Lecture Series, TU Munich
October 22, 29 & November 5, 2013

Glocal Control for Hierarchical Dynamical Systems

Theoretical Foundations with Applications in Energy Networks

Shinji HARA
The University of Tokyo, Japan

OUTLINE

1. Glocal Control & Energy Networks
2. A Unified Framework for Networked Dynamical Systems with Stability Analysis
3. From Homogeneous to Heterogeneous
4. From Frat to Hierarchical
5. Decentralized Hierarchical Control Synthesis
6. Applications in Energy Networks

OUTLINE : Part 1

1. Glocal Control & Energy Networks

- Glocal Control (background, idea, goal)
- Urban Heat Island Problem
- Integrated Energy Networks

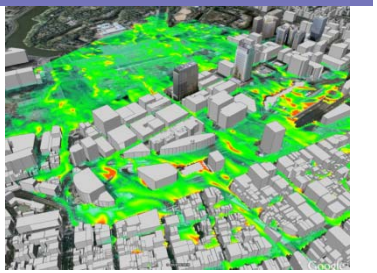
Why “Glocal Control” ?

Recently, systems to be treated in various fields of engineering including control have became large and complex, and more high level control such as adaptation against changes of environments for open systems is required. Typical examples include meteorological phenomena and bio systems, where our available actions of measurement and control are restricted locally although our main purpose is to achieve the desired global behaviors.

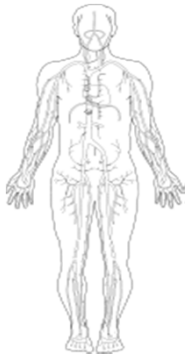
This motivates us to develop a new research area so called "Glocal Control," which means that the **desired global behavior is achieved by only local actions**.

Future Direction in Control

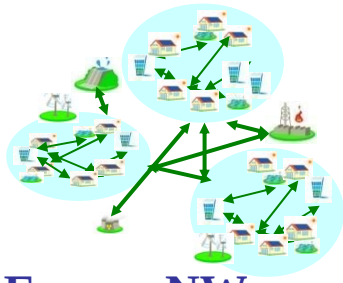
Realization of High Quality Products
→ Solving Social Problems such as Energy, Environments, and Medicine



Meteorological Phenomena



Bio-systems



Energy NWs

Multiple Functions

High Performance

Automation

Stabilization

Hybrid Control

Robust Control

Modern Control

Classical Control

Linear motor car

Engine control

Robotics

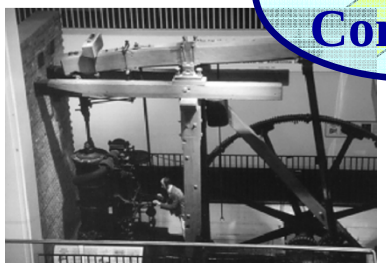
Mechatronics

Aerospace

Steel process

Chemical process

Watt



Transportation

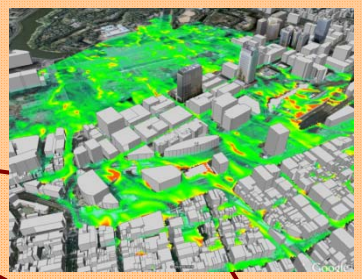
Glocal Control

Idea of "Glocal Control" ?

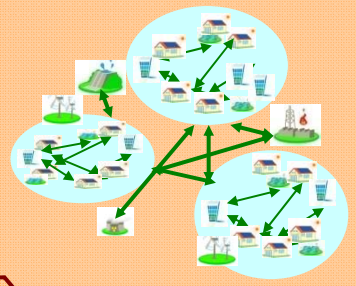
Glocal Control : to achieve **desired global behavior** by only **local actions** of measurement and control

