 10 B$/year (energy import) & 1.3 B$/year ($CO_2$ emission)

(**Ref.**) 2016 Energy statistics in Korea, **2017.**

Statistics of peak and VRE generation in 2015

Rank	Country	Peak (GW)	RE (GW)	VRE (GW)	Wind (GW)	Total Gen (TWh)	RE Gen (TWh)	VRE Gen (TWh)	Wind Gen (TWh)	RE/ Total (%)	VRE/ Total (%)
1		830	520 (1)	188(1)	145 (1)	5,811 (1)	1403 (1)	224(2)	185 (2)	24.14 (15)	3.90 (14)
2		723	219 (2)	98 (2)	73 (2)	4,303 (2)	571 (2)	232(1)	193 (1)	13.27 (23)	5.40 (11)
3		159	90 (5)	36 (4)	3 (13)	1,036 (5)	161 (7)	36 (8)	5 (16)	15.54 (19)	3.50 (17)
4		155	52 (9)	1 (24)	1 (32)	1063 (4)	171 (6)	0 (32)	0 (32)	16.09 (17)	0.00 (32)
5		148	82 (6)	30 (5)	25 (4)	1,305 (3)	193 (5)	48 (5)	41 (5)	14.79 (21)	3.70 (16)
6		85	114 (3)	9 (10)	9 (9)	580 (7)	433 (3)	22(10)	22 (7)	74.66 (3)	3.70 (15)
7		83	105 (4)	85 (3)	45 (3)	647 (6)	196 (4)	126(3)	88 (3)	30.29 (11)	19.50 (5)
8		83	44 (10)	17 (9)	10 (7)	569 (8)	89 (10)	28 (9)	20 (8)	15.64 (18)	4.80 (13)
9		77	13 (13)	4 (15)	1 (17)	522 (9)	16 (21)	5 (17)	2 (20)	3.07 (29)	1.00 (22)
10		59	55 (7)	28 (6)	9 (8)	282 (12)	109 (8)	40 (7)	15 (9)	38.65 (9)	14.20 (7)
World Total			1,985	643	431	24,098	5,559	1,094	841	23.1	4.5

(**Ref.**) World energy council, "World energy perspectives: Renewables integrations," 2016.

Key Indicators on Energy Transition

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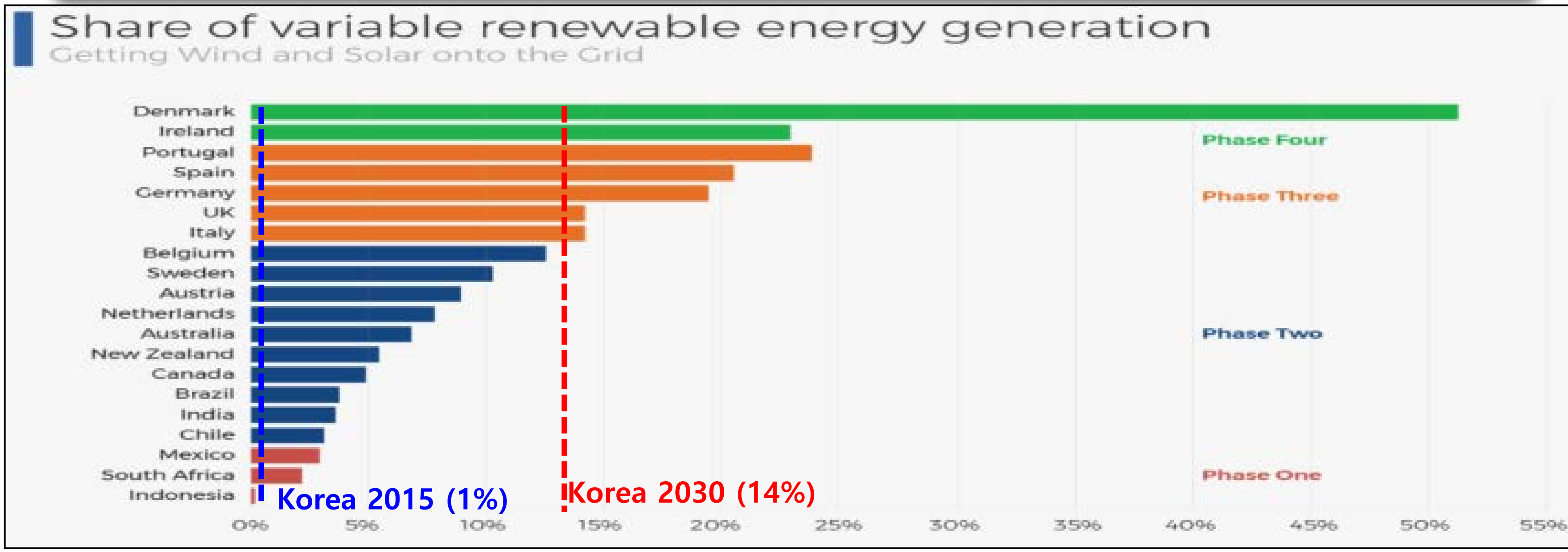
Table 1. Key indicators relevant to the energy transition in selected countries (REmap Case)

	CHINA 2015	CHINA 2050	EU 2015	EU 2050	INDIA 2015	INDIA 2050	USA 2015	USA 2050
Share of renewable energy in primary energy supply	5%	69%	13%	74%	9%	75%	9%	63%
Share of renewable energy in final energy use	7%	67%	17%	70%	10%	73%	8%	63%
Electricity use in final energy consumption	19%	54%	22%	41%	18%	48%	20%	51%
Share of renewable energy in power	26%	94%	29%	94%	15%	92%	14%	78%

Energy Transition → Energy Transformation

(**Ref.**) IRENA, “Global energy transformation: A roadmap to 2050” **2018.**

Phases of VRE penetration



Phase I	• VRE is not relevant at the all-system level.
Phase II	• VRE becomes noticeable → VRE forecast is relevant.
Phase III	• Power system flexibility becomes a priority.
Phase IV	• Power system stability becomes relevant.

Korea: Phase I (2015) → Phase III (2030)

(**Ref.**) IEA, "Getting wind and sun onto the grid: A manual for policy makers," **2017.**

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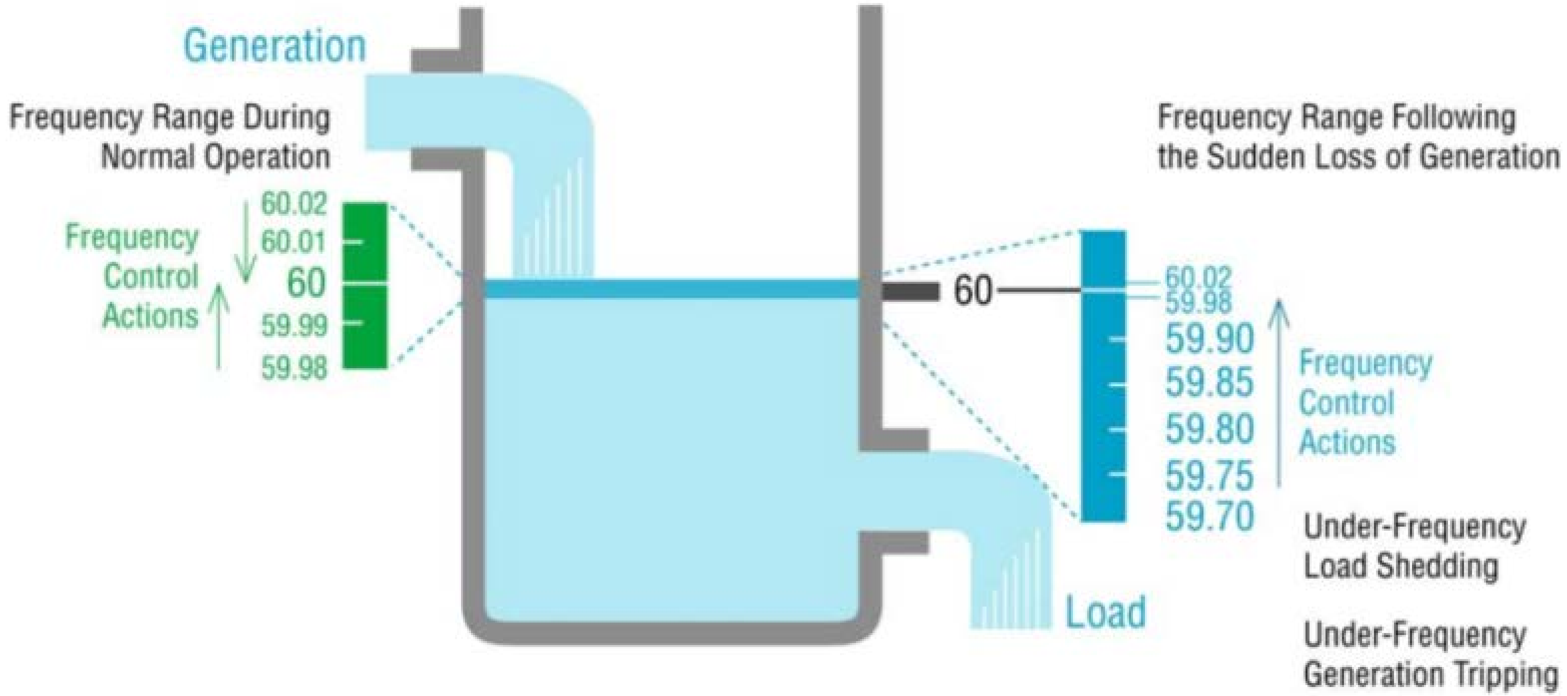
Operation of a power grid

Frequency is the heartbeat of a power system!!!



