Stochastic Energy Management of Energy-Efficient Building under the Risk of Uncertain Solar Power Supply

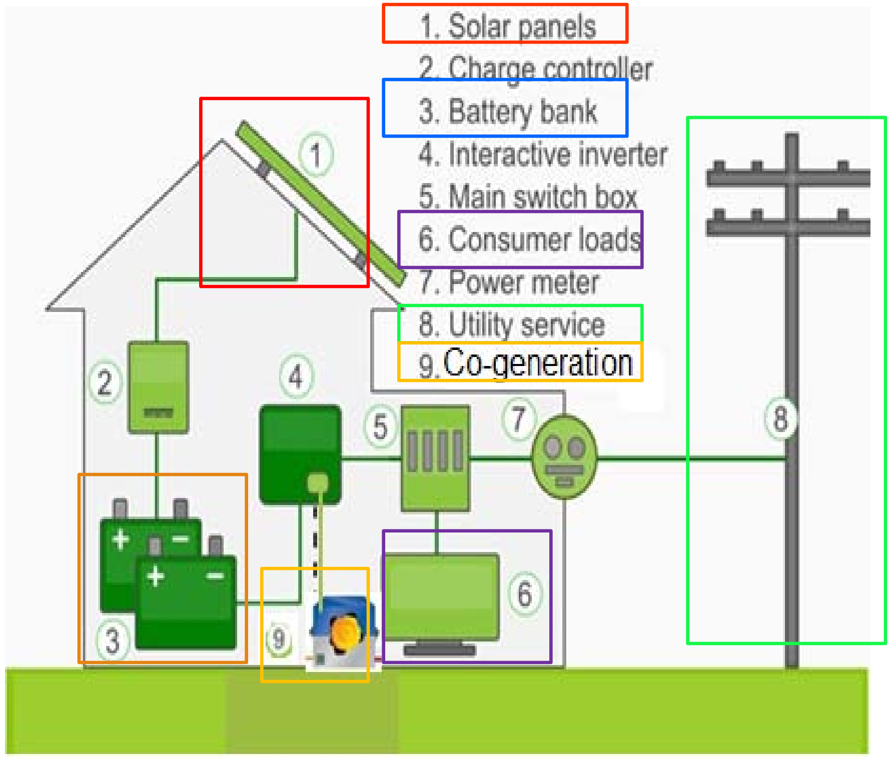
Ping Liu

MISSISSIPPI STATE UNIVERSITY

U.S.A

Smart grid

➢ The goal of smart grid is to make the next generation power grid a green, reliable, and intelligent system.

