# Multi-market Optimization of a Data Center without Storage Systems

For 2020 NA Modelica Conference

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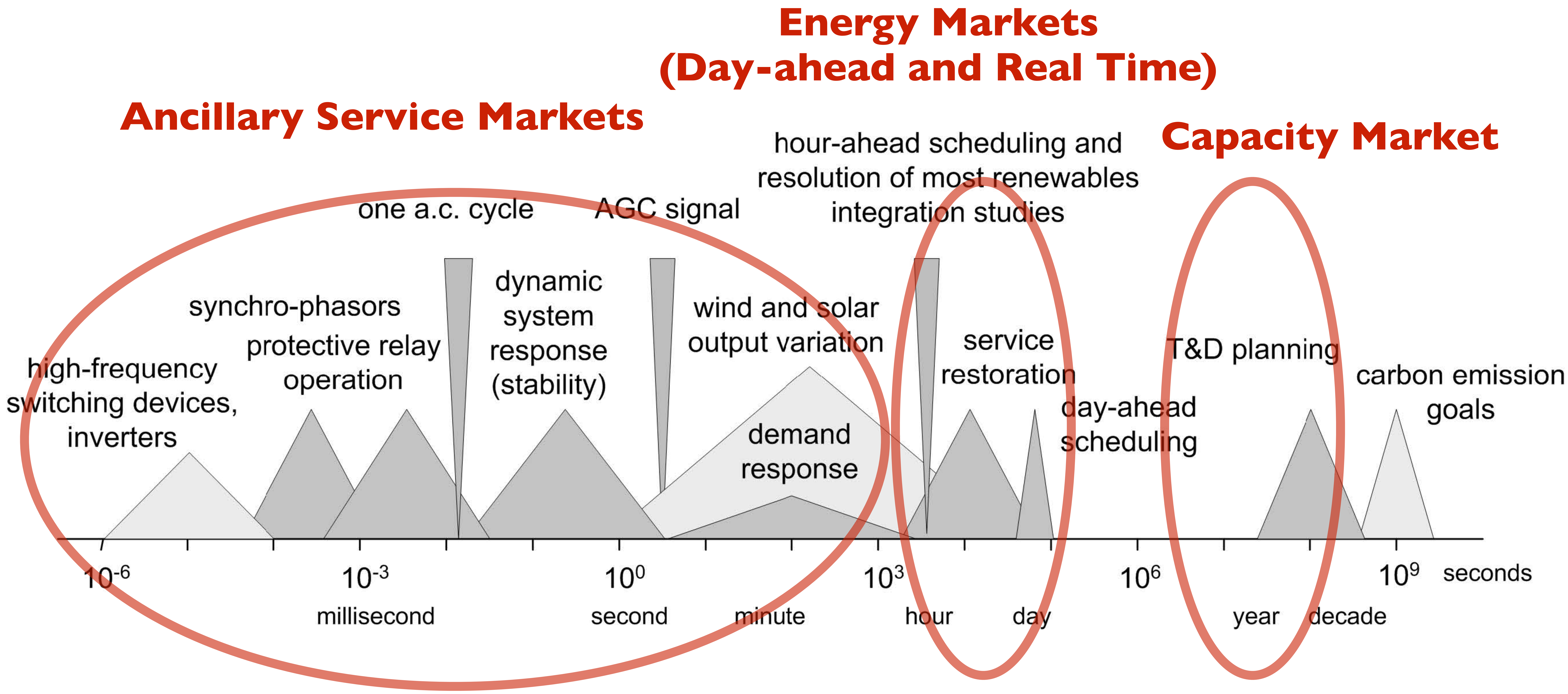
# Agenda

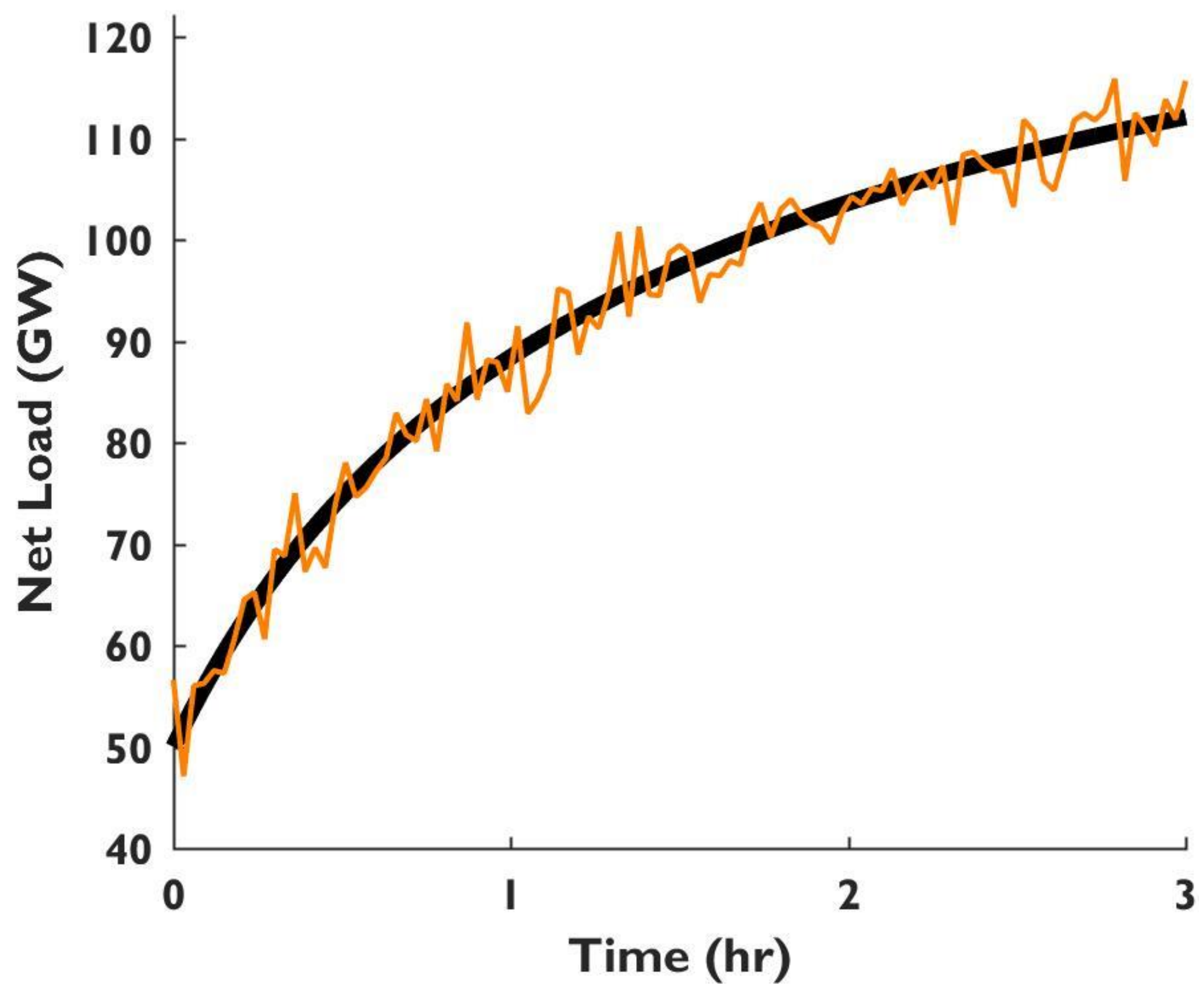
- Background
- Synergistic Frequency Regulation Control
- Model-based Optimal Control Framework
- Case Study
- Conclusions