- **Normal operation (Load variation)**: $\Delta f \le$ **36 mHz**
- **Contingency operation (Loss of generation)**:
  - Δf > **36 mHz: Governor activation**
  - Δf > **200 mHz: AGC deactivation**
  - Δf > **1000 mHz: Under-frequency load-shedding relay activation**

(**Ref.**) LBNL report, "Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation," Lawrence Berkley National Laboratory, LBNL-4142E, Dec. **2010.**

Operating reserves in a power grid (Uncertainty)

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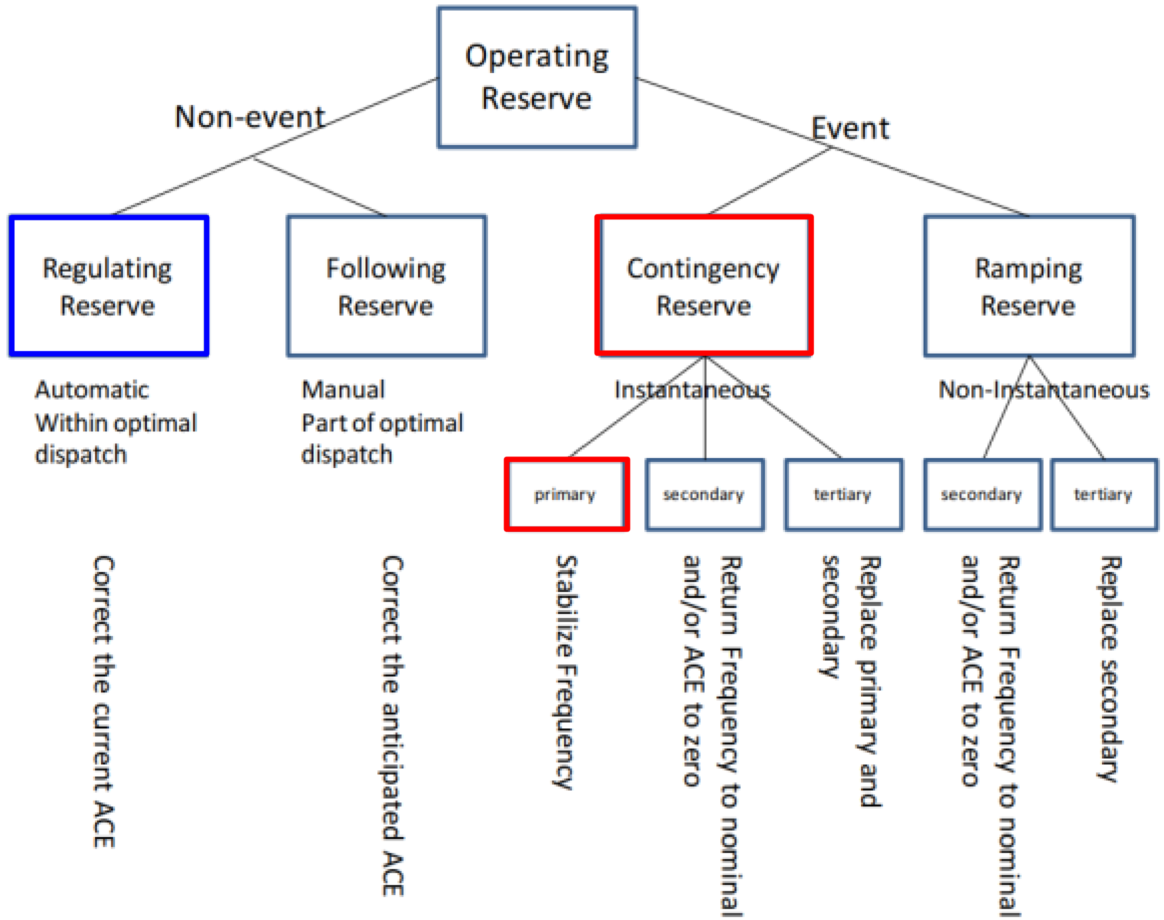
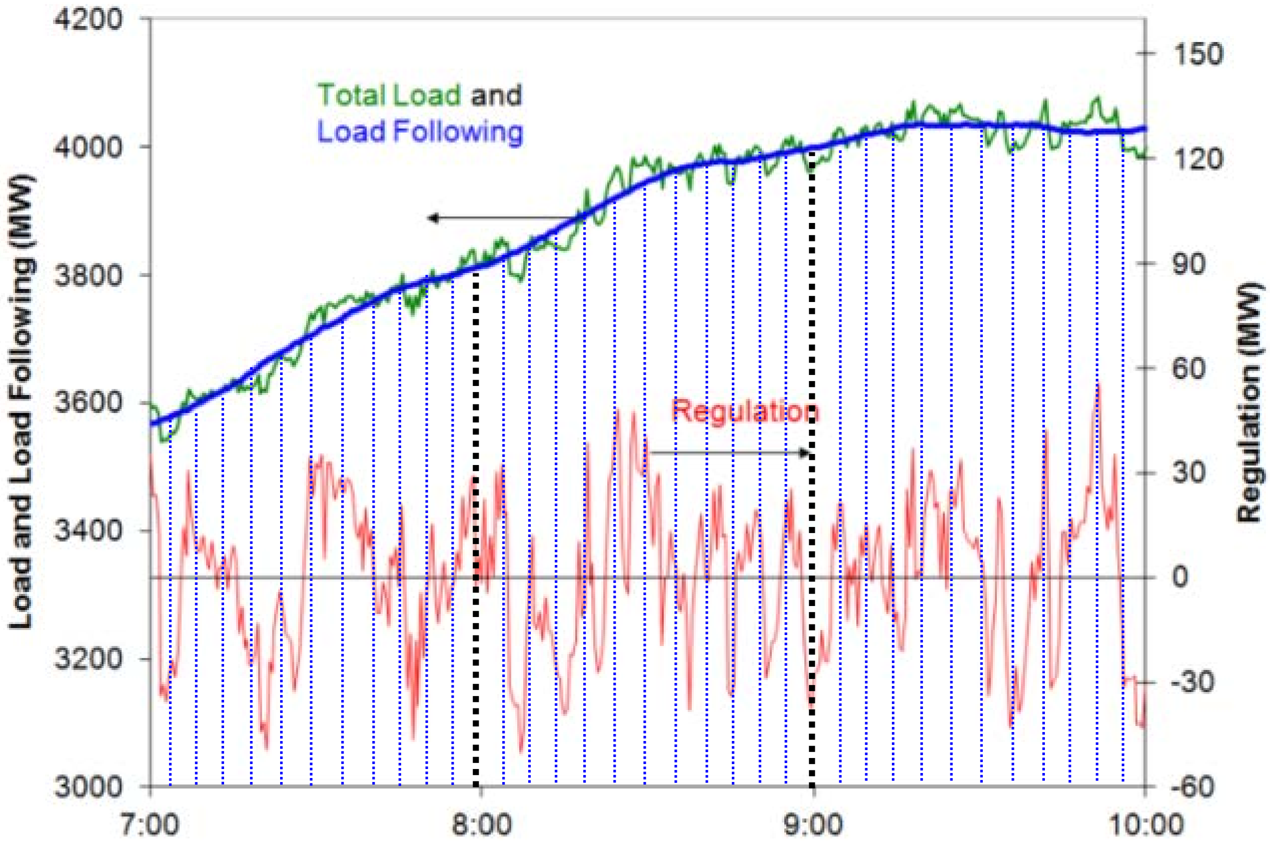


Fast-acting reserve = Primary reserve (1000 MW) + Regulating reserve (500 MW)

As penetrations of VRE increase, which kind of reserve is required more?

(**Ref.**) E. Ela, M. Miligan, and B. Kirby, "Operating reserves and variable generation," NREL/TP-5500-51978. National Renewable Energy Laboratory. Aug. **2011.**