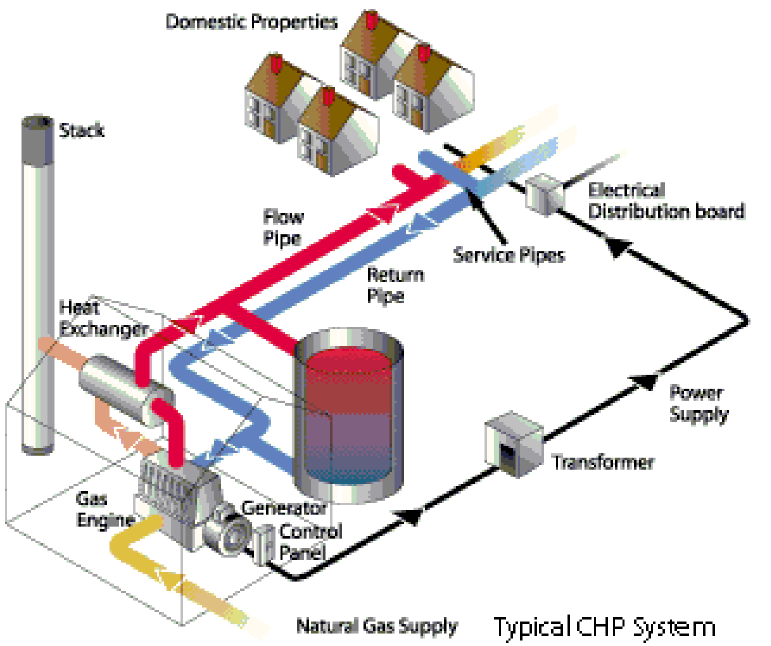


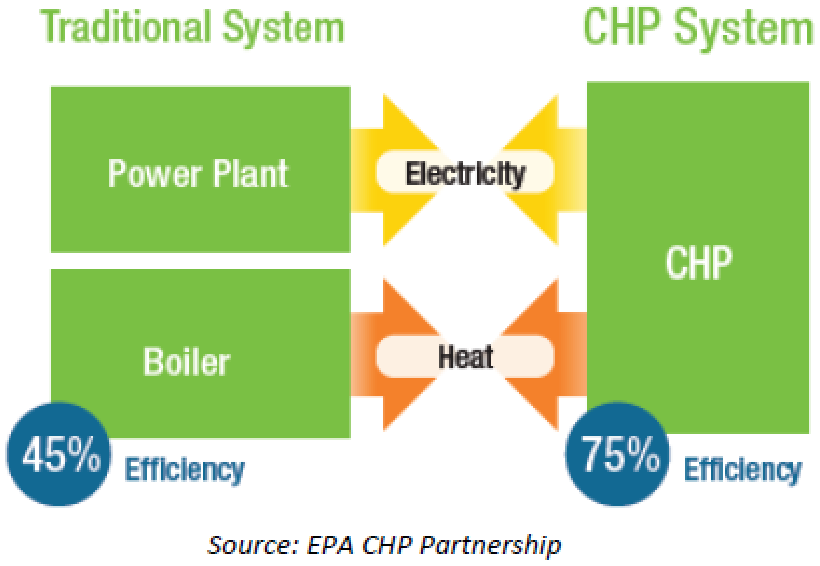
Smart building energy systems

Solar powered house (*www.energy.gov*)

Combined Heat and Power system

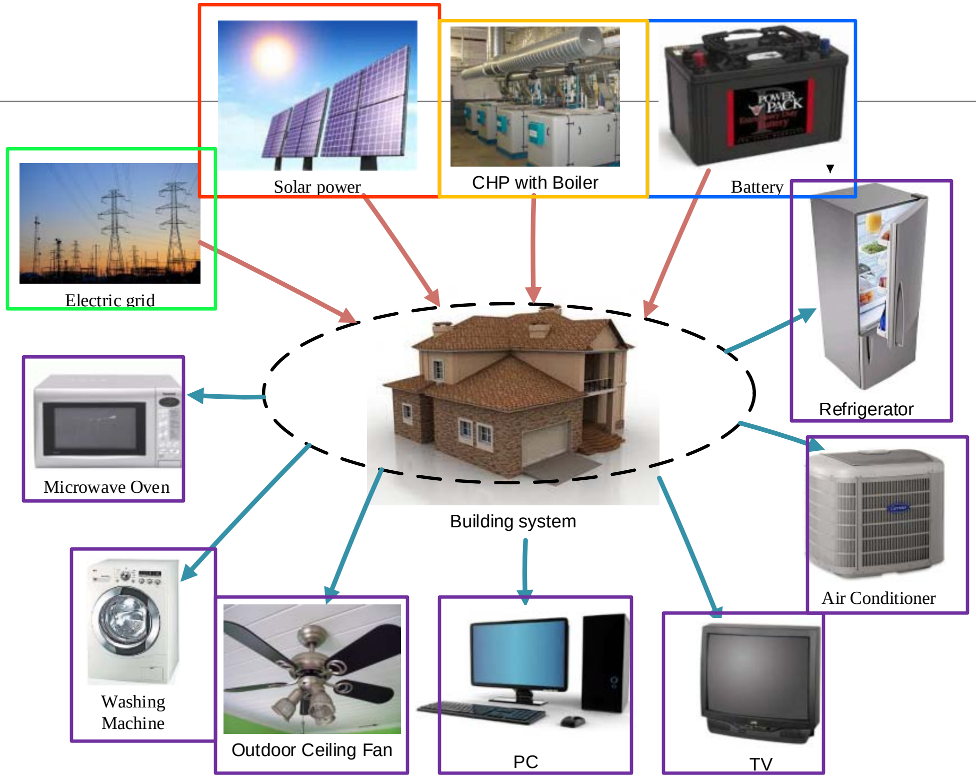
- Benefits of CHP
  - Improve power reliability by reducing or eliminating a building's dependence on the electric power grid.
  - Meet not only the electricity demand of the new buildings but also to provide for their cooling and heating requirements.