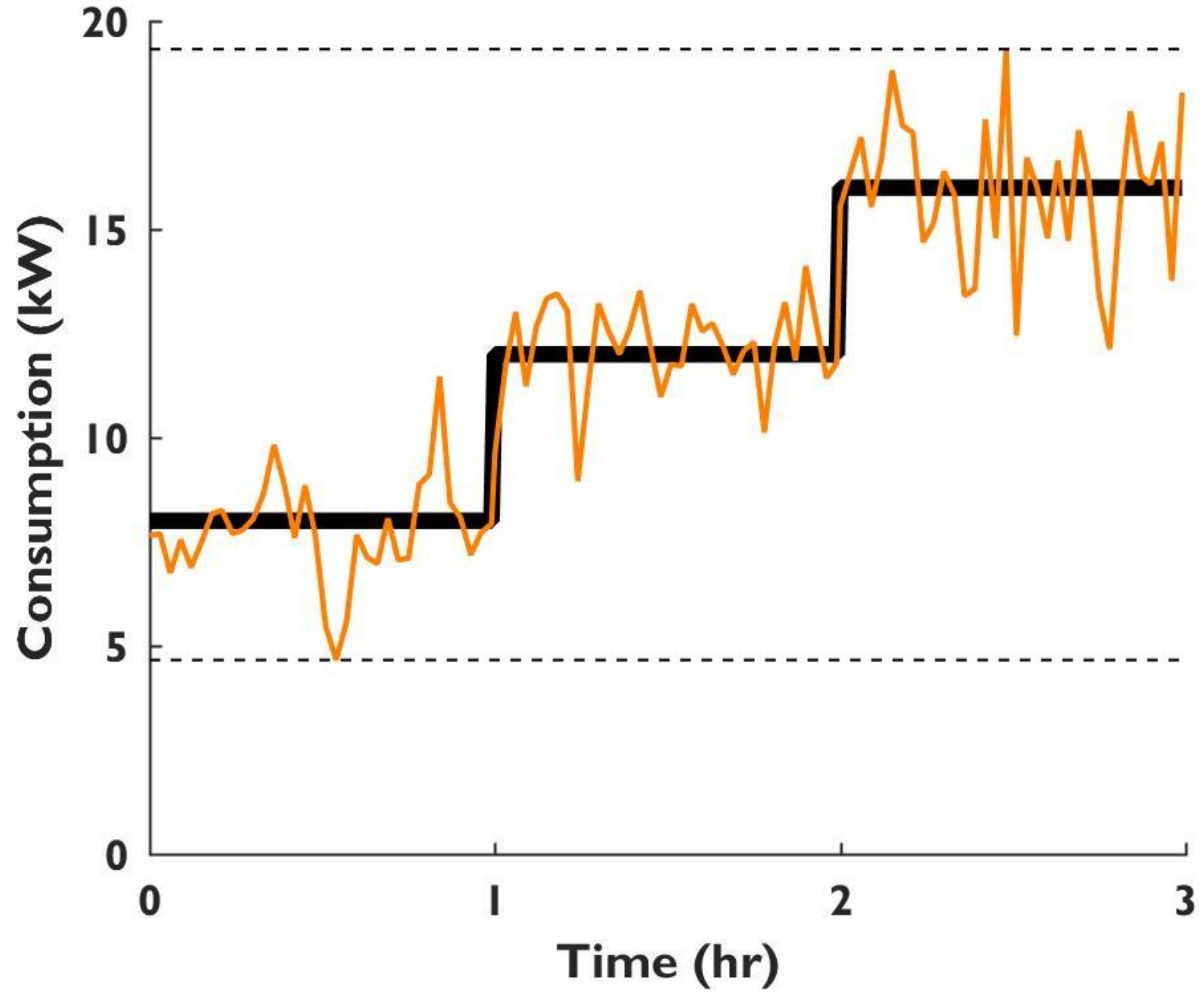
# Electric Market

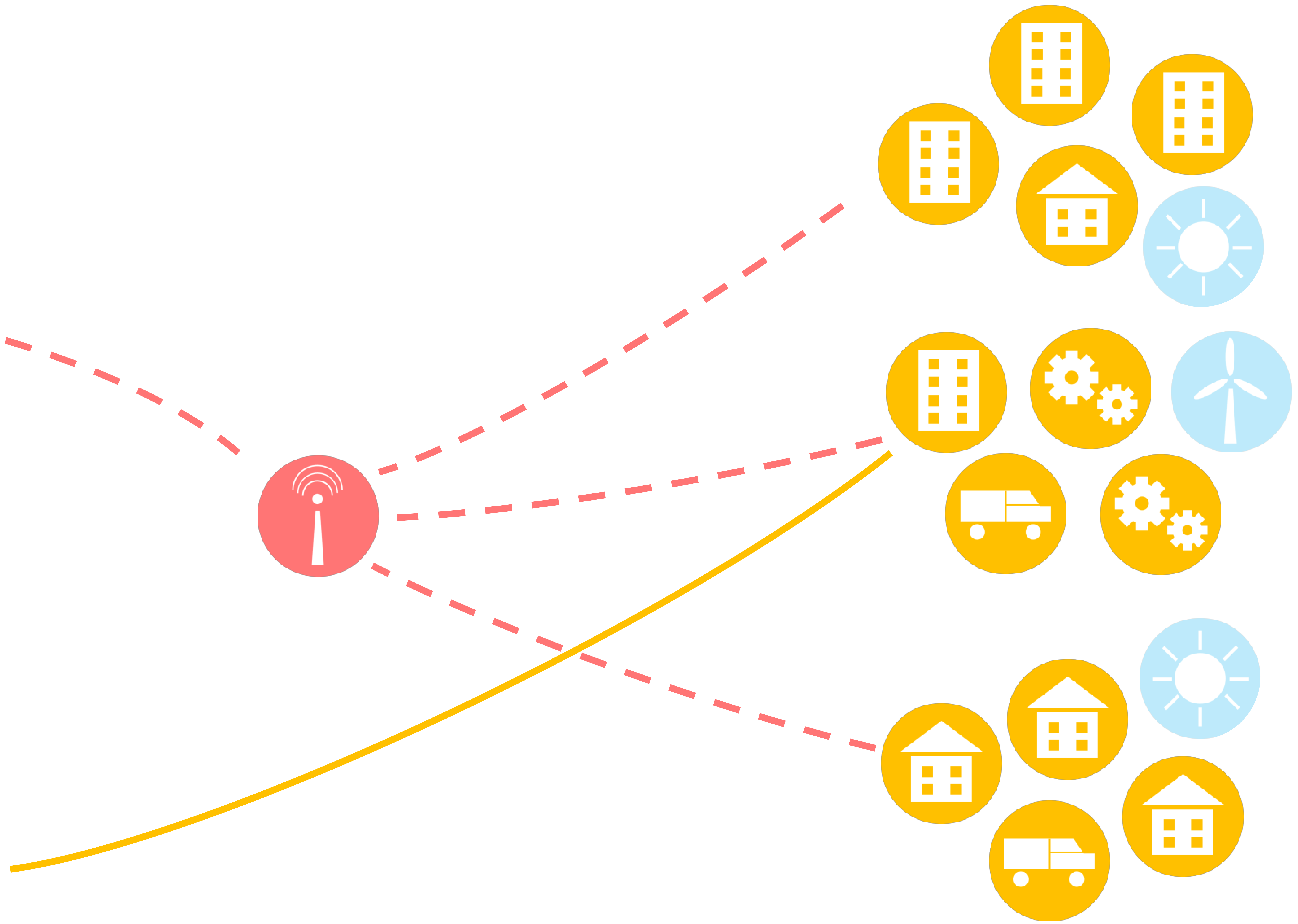


# Buildings-to-Grid Services: Frequency Regulation

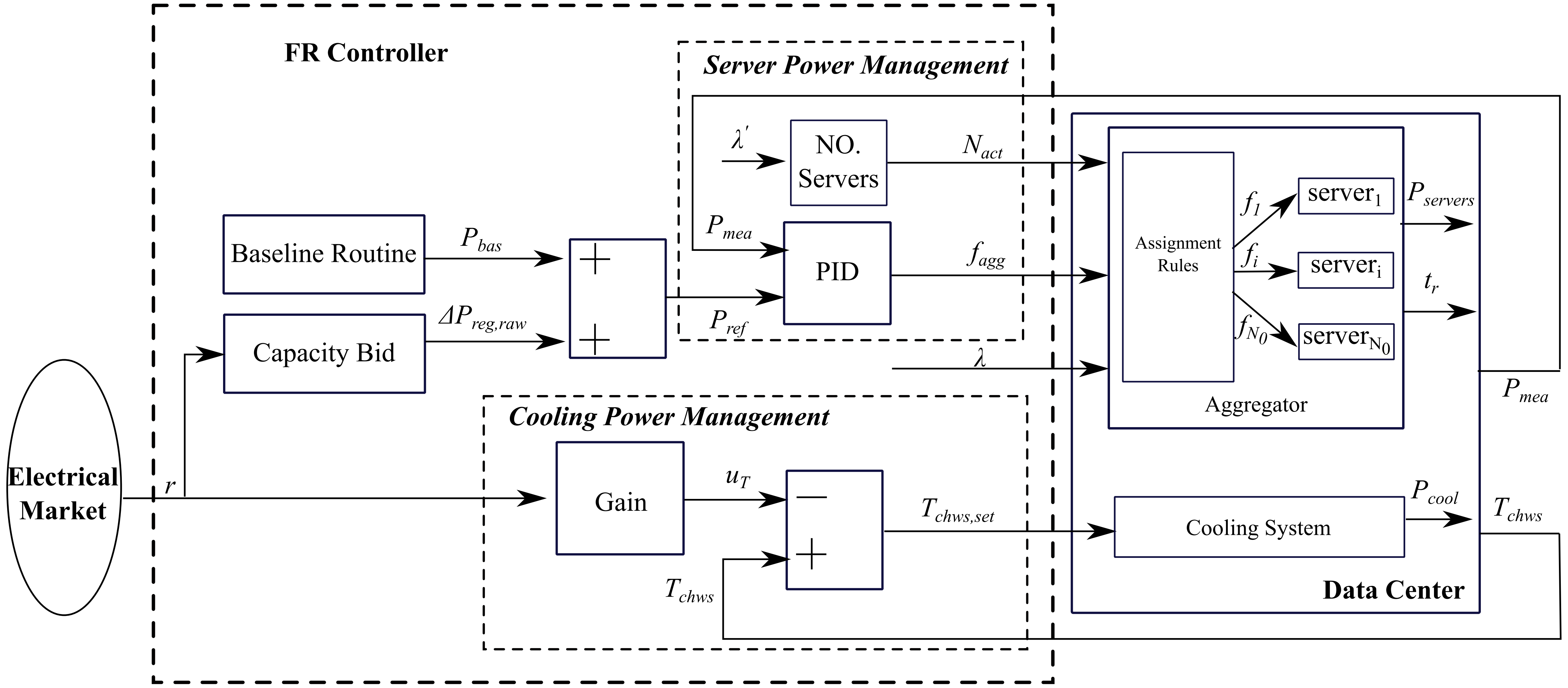
## Regulation



# Proposed FR Control Strategy



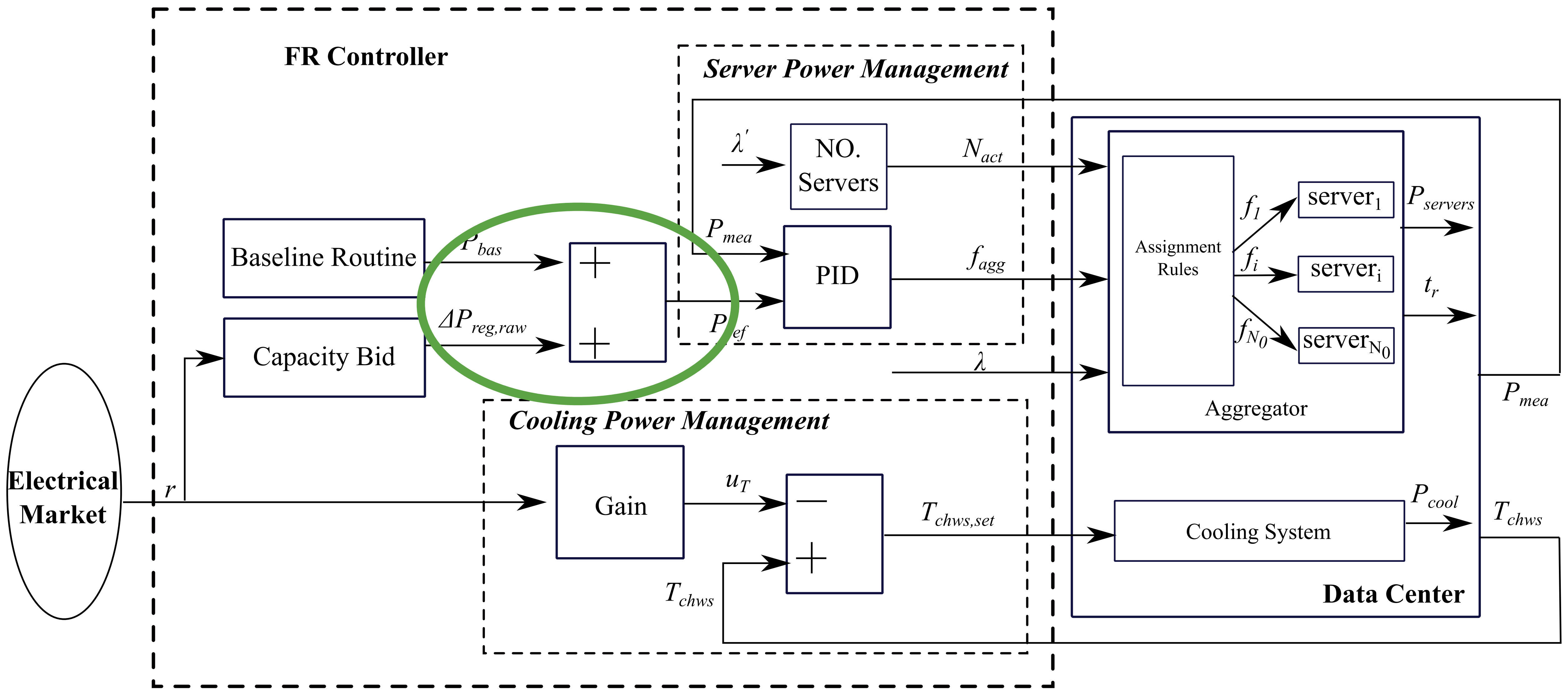

**Baseline Routine**: baseline power without providing FR

**Reference Power Signal**: calculate reference power signal to be tracked

**Server Power Management**: regulate aggregated server power

**Cooling Power Management**: regulate cooling system power

## FR Control: Reference Power Signal




### Reference Power Signal

(1) determine the regulation capacity offer