Normal operation

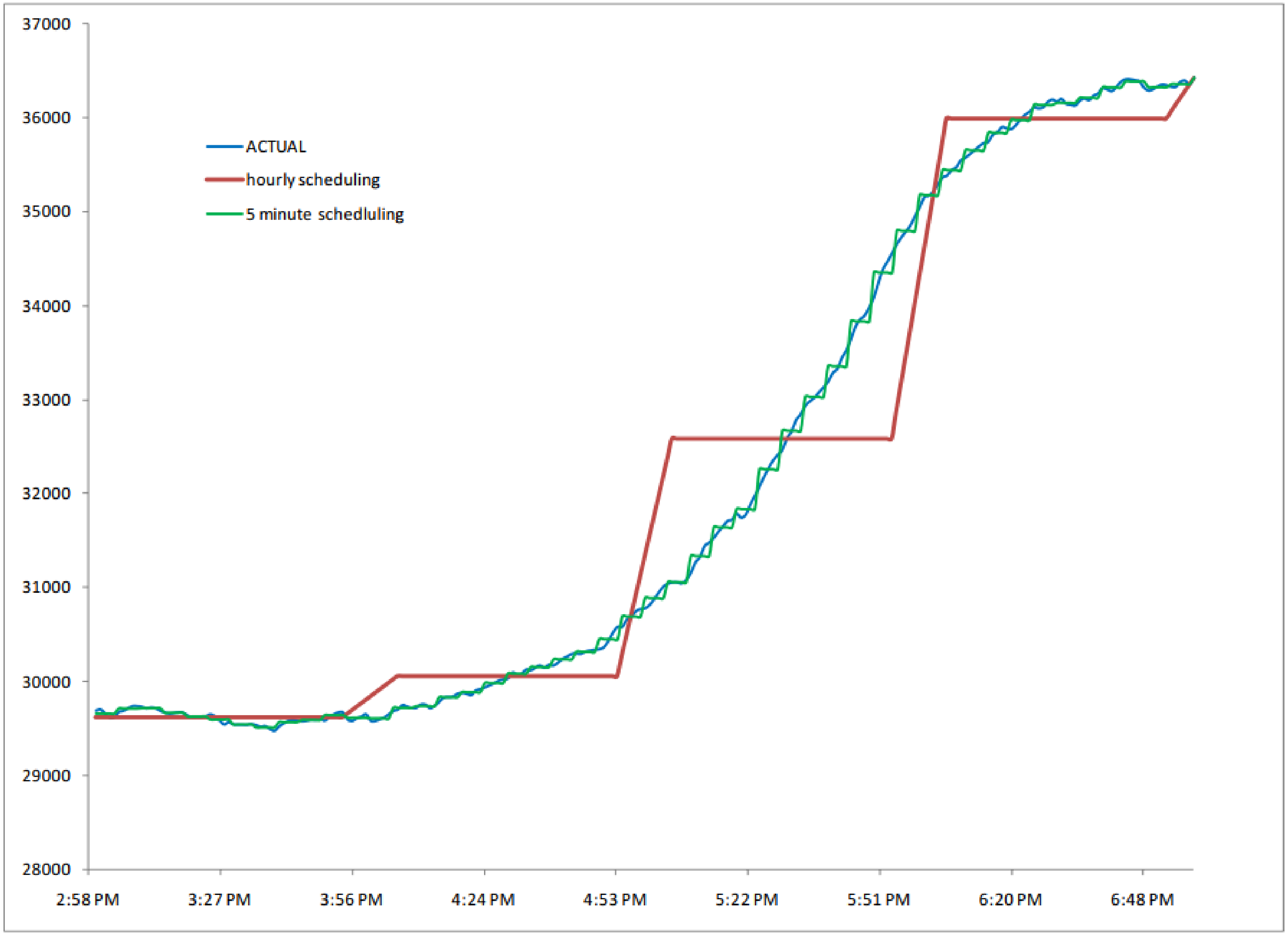


Economic dispatch
- Ramp rate (%/min)
- Min output (MW)

- **Day-ahead Hourly Unit Commitment**
- **Economic dispatch**: **Sub-hourly** trend in loads, every **5 mins (Variability)**
- **AGC**: **Moment-to-moment fluctuations in loads**, every **4 s (zero-energy service) (Uncertainty)**

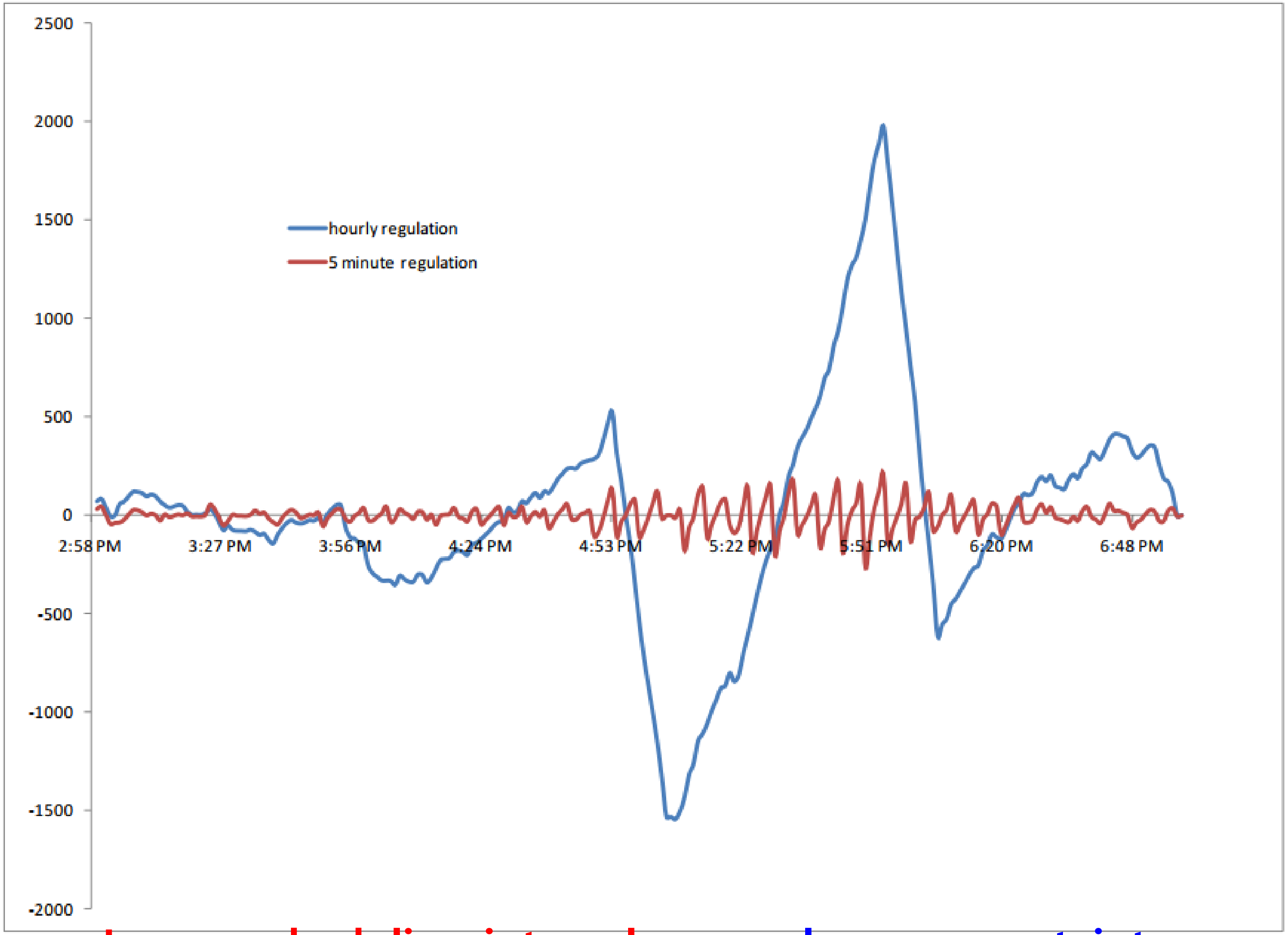
(**Ref.**) B. J. Kirby, "The Value of Flexible Generation,", PowerGen **2013.**

Hourly scheduling vs 5 min scheduling



(**Ref.**) E. Ela, M. Miligan, and B. Kirby, "Operating reserves and variable generation," NREL/TP-5500-51978. National Renewable Energy Laboratory. Aug. **2011.**

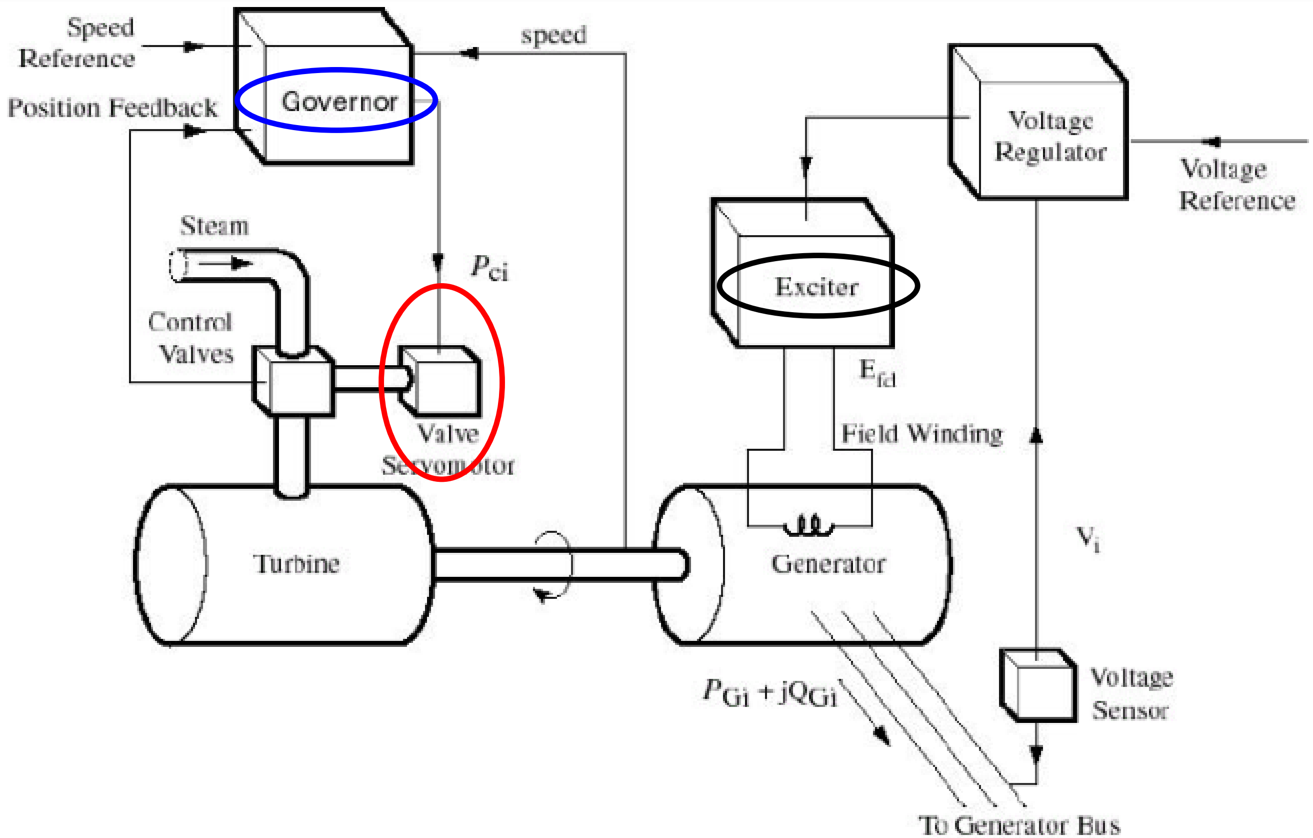
Hourly regulation vs 5 min regulation



Larger scheduling interval causes larger uncertainty

(**Ref.**) E. Ela, M. Miligan, and B. Kirby, "Operating reserves and variable generation," NREL/TP-5500-51978. National Renewable Energy Laboratory. Aug. **2011.**

A SG controls P_m by opening/closing a valve



$$J\omega \frac{d\omega}{dt} = P_m - P_e$$

A SG controls not P_e but P_m by using reserves!