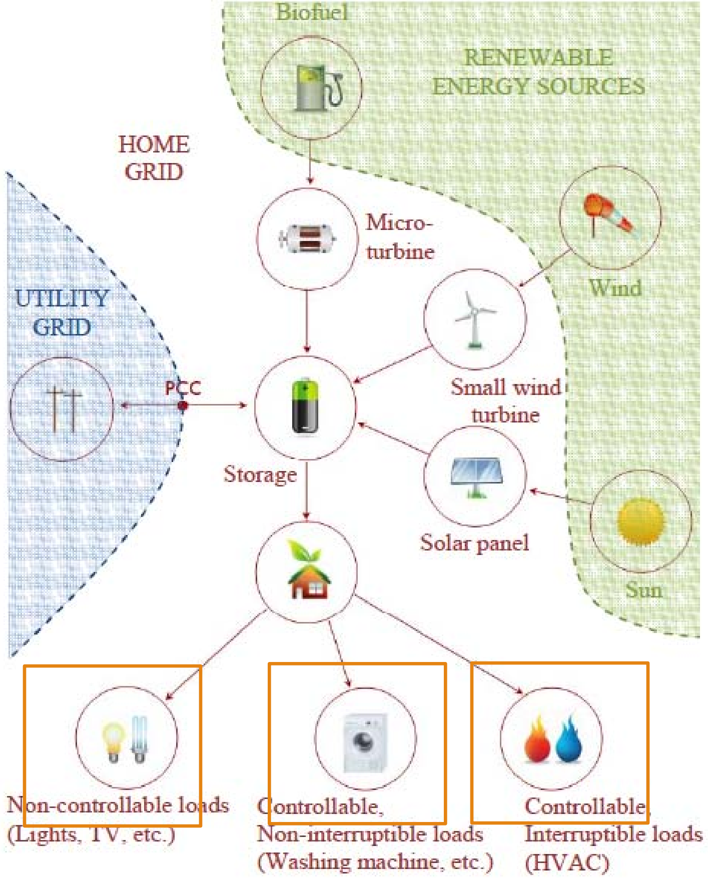




CHP efficiency comparison

Categories of building appliances



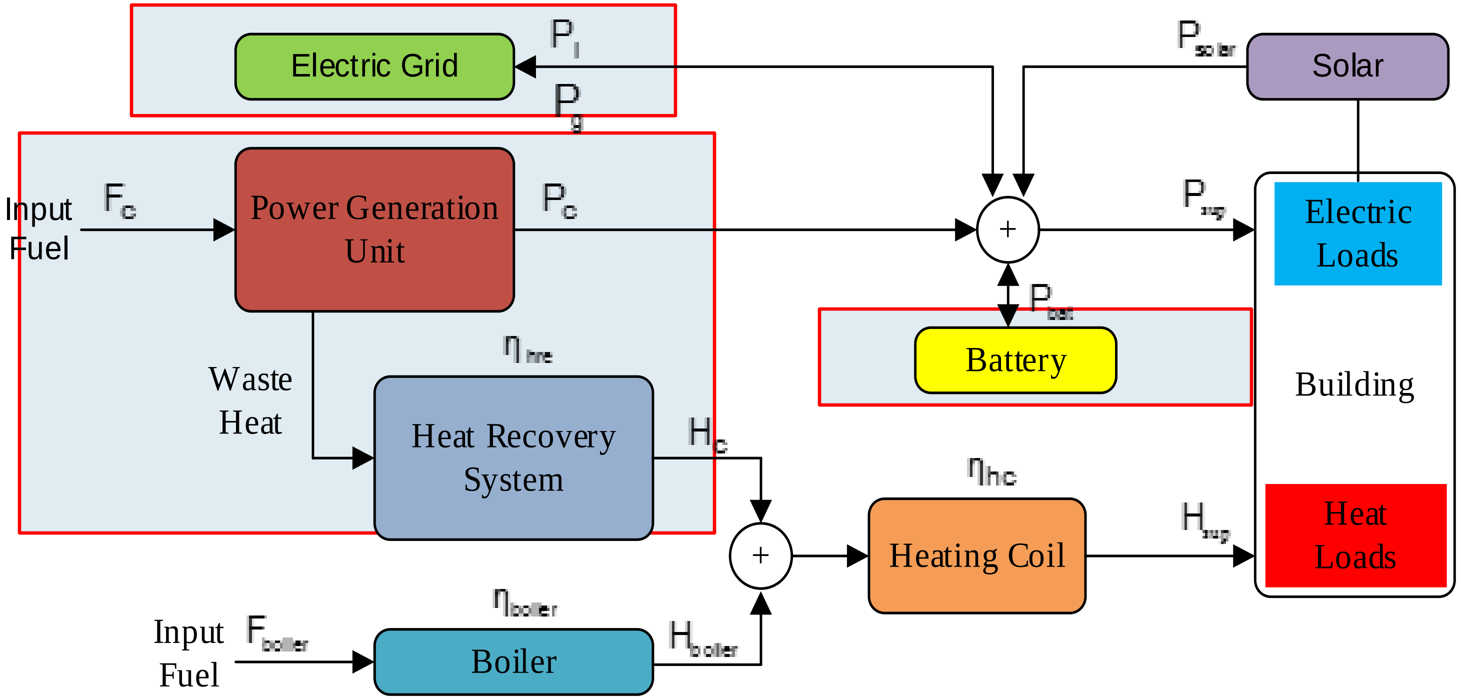


Home Grid – Potential components

Source: T. Hubert, S. Grijalva, realizing smart grid benefits requires energy optimization algorithms at residential level