(2) calculate reference power signal

### Reference Power

$$\Delta P_{reg,raw}(t) = r(t)C_{reg}$$

$$P_{ref}(t) = P_{bas}(t) + \Delta P_{reg,raw}(t)$$

***r***: normalized FR signal from PJM market

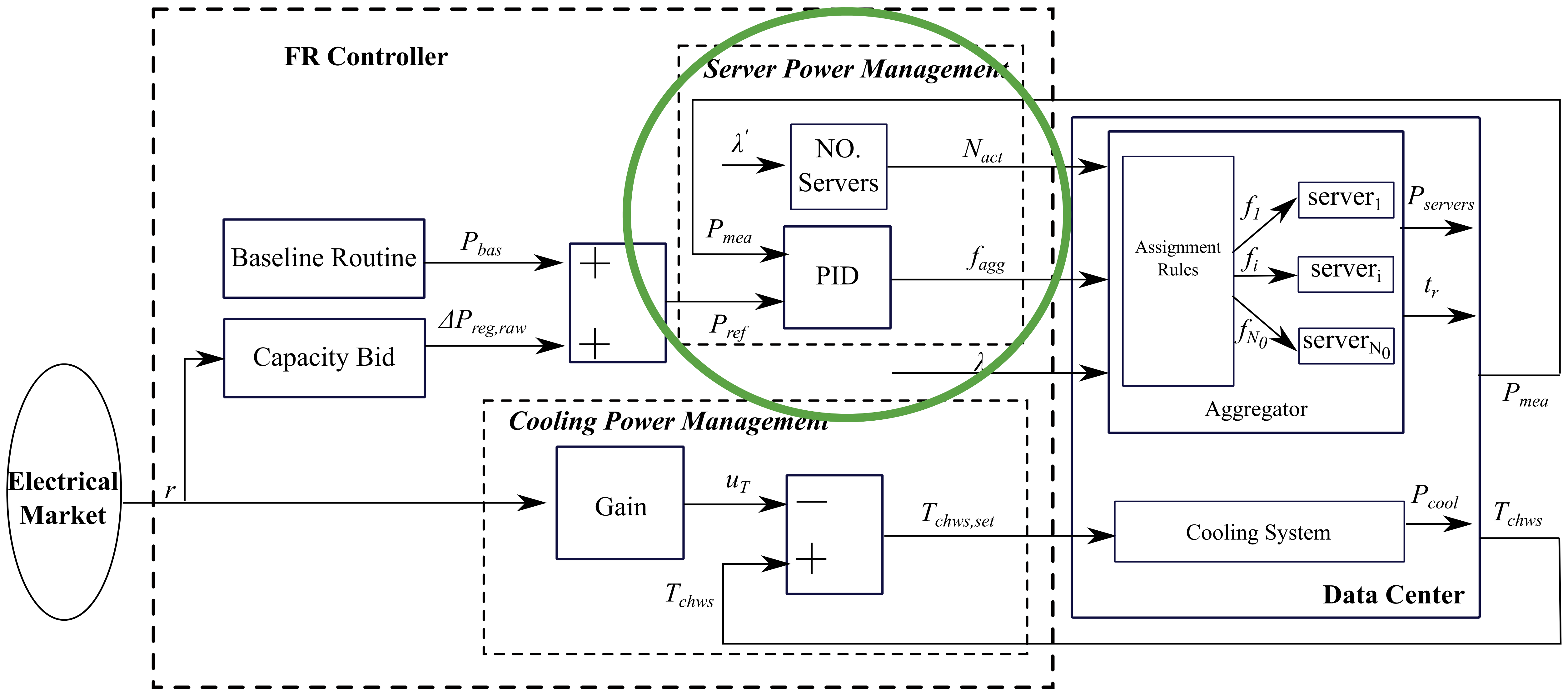
***$C_{reg}$***: regulation capacity offer by data center

***$P_{bas}$***: baseline power without providing FR

***$\Delta P_{reg,raw}$***: regulated power data center should provide

***$P_{ref}$***: reference power signal data center should follow

# FR Control: Server Power Management




## Server Power Management

(1) determine the number of active servers every hour based on predicted workload