Small load variation ($\Delta f \leq$ 36 mHz): Secondary control, AGC

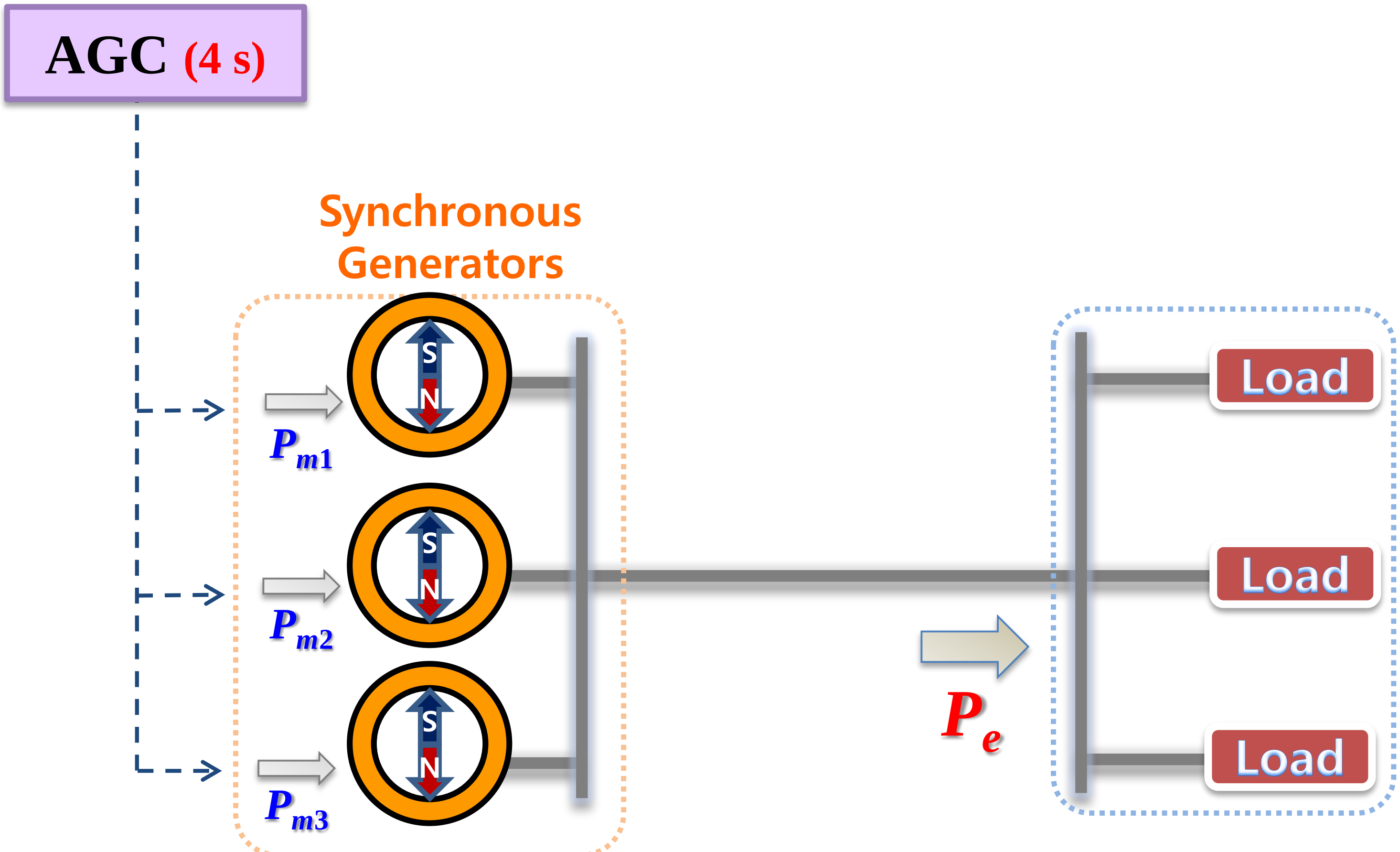
AGC (4 s)

$$J\omega \frac{d\omega}{dt} = P_m - P_e$$

1. Small increase in load → Frequency decline
2. Increase in P_m based on AGC (I controller) → Restores frequency to ω_0

Only regulating reserve is deployed!

Small load variation in a multi-machine system ($\Delta f \leq 36$ mHz)



1. Small increase in load → Frequency decline
2. Increase in P_m based on AGC (I controller) → Restores frequency to ω_0

Only regulating reserve is deployed!

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General of a wind turbine generator

$$P_m = P_{air} C_p(\beta, \lambda) = \frac{1}{2}\rho V^3 \cdot \pi R^2 \cdot C_p(\beta, \lambda)$$

***R* : Rotor Radius**

***ρ* : Air density**

***V* : Wind speed**

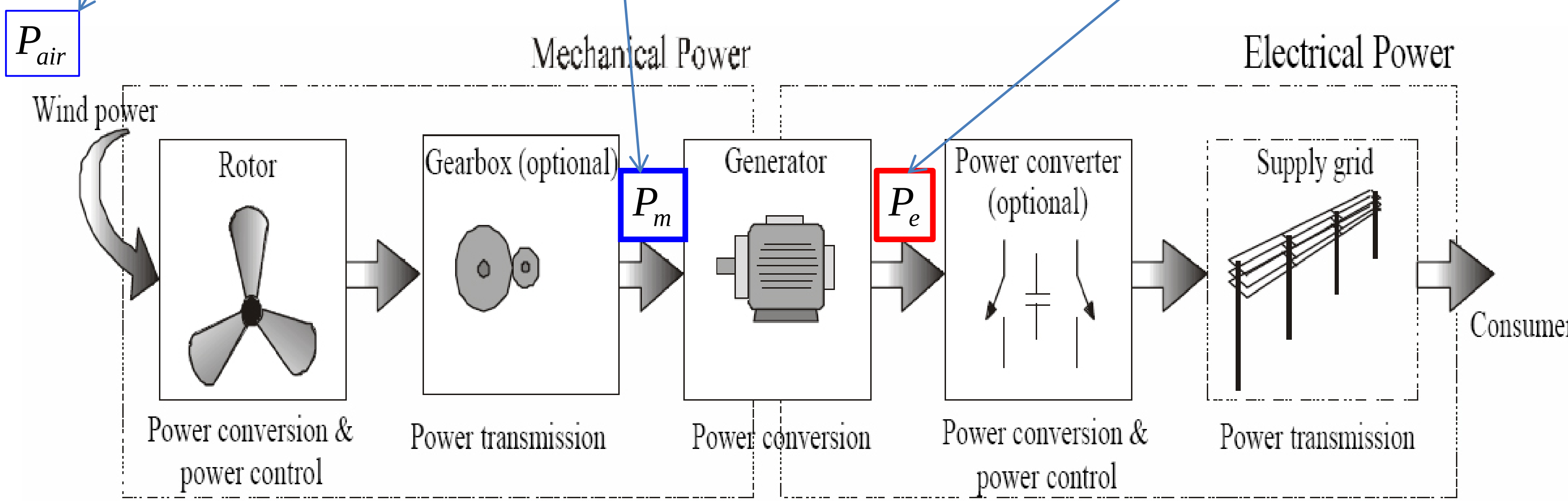
$C_p(\beta,\lambda)$: ***Performance Coefficient***