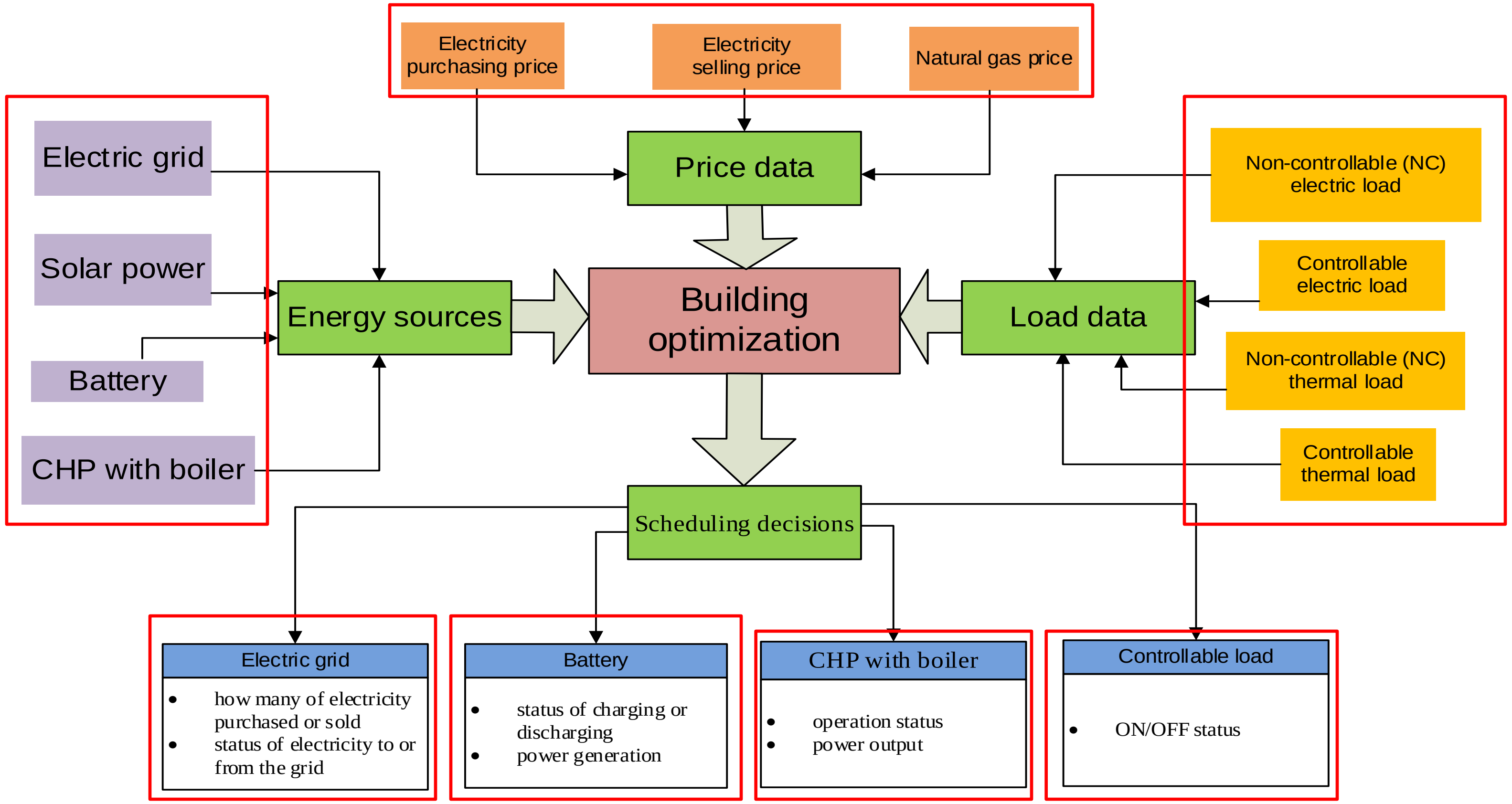
Smart meter is introduced in smart grid to increase operation efficiency, reliability and flexibility.

Modeling of building energy system



Energy flow diagram of energy-efficient building

Problem statement



Stochastic optimal operation

- Properties of stochastic programming
  - Explicitly incorporates a probability distribution of the uncertainty;
  - Relies on pre-sampling discrete scenarios of the uncertainty realizations;
  - Provides probabilistic guarantees to the system reliability with stochastic solutions;
  - Provides the optimal strategy (policy) for the realization of uncertainty.

Multi-stage stochastic linear programming

$$F(x) = c \cdot x_1 + E\{Min_{x_2}(q_1 \cdot x_2 + E(Min_{x_3}(q_2 \cdot x_3) + ...))\} \rightarrow Min$$

Intra-period constraints $Ax_1 = b, \quad x_1 \in X,$

Inter-period constraints $W_1 \cdot x_2 + T_1 \cdot x_1 \le h_1, \; W_2 \cdot x_3 + T_2 \cdot x_2 \le h_2, \, ...,$

$$x_2 \in R_+^{m_1}, \; x_3 \in R_+^{m_2}, \quad ...$$

The multi-stage stochastic programming is a promising approach to account for the impact of the uncertainties in the energy consumption and renewable energy generation on power dispatch decisions of energy-efficient buildings.

Uncertainty modeling

- ARMA (1,1)—Auto regressive moving average series

$$X(0) = 0$$

$$Z(0) = 0$$

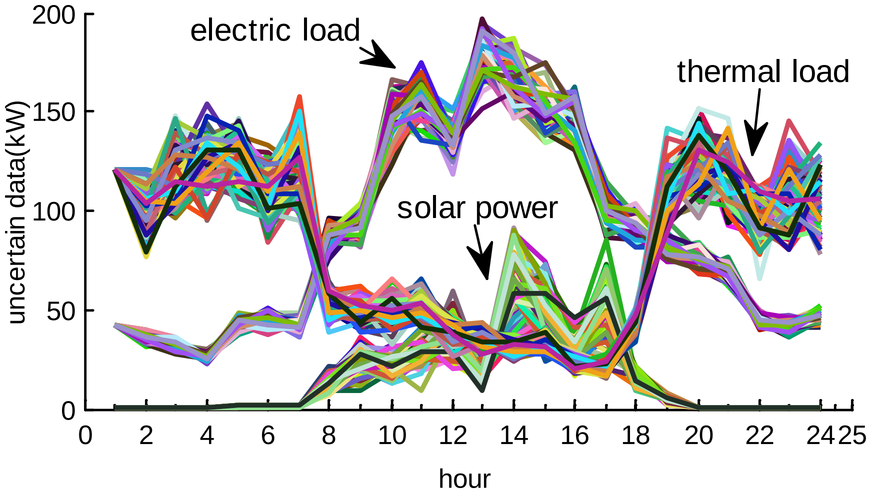
$$X(k) = \alpha X(k-1) + Z(k) + \beta Z(k-1)$$