(2) regulate aggregator frequency every 4 seconds based on FR signals from the electrical market

## Number of active servers:

$$N_a(t) = \lceil \beta \frac{\gamma \lambda_{mean}(t)}{k} \rceil, N_a(t) \in \{0, N_0\}$$

Number of Active Servers

Design Factor

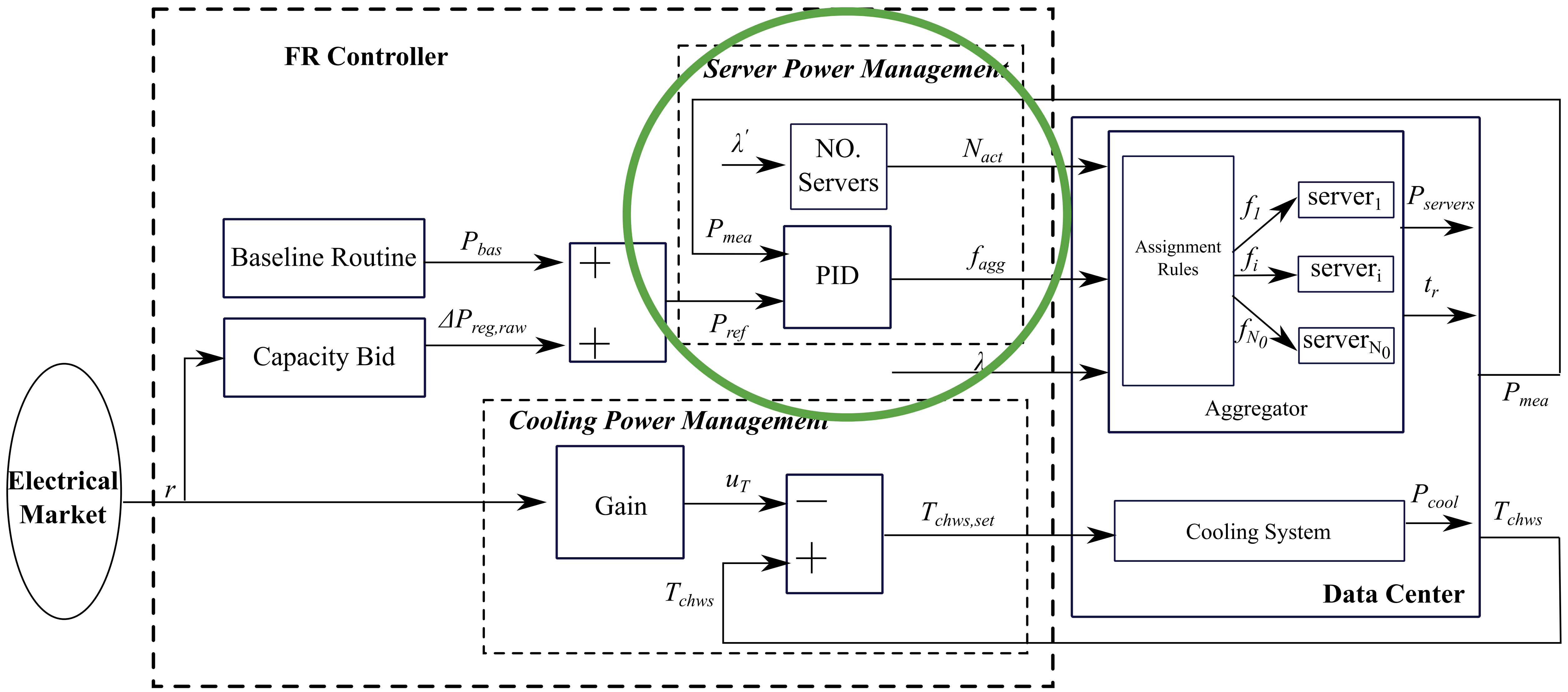
Mean Work Load

Nominal Number of Servers

**Introduced Flexibility Factor**

Nominal Service Rate

# FR Control: Server Power Management




## Server Power Management

(1) determine the number of active servers every hour based on predicted workload