β : *Pitch angle*

P_{air} $\qquad$ P_e

Mechanical energy → **Kinetic Energy** → **Electric Energy**

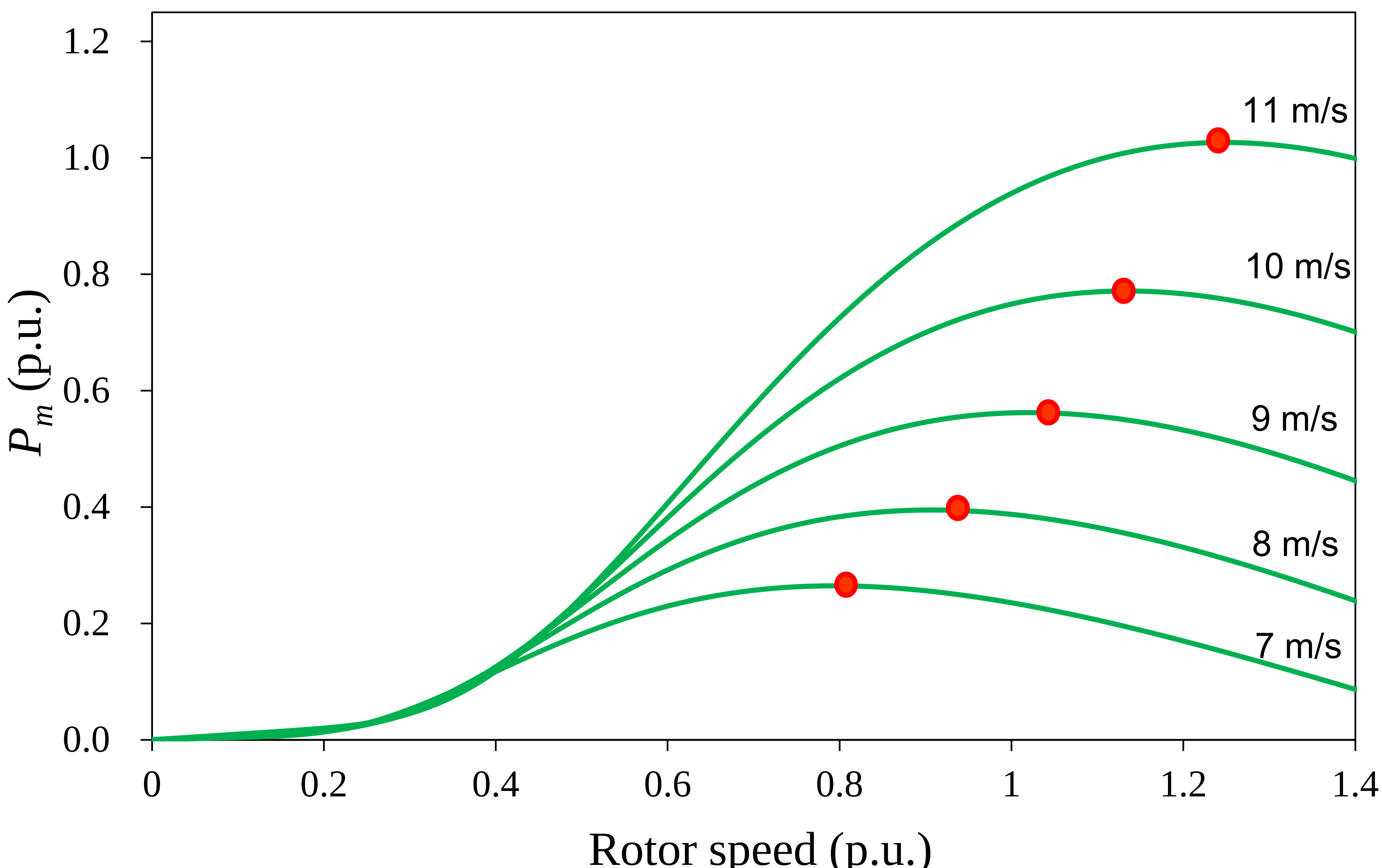
Blades $\qquad$ **Generator**



➔ **Energy conversion system!!**

Features of Pm with wind speeds

$P_m(V, \lambda, \beta)$



- P_m **depends on the rotor speed (Concave) → It has the global max.** P_m
- **The optimum rotor speed depends on the wind speed → Requires a wider rotor speed range**

MPPT control of a variable-speed WTG

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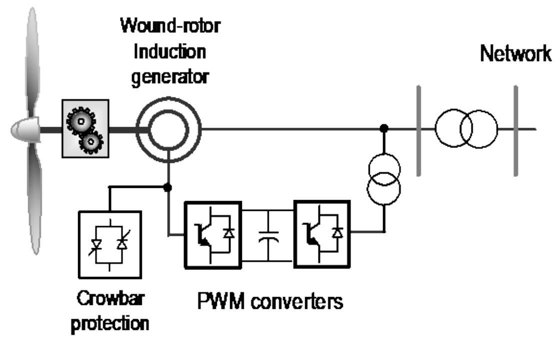
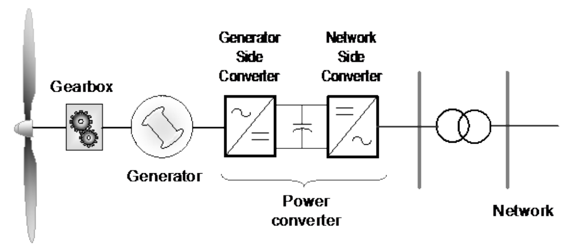
Doubly-fed induction generator (DFIG)



Fully-rated converter (FRC) WTG



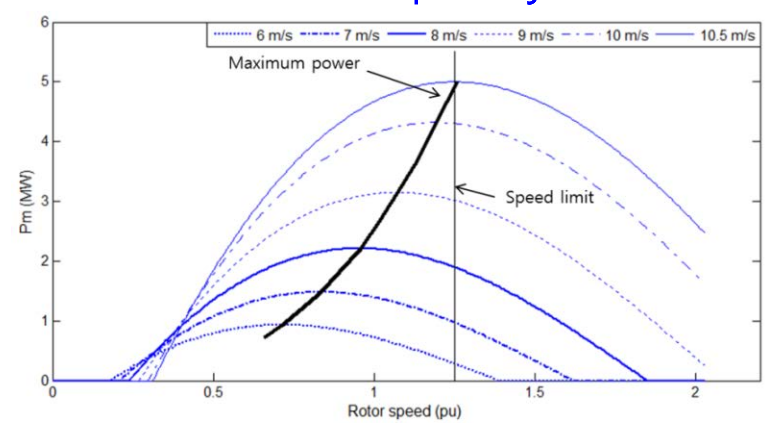
▪ MPPT (Maximum power point tracking) control

- $P_e = k\omega^3$
- Responds to rotor speed variation instead of frequency deviation

Mechanical input power depending on the **wind** and **rotor** speeds

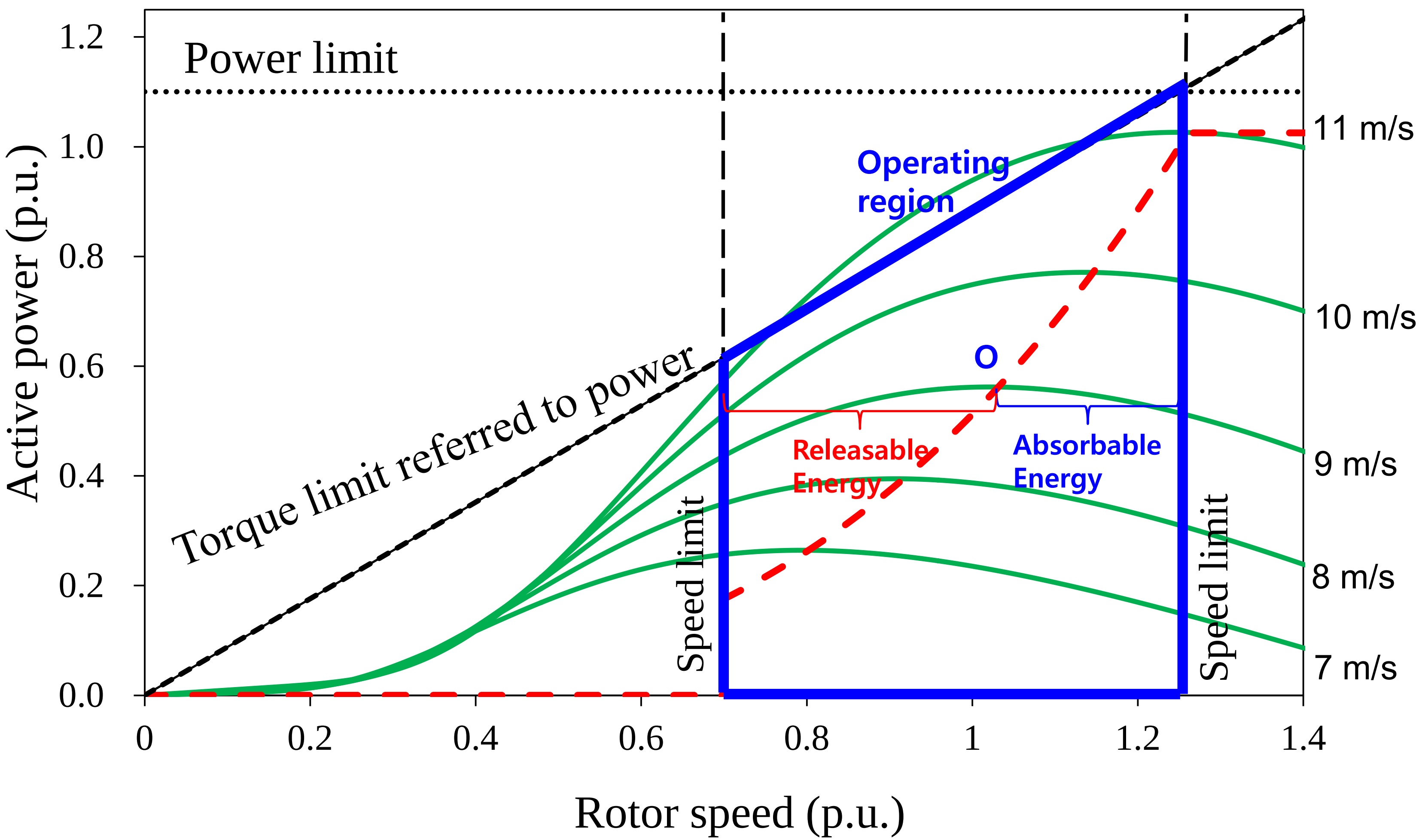
$$J\omega\frac{d\omega}{dt} = P_m - P_e$$