Real World

Meteorological Phenomena

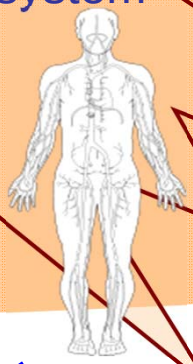


Energy NWs



Transportation NWs

Bio-system



Large-scale & Complex

Locally

Control

Global Behaviors By Locally

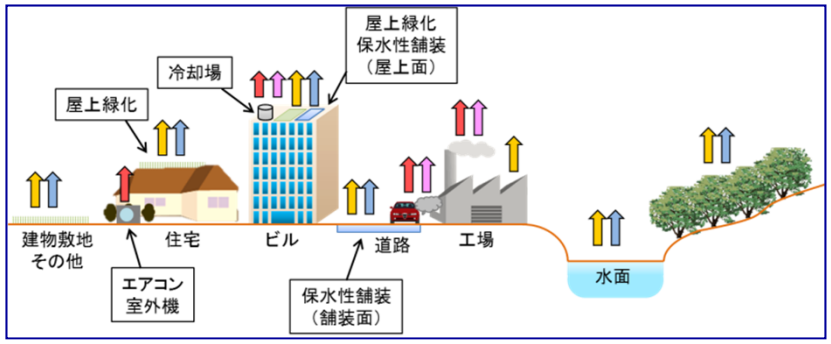
Prediction

Locally

Measurement

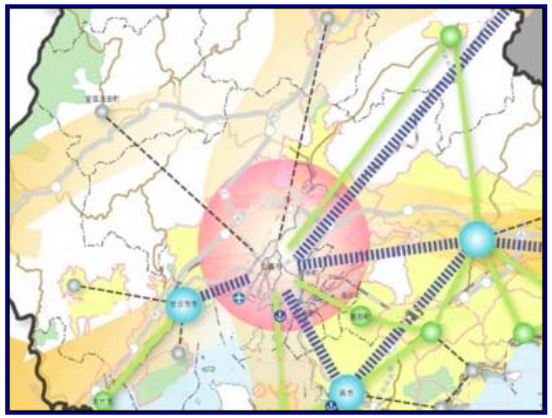
Urban Heat Island Problem

Local Actions of Measurement & Control

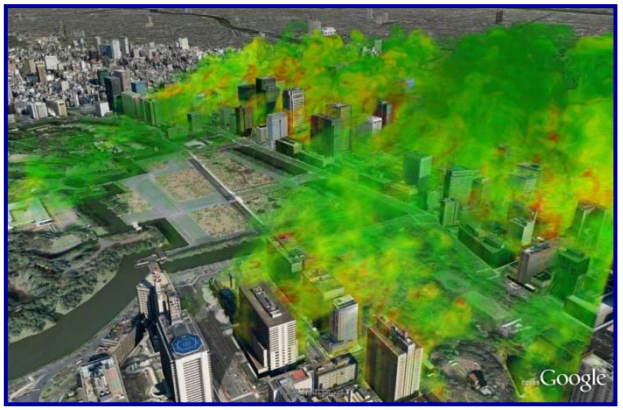


Scale of buildings and roads