(2) regulate aggregator frequency every 4 seconds based on FR signals from the electrical market

## Aggregated frequency regulation

(1) A PID controller is used to track reference power

(2) Service average response time determines the minimum aggregated frequency

### PID control

$$f(t) = K_p e(t) + K_i \int_0^t e(x)dx + K_d \frac{\mathrm{d}e(t)}{\mathrm{d}t}, f(t) \in (f_{min}, f_{max})$$

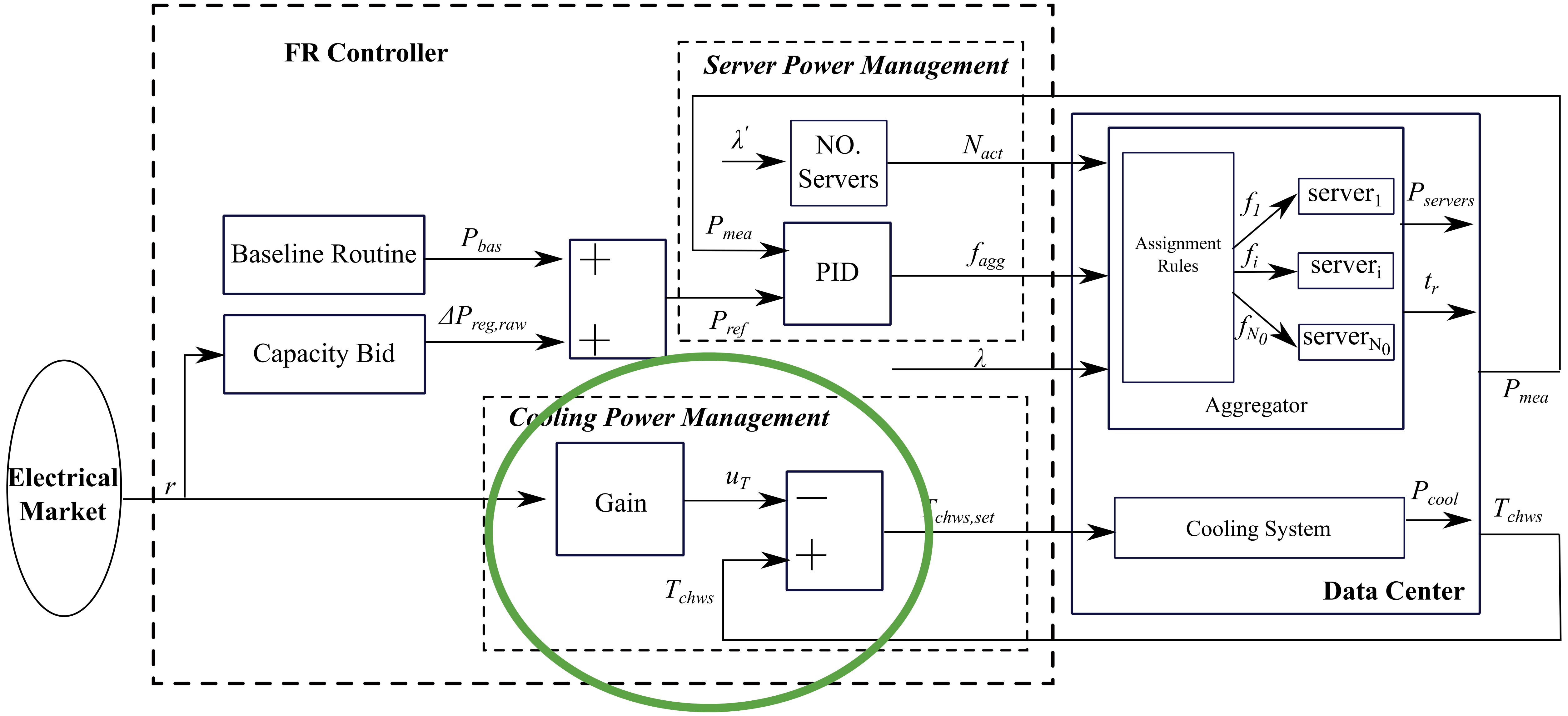
$$e(t) = P_{ref}(t) - P_{mea}(t)$$

$f_{min}$: service stability, response time

$$f_{min}(t) = \frac{\lambda(t)}{kN_a(t)\rho^*(t)}$$

$f_{max}$: nominal frequency, normalized as 1

# FR Control: Cooling Power Management




## Chilled Water Temperature Reset

$$T_{chws,set}(t) = T_{chws}(t) - \Delta T r(t)$$

CHWT Setpoint

CHWT

Regulation Range

FR Signal

## Thermal Dynamics

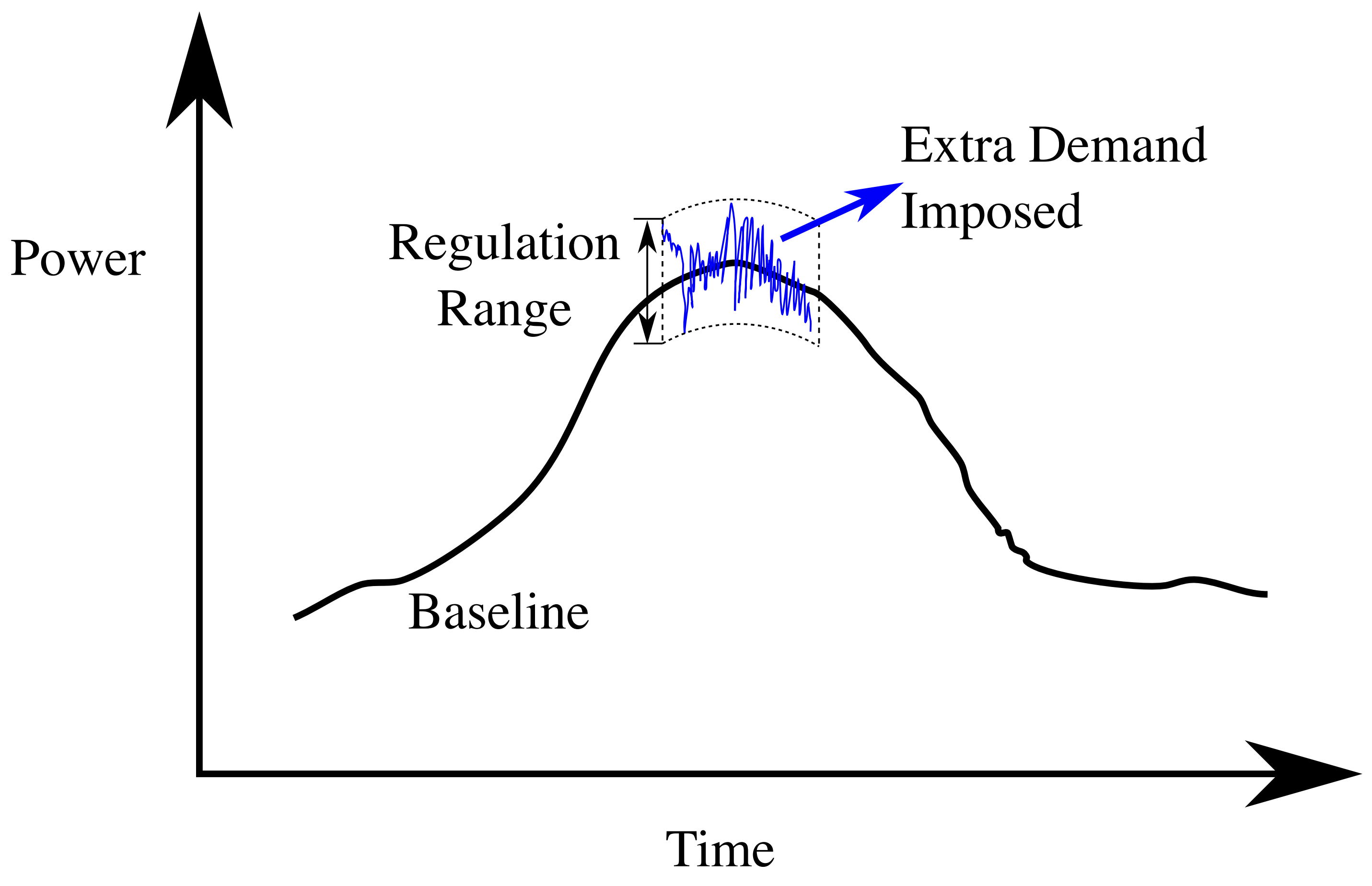
$$mC_p \frac{dT}{dt} = \dot{m}_i C_p T_i - \dot{m}_o C_p T + \dot{q}$$