Electrical output power
Control variable



(**Ref.**) B. Shen, B. Mwinyiwiwa, Y. Zhang, and B. Ooi, "Sensorless maximum power point tracking of wind by DFIG using rotor position phase lock loop," *IEEE Trans. Power Electron.*, vol. 24, no. 4, pp. 942–951, **Mar. 2009.**

Operating region of a DFIG



- **Operating range of the rotor speed: 42 Hz–75 Hz (55%)**
- **Releasable energy and absorbable energy depends on the wind speed.**
- **A variable WTG inherently incorporates an ESS!!**

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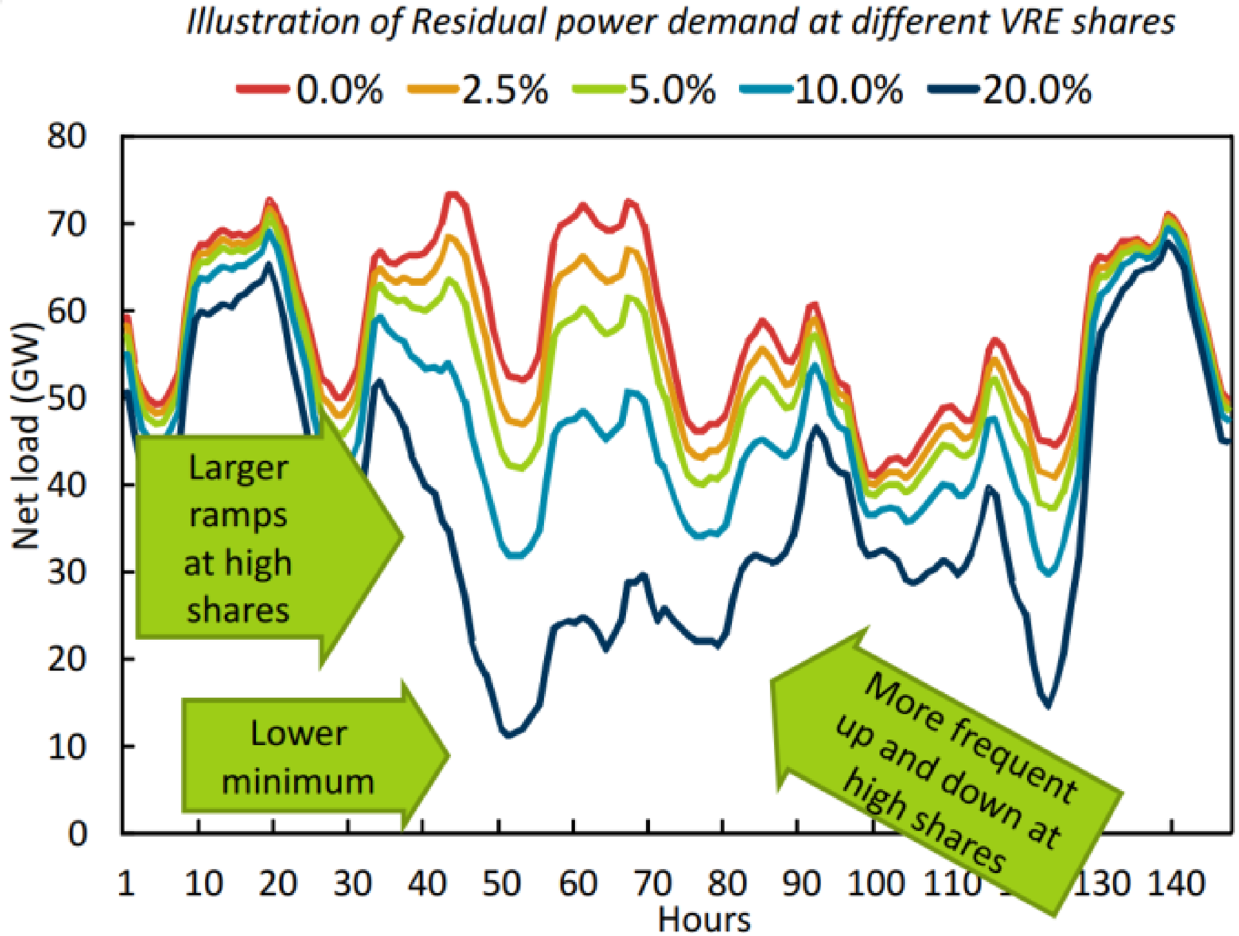
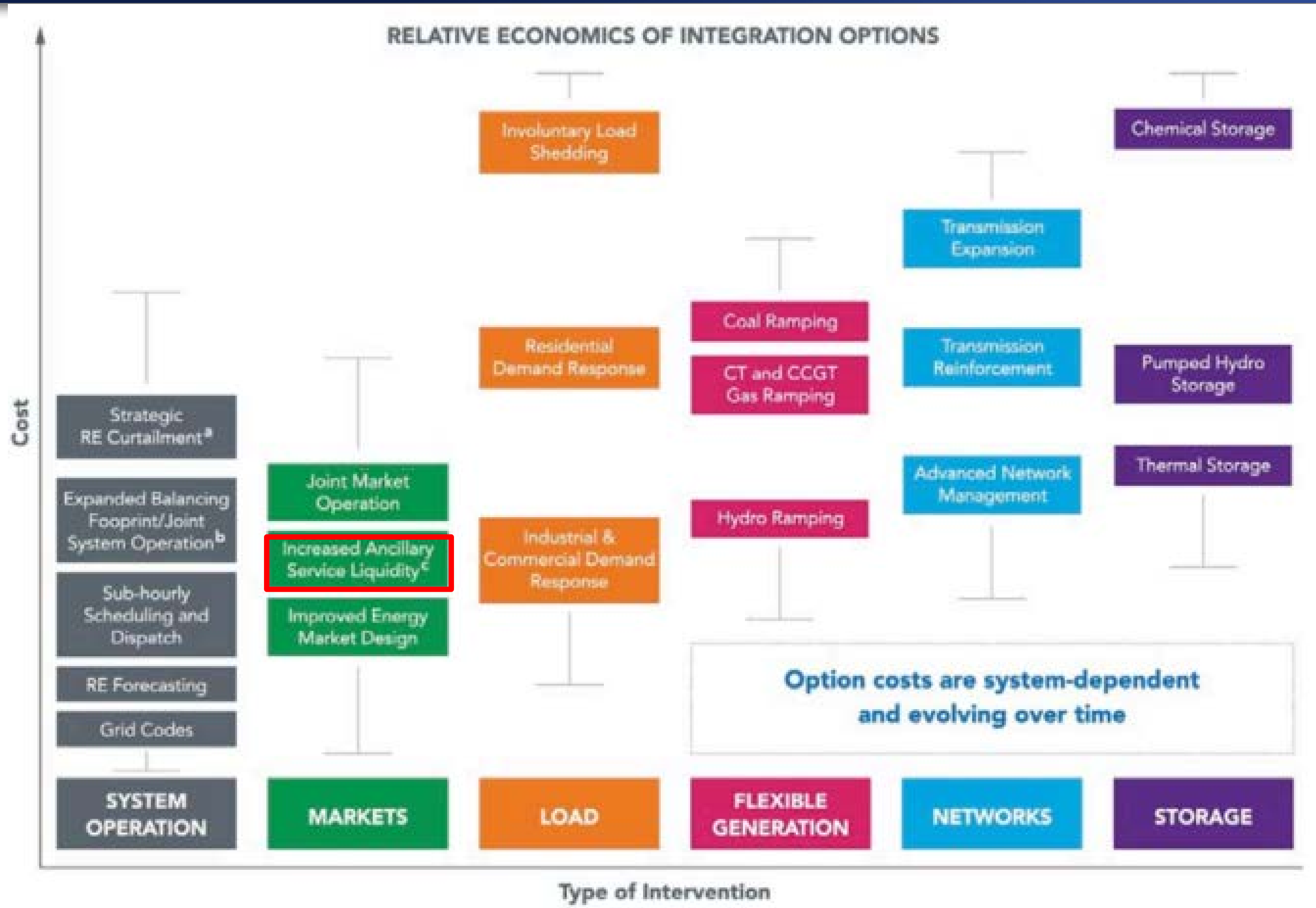
Net Load with VRE penetrations



Steeper ramps: **quicker ramp rates** of dispatchable generation
Lower minimum: **lower minimum output** of dispatchable generators
More frequent up and down: increased uncertainty in load variation.

For high penetrations of VRE, how can we secure the power grid flexibility?