Where X(k) = forecast error in forecast hour k

Z(k) = random Gaussian variable with standard deviation σ_Z in forecast hour k ∈ N

α, β = parameter of the ARMA-series.

- The auto-regressive parameter α_i is 0.95,
- The moving average parameter β_i is 0.02.
- The standard deviation of the noise process z_{tj} for the error of non-controllable electric and thermal loads, solar power output is 0.2, 0.3, and 0.5, respectively.



Scenarios generated for each uncertainty with ARMA model (100 groups)

Scenarios Reduction

- **A scenario is defined as a sequence of nodes of the tree**:

$$\xi^{(i)} = \left(\eta_0, \eta_1^{(i)} \ldots, \eta_{n_T}^{(i)}\right),\ i = 1,2,\ldots,n_S$$

- **Determine the scenario to be deleted**

$$\pi^{(s^*)} \min_{s \neq s^*} d\left(\xi^{(s)}, \xi^{(s^*)}\right) = \min_{m \in \{1,\ldots,n_S\}} \pi^{(m)} \min_{n \neq m} d\left(\xi^{(n)}, \xi^{(m)}\right)$$

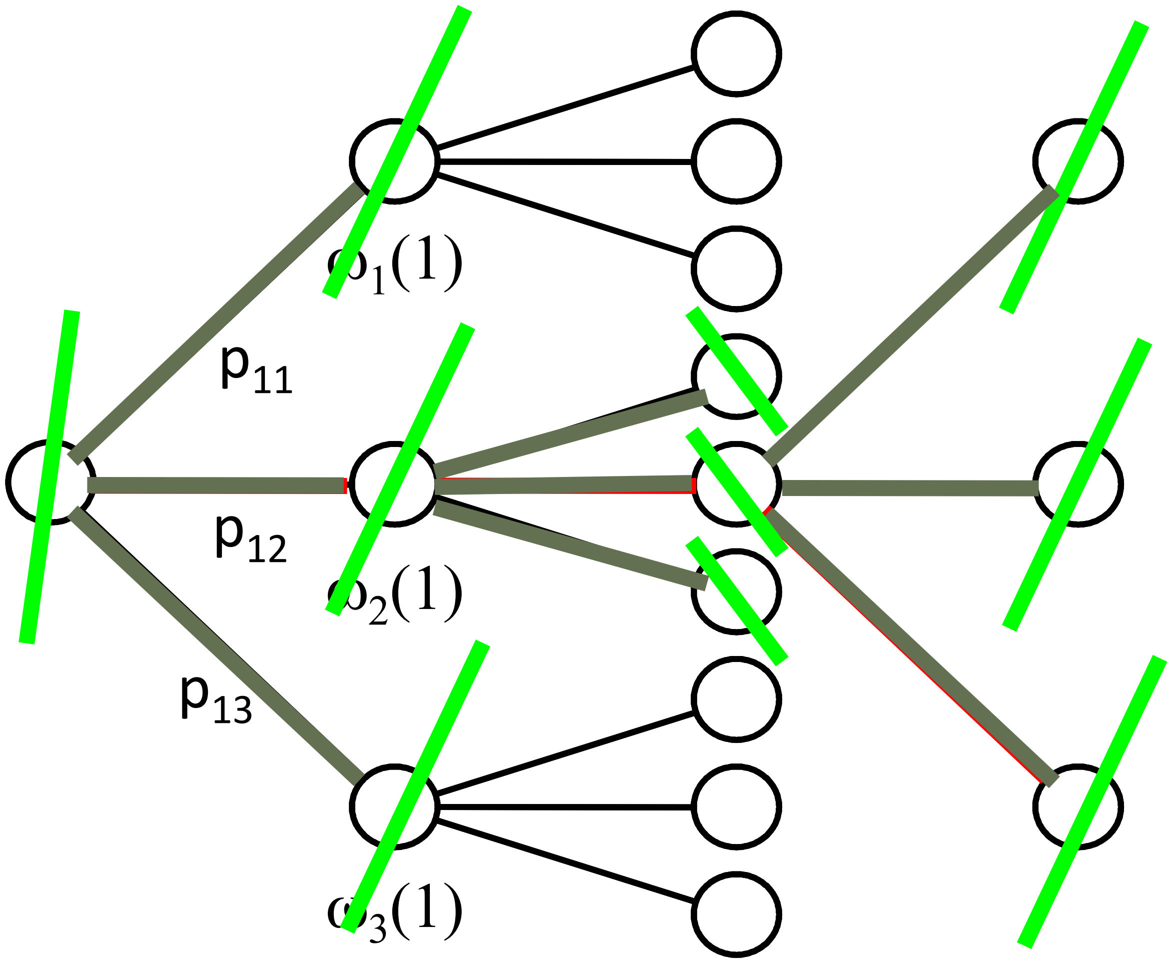
- **Change the probability of the scenario that is the nearest to the deleted one**