$$\dot{m}_i = \dot{m}_o = \dot{m}$$

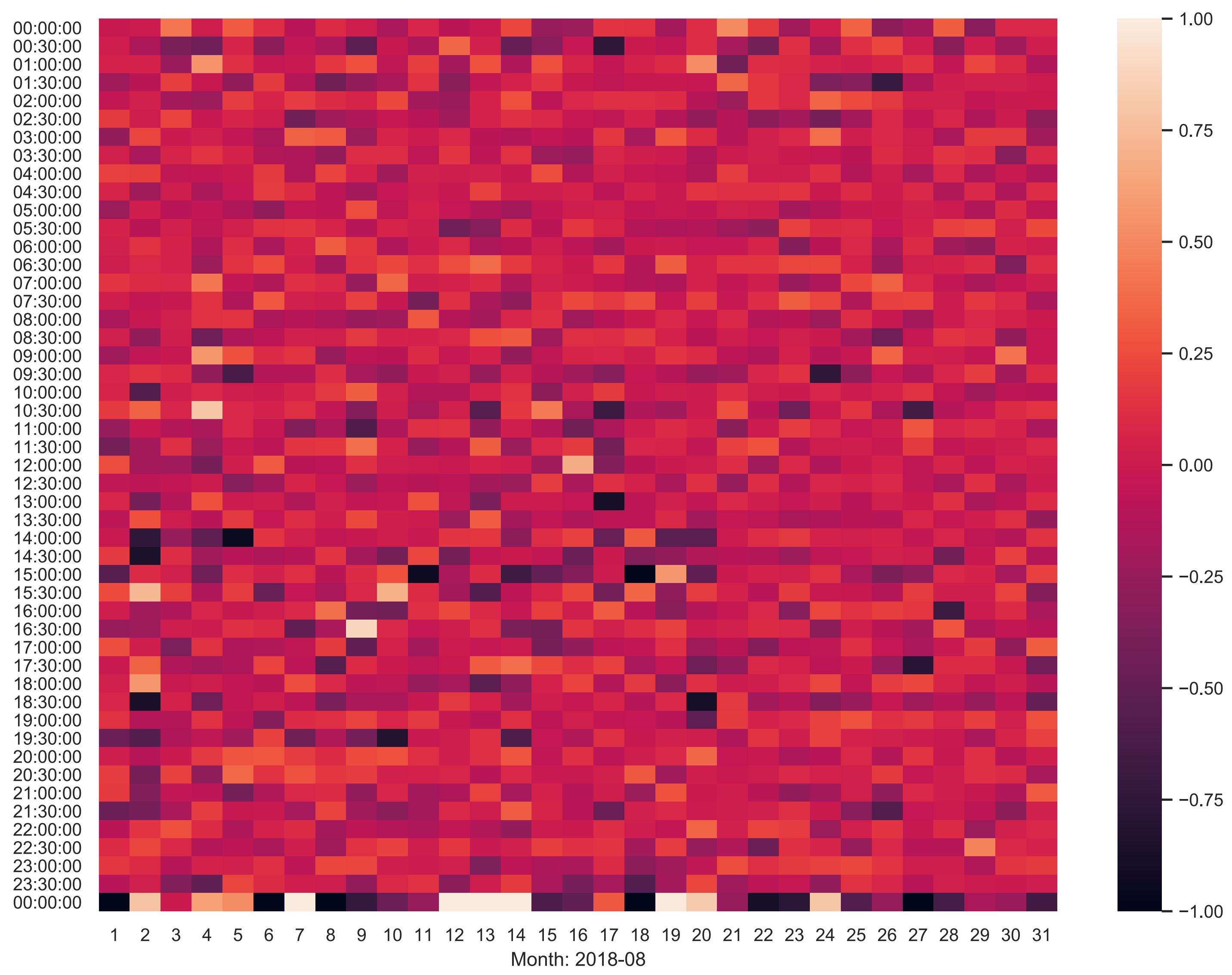
$$\tau = \frac{m}{\dot{m}}$$

***Time Constant in Chiller Evaporators***

# Model-based Optimal Control Framework




(a) extra demand exposed to FR baseline




(b) Normalized extra demand of 30 minutes during July, 2018 in PJM

**Objective**

$$\min J(C_{reg}) = E_{cos} + D_{pen} - R_{rev}$$ Operation costs