Integration options for flexibility

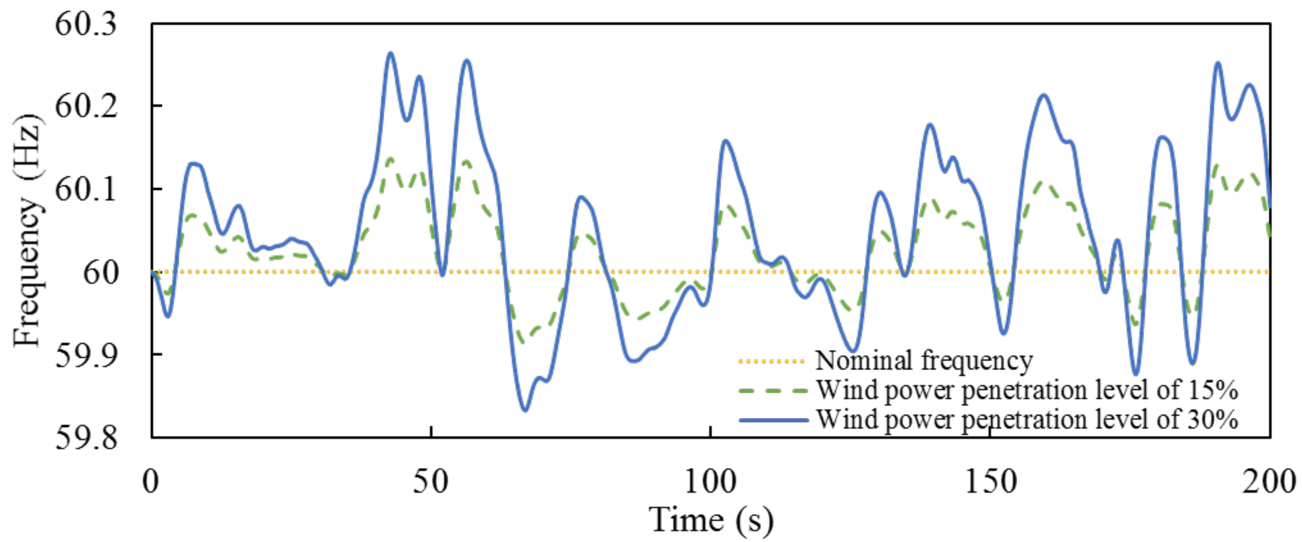


1) Grid code, 2) Market design, 3) RE forecasting, 4) Sub-hourly UC/ED, 5) FR of WTGs, 6) DR/EVs

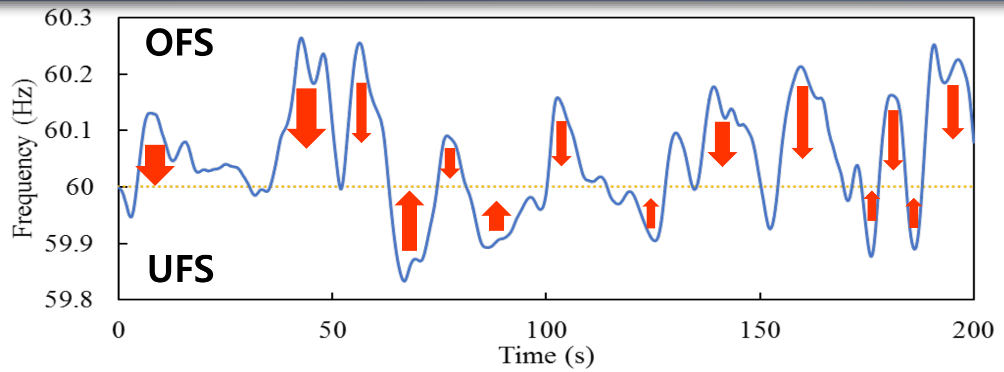
(**Ref.**) J. Cochran, P. Denholm, B. Speer, and M. Miller, "Grid integration and the carrying capacity of the US grid to incorporate variable renewable energy," NREL/TP-6A20-62607. National Renewable Energy Laboratory. Apri. 2015.

Frequency fluctuation caused by VRE variation

- Weather variation → Output power fluctuation of VRE → Frequency fluctuation
- High penetration → Severe output power fluctuation of VRE → Severe frequency fluctuation (MPPT control)

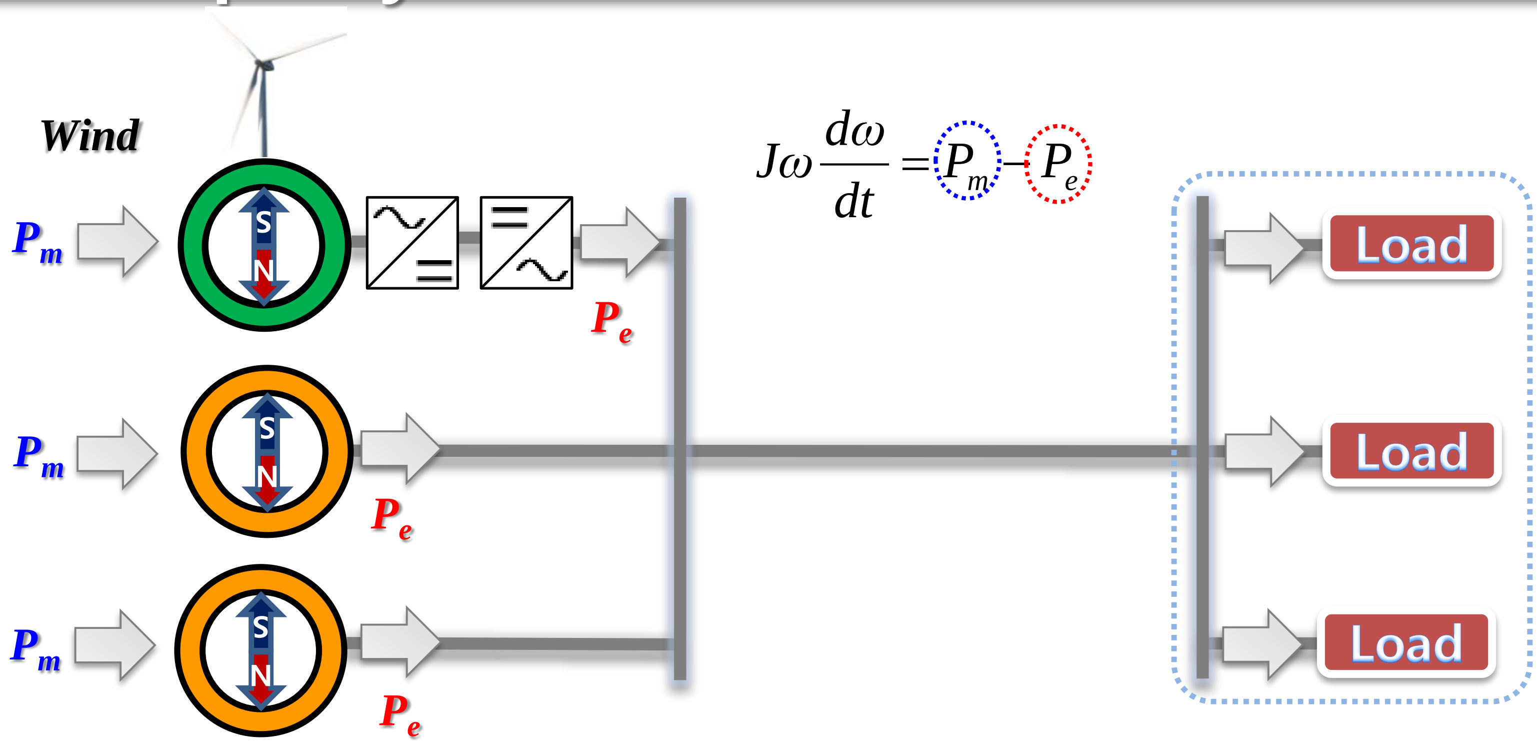


Frequency regulation of a WTG



- **Δf > 0 (Over-frequency)**
  - Reduces output power of a WTG
    - **Frequency decreases**
    - KE is absorbed into the rotating masses, thereby increasing the rotor speed
- **Δf < 0 (Under-frequency)**
  - Increases output power of a WTG
    - **Frequency increases**
    - KE is released from the rotating masses, thereby decreasing the rotor speed
  - Overdeceleration of a WTG should be avoided for stable operation of a WTG

Not Converter but MPPT increases frequency fluctuation!

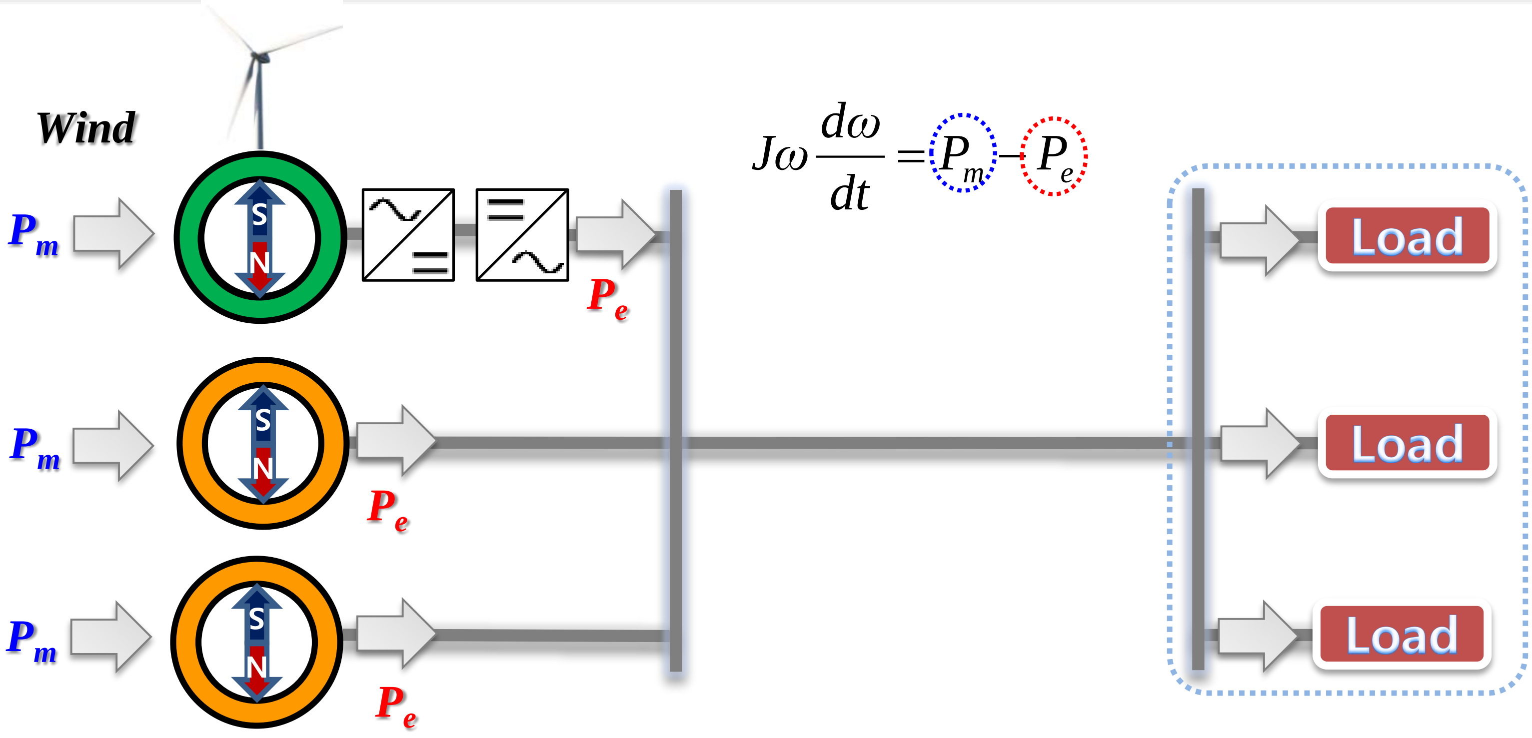


MPPT of a WTG:
- Wind fluctuation → P_e Fluctuation

Frequency fluctuation!