$$d\left(\xi^{(\bar{s})}, \xi^{(s^*)}\right) = \min_{s \neq s^*} d\left(\xi^{(s)}, \xi^{(s^*)}\right)$$

$$\pi_{0,1}^{(\bar{s})} := \pi_{0,1}^{(\bar{s})} + \pi_{0,1}^{(s^*)}$$

- **Change the number of scenarios**

$$n_S := n_S - 1$$



Andy Philpott, Stochastic Optimization in Electricity Systems, SPXI Tutorial, August 26, 2007

Stochastic formulation

$$Min \quad [C_{gf,1}\cdot P_{gf,1} - C_{gt,1}\cdot P_{gt,1} + C_{gas,1}\cdot(F_{chp,1}+F_{boi,1})] + \sum_{t=2}^{6}\sum_{j=1}^{3}\rho_{tj}[C_{gf,t}\cdot P_{gf,tj} - C_{gt,t}\cdot P_{gt,tj} + C_{gas,t}\cdot(F_{chp,tj}+F_{boi,tj})]$$

$$+\sum_{t=7}^{24}\sum_{j=1}^{9}\rho_{tj}[C_{gf,t}\cdot P_{gf,tj} - C_{gt,t}\cdot P_{gt,tj} + C_{gas,tj}\cdot(F_{chp,tj}+F_{boi,tj})]$$

Electric balance

$$P_{gf,tj} - P_{gt,tj} + P_{chp,tj} + P_{bd,tj} - P_{bc,tj} + P_{sol,tj} = P_{nc,tj} + P_{cntr,t}\cdot x_{ele,tj}$$

grid

$$0 \le P_{gf,tj} \le M_{gf}\cdot x_{gf,tj}$$

$$0 \le P_{gt,tj} \le M_{gt}\cdot x_{gt,tj}$$

$$x_{gf,tj} + x_{gt,tj} \le 1$$

battery

$$S_{bat,t+1,j} = S_{bat,tj} + (\eta_{bc}\cdot P_{bc,t+1,j} - P_{bd,t+1,j}/\eta_{bd})\cdot T_d / C_{bat}^{max}$$

$$P_{bc}^{min}\cdot x_{bc,tj} \le P_{bc,tj} \le P_{bc}^{max}\cdot x_{bc,tj}$$

$$P_{bd}^{min}\cdot x_{bd,tj} \le P_{bd,tj} \le P_{bd}^{max}\cdot x_{bd,tj}$$

$$x_{bc,tj} + x_{bd,tj} \le 1$$

Thermal balance

$$\eta_{hc}(H_{chp,t}^{j} + H_{boi,t}^{j}) = H_{nc,t}^{j} + H_{cntr,t}\cdot x_{heat,t}^{j} + H_{exh,tj}$$

CHP

$$F_{chp,tj} = \alpha\cdot P_{chp,tj} + \beta\cdot x_{chp,tj}$$

$$H_{chp,tj} = \eta_{hre}(F_{chp,tj} - P_{chp,tj})$$

$$P_{chp}^{min}\cdot x_{chp,tj} \le P_{chp,tj} \le P_{chp}^{max}\cdot x_{chp,tj}$$

Boiler

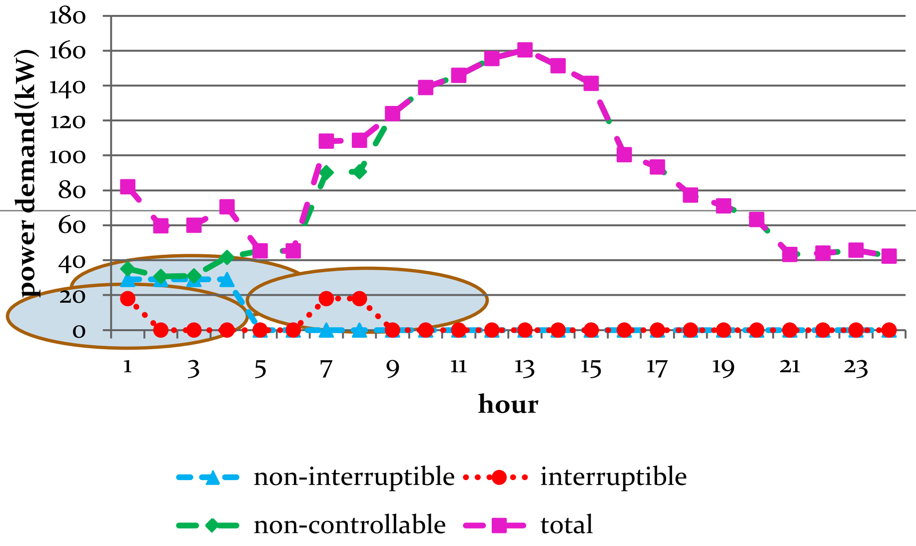
$$H_{boi,tj} = \eta_{boi}\cdot F_{boi,tj}$$

$$H_{boi}^{min}\cdot x_{boi,tj} \le H_{boi,tj} \le H_{boi}^{max}\cdot x_{boi,tj}$$