Realization of Global Desired Environment of a Whole City



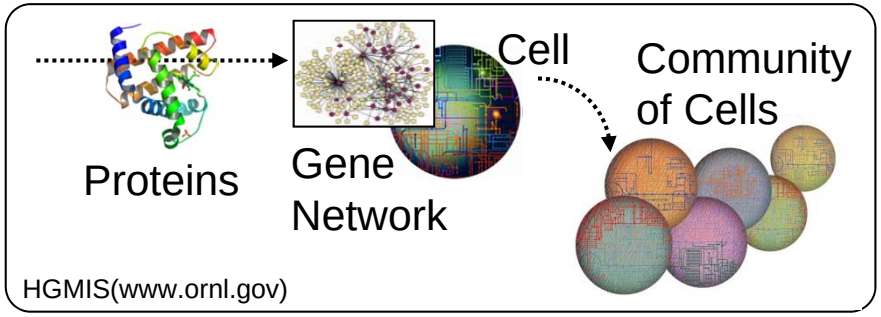
Glocal Control

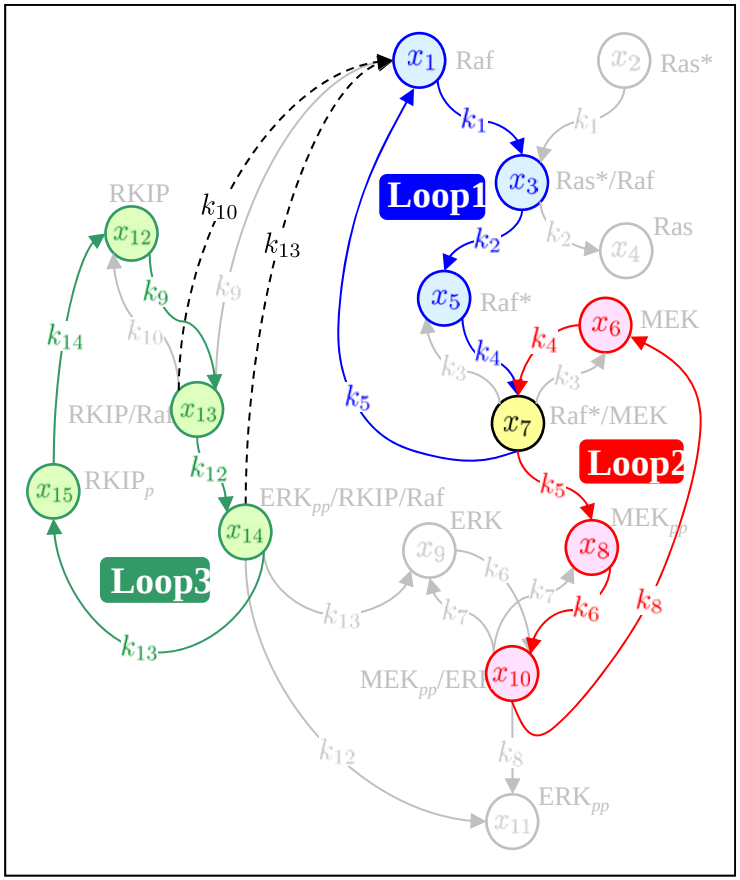


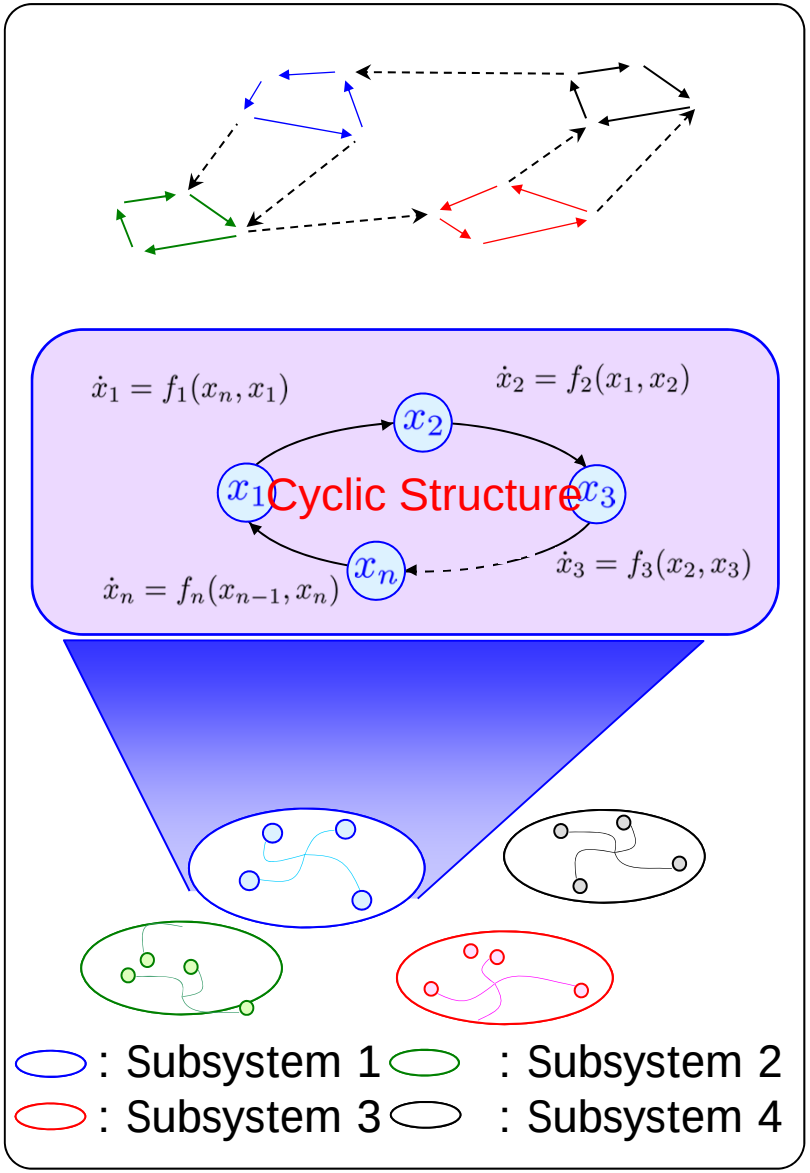
Scale of residential and business areas

Scale of districts/towns

Hierarchical Bio-Network Systems



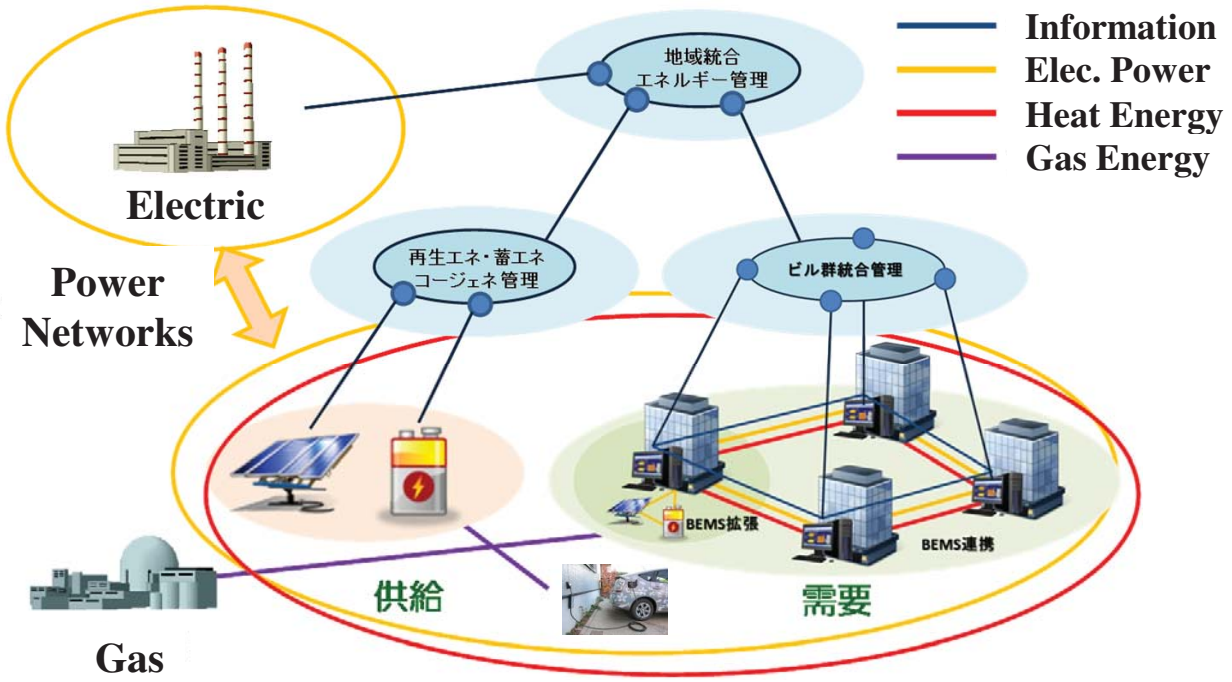




Integrated Energy Networks

Integrated Energy Network

Multi-resolved Hierarchical

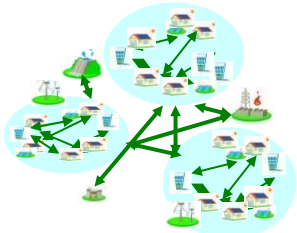


Regional Energy Network System

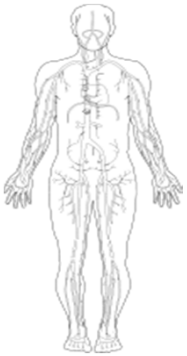
Framework for Glocal Control

Realization of Global Functions by Local Measurement and Control

Real World



Power NWs



Bio-Systems

Hierarchical Dynamical Systems with Multi-resolution

Glocal Control System

Local Control

Global Prediction through hierarchical model with multiple-resolution

Local Measurement