$$E_{cos} = \int_t^{t+\Delta t} p_{em}(t) P_{DC}(t) dt$$ Energy costs

$$D_{pen} = p_{dm} \cdot \max((P_{dm} - P_{dm,lim}), 0)$$ Demand penalty

$$R_{rev} = \int_t^{t+\Delta t} p_{rm}(t) s(t) C_{reg}(t) dt$$ FR revenues

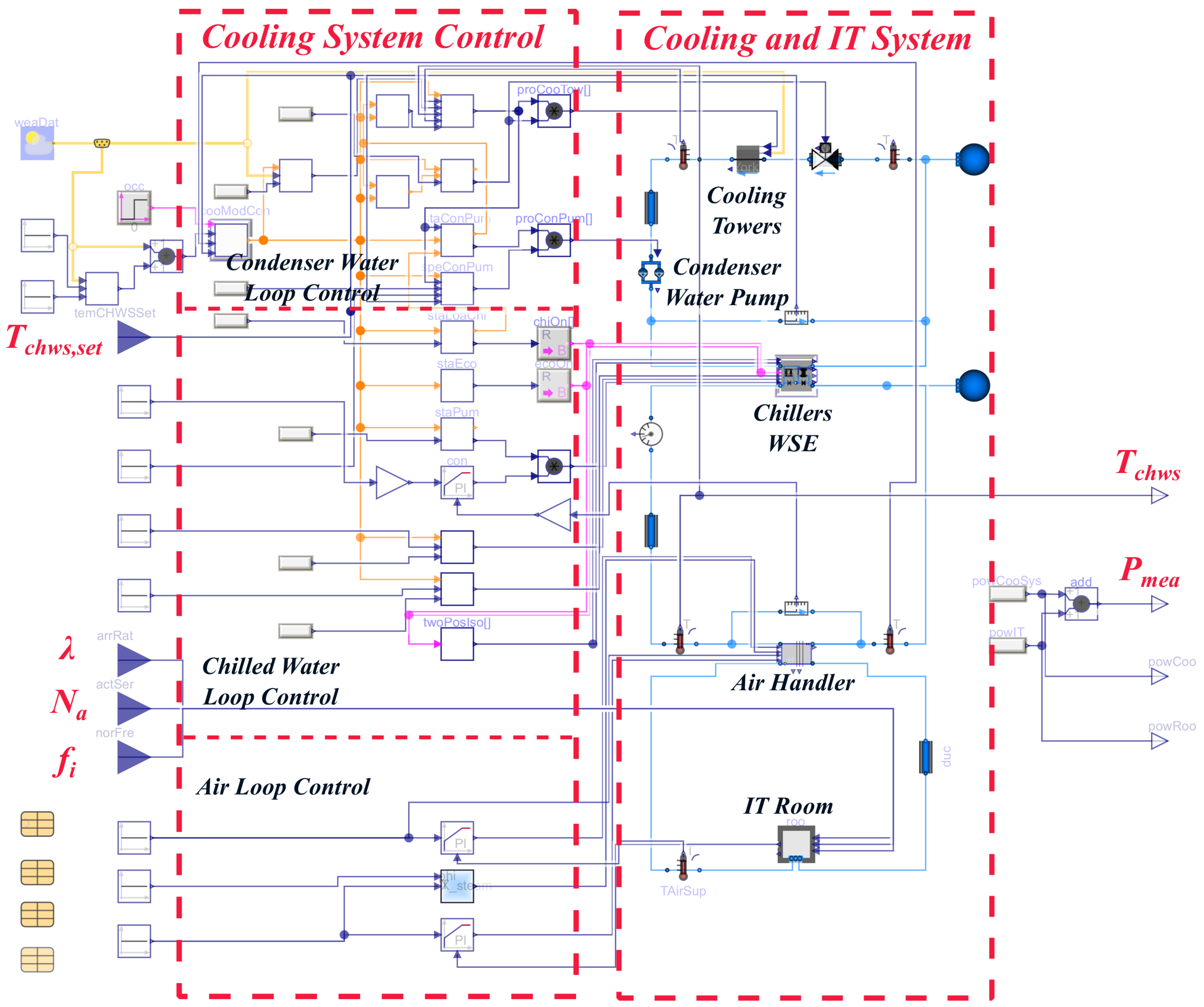
**Constraints**

$$0 \leq C_{reg}(t) \leq C_{reg,max}(t)$$ FR capacity bids

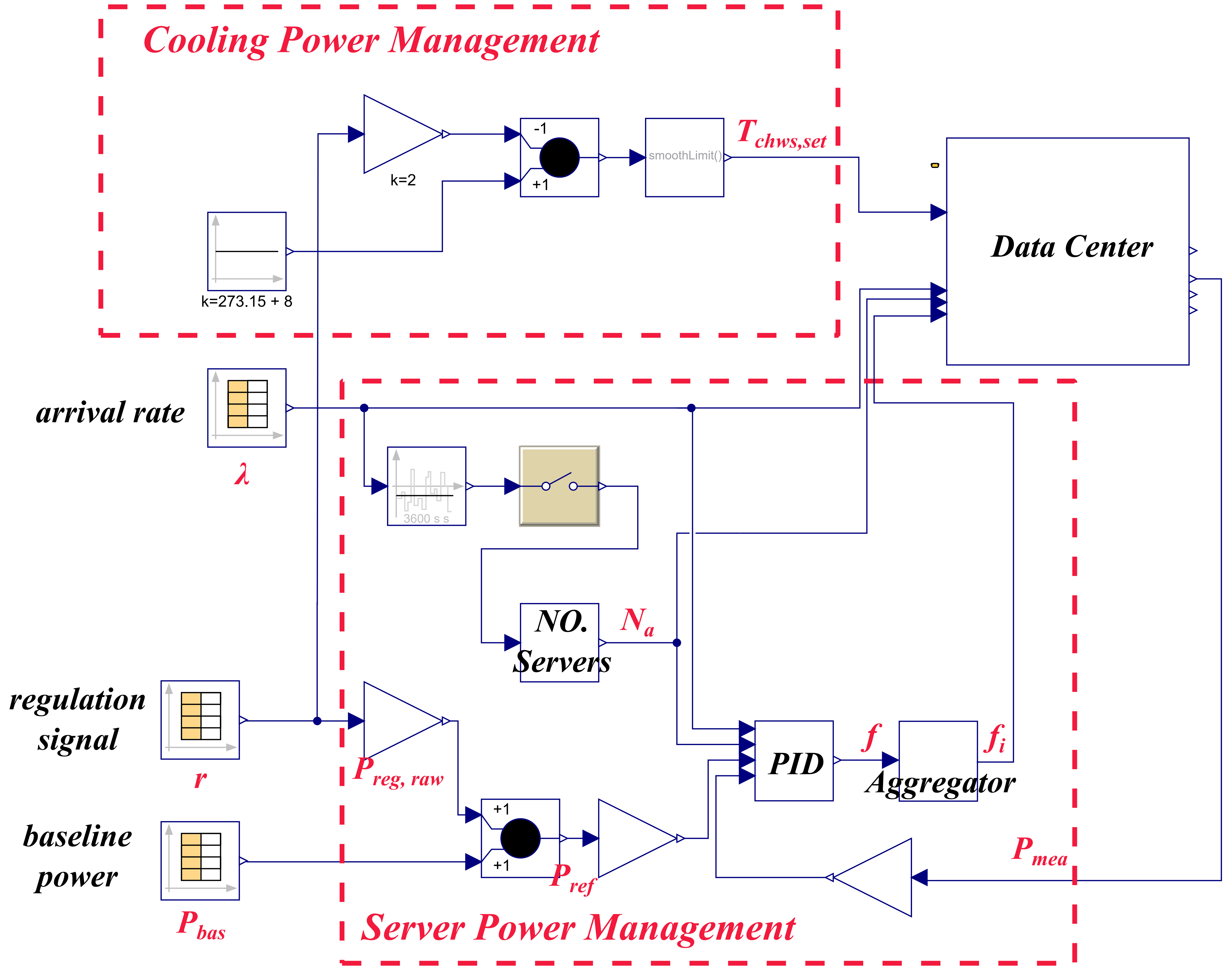
$$t_r(t) \leq t_{r,u}$$ Server service response time