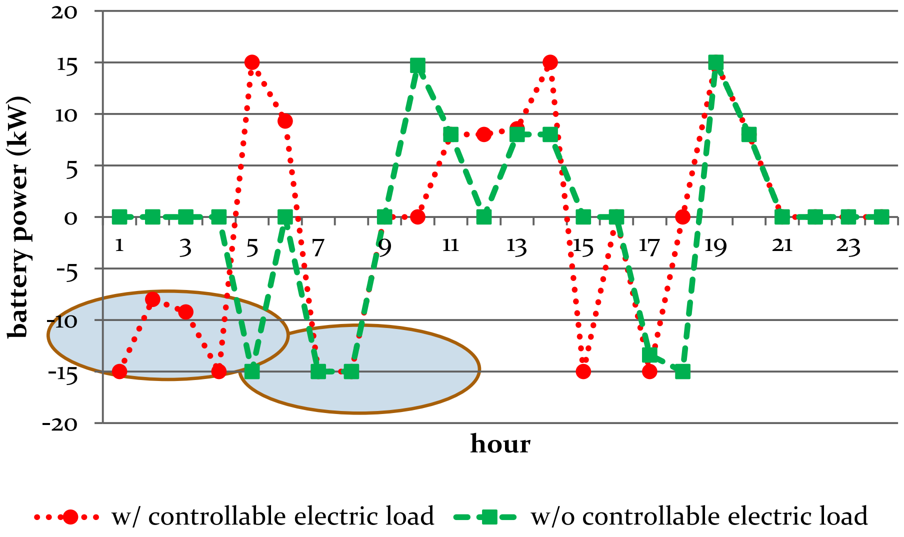
- Here-and-now variables on the first stage :
  - electric outputs ($P_{gf}, P_{gt}, P_{chp}, P_{bc}, P_{bd}$)
  - thermal outputs (F_{chp}, F_{boi})
- Wait-and-see variables at the following stages $t \ge 2$:
  - the future operation status and energy outputs of the electric grid, battery, and CHP with boiler unit

Results

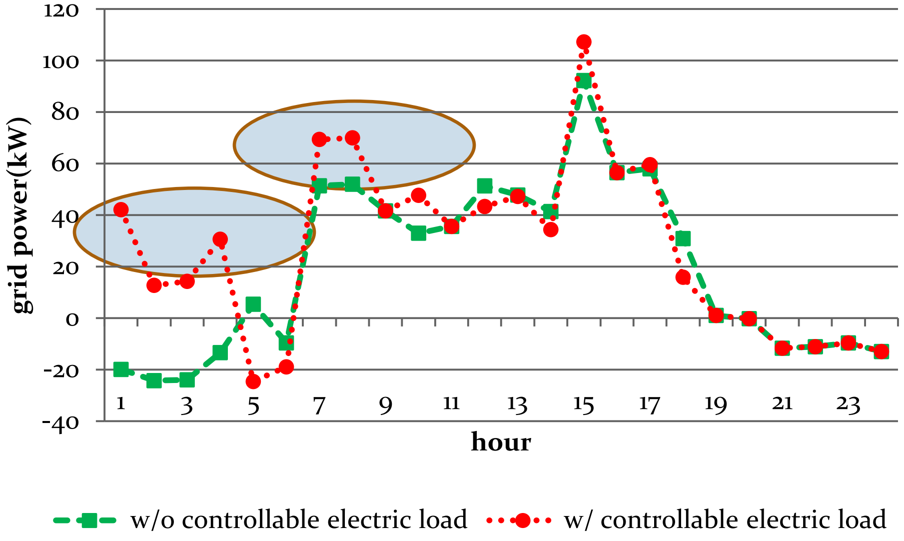
- Scheduling of controllable electric load:
  - The consideration of interruptible electric load increases the expected daily operation cost by 5.6% compared with the case without interruptible electric load.
  - Power supply from CHP system is not changed.
  - Both the power output from electric grid and battery would be changed accordingly in order to meet the extra operation requirement for interruptible electric load.