- **Faster ramping capability is required (?)**
- **More reserve is required (?)**

FR of a WTG can mitigate frequency fluctuation!

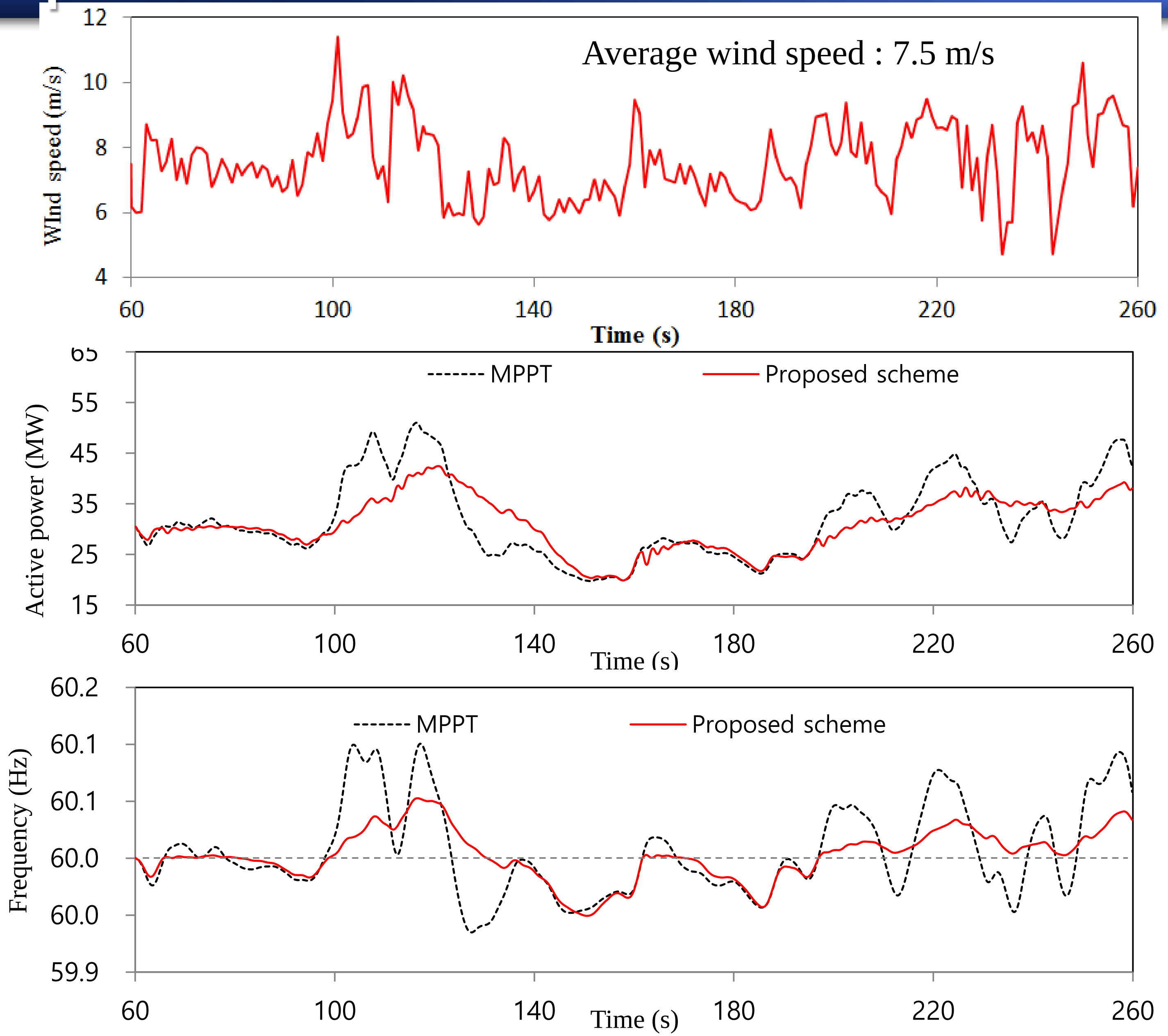


FR of a WTG:
- Fluctuation in wind speed → Smoothing P_e

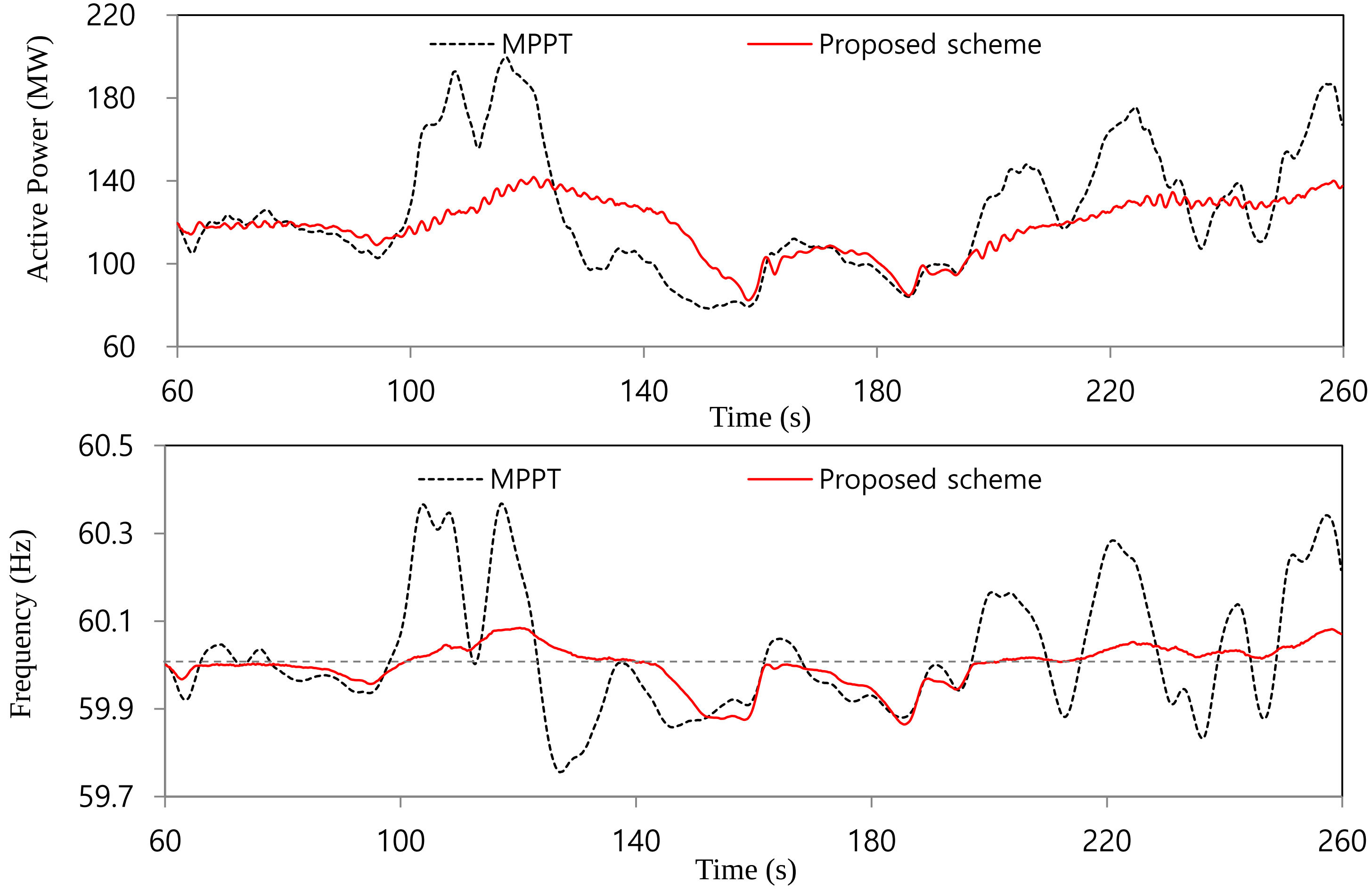
- Stores energy into the rotating masses
- Frequency fluctuation mitigation

FR of a WTG: Same function as ESSs but NO ADDITIONAL COST!!

Frequency regulation for 20% penetration



Frequency regulation for 60% penetration



眾惡之 必察焉
眾好之 必察焉

- 論語 -