$$s(t) \geq s_l$$ FR performance score

# Case Study

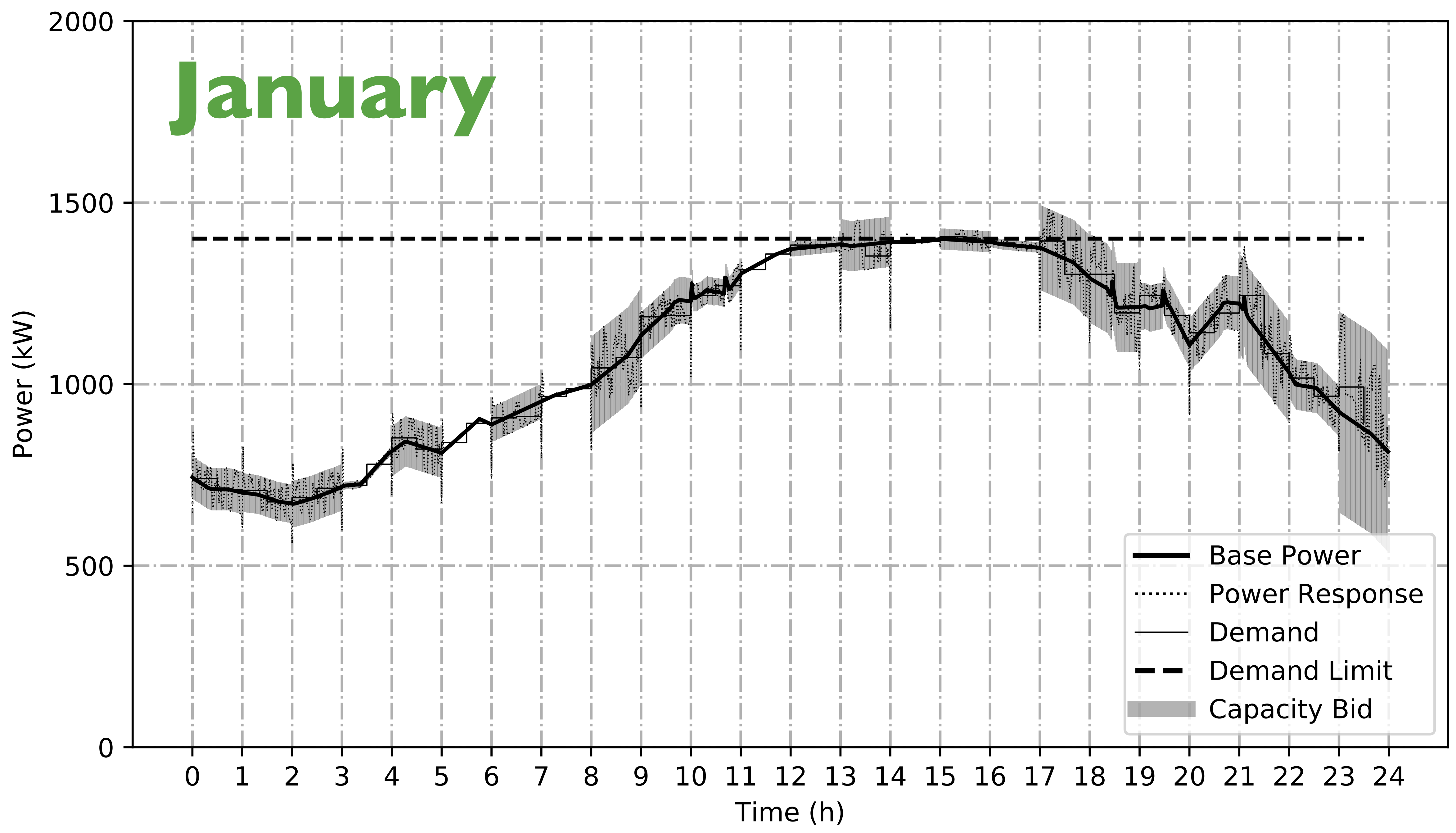


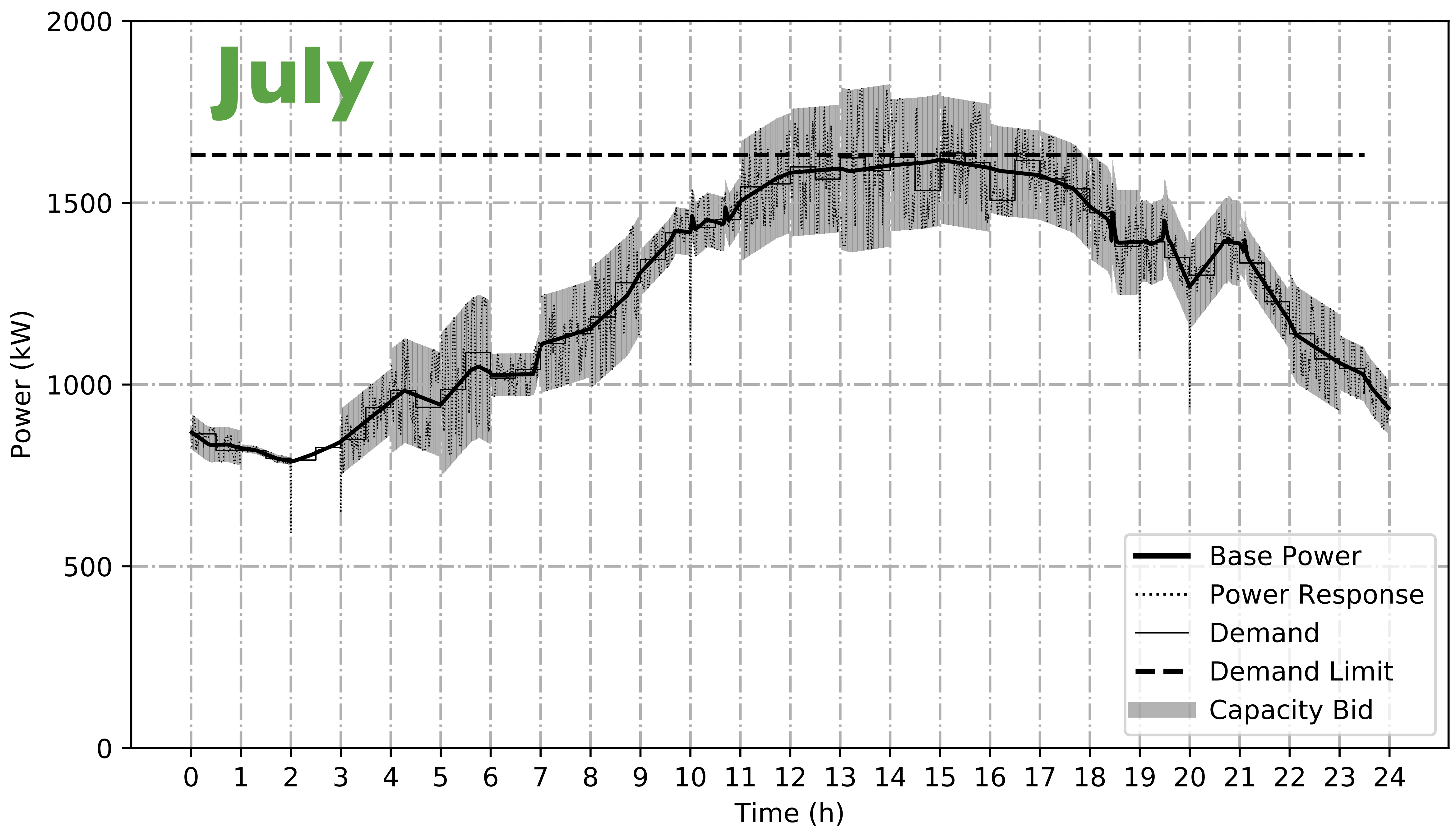

Modelica Model of Data Center Cooling and IT System




Model of Frequency Regulation Controller

# Case Study: Simulation Results




- The optimal FR capacity bid is a result of RegA/D signal profile, energy prices, and FR service prices.
- The capacity bid is about **5 kW to 223 kW**
- The optimization framework can save **$23.6** and **$123.6** over two days in January and July, respectively. The savings mainly from providing FR service.

# Conclusions

(1) A synergistic control strategy is proposed to enable FR service in data centers without TESS

(2) Real-time optimal control framework enables data centers to minimize operational costs from energy market and regulation market.