Power demand with controllable electric load (S4)



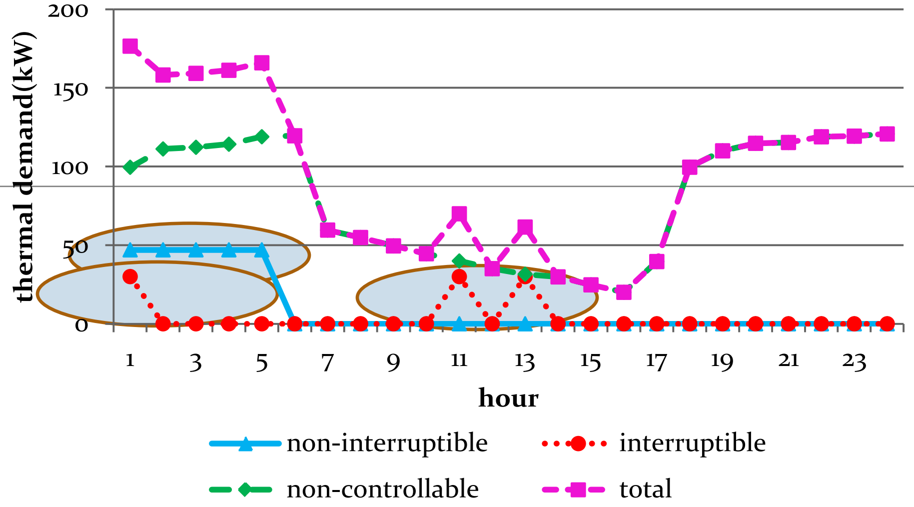
Impact of controllable electric load on battery power supply (S4)



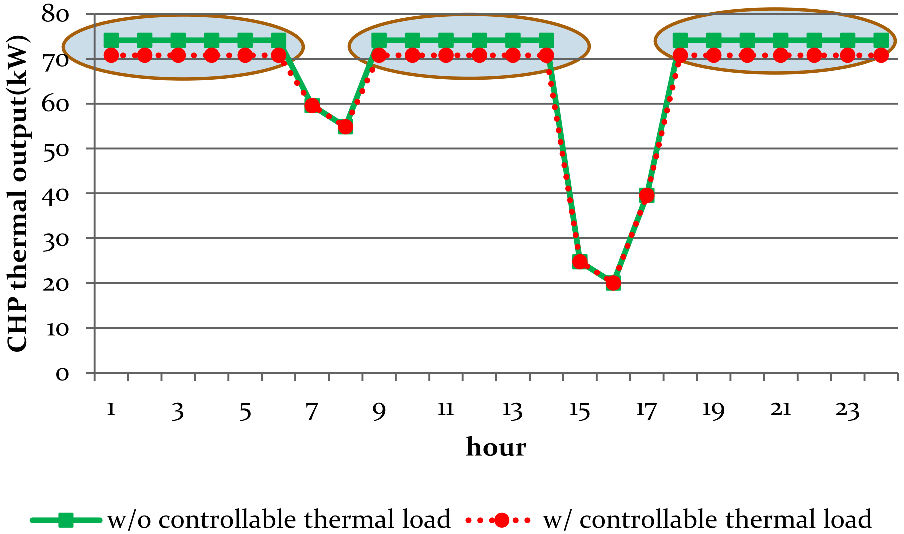
Impact of controllable electric load on grid power supply (S4)

Results

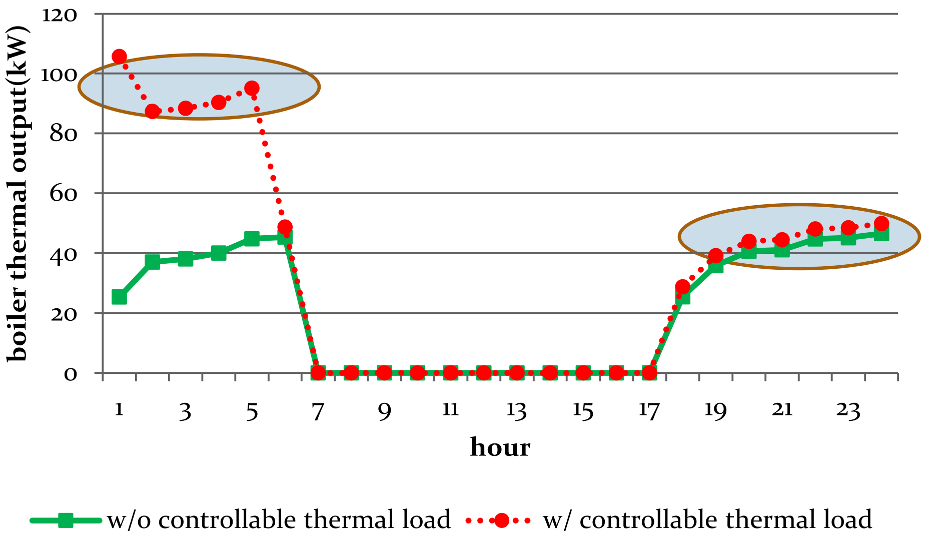
- Scheduling of controllable thermal load:
  - The expected daily operation cost increases by 3.2%
  - The scheduling of interruptible thermal load is influenced by both electricity price and natural gas price
  - The maximum thermal output from the CHP unit decreases from 74.1 kW per hour to 70.8 kW per hour
  - The boiler unit increases its maximum thermal output from under 50 kW per hour to above 100 kW per hour



Thermal demand with controllable thermal load (S4)



Impact of controllable thermal load on CHP thermal supply (S4)



Impact of controllable thermal load on boiler thermal supply (S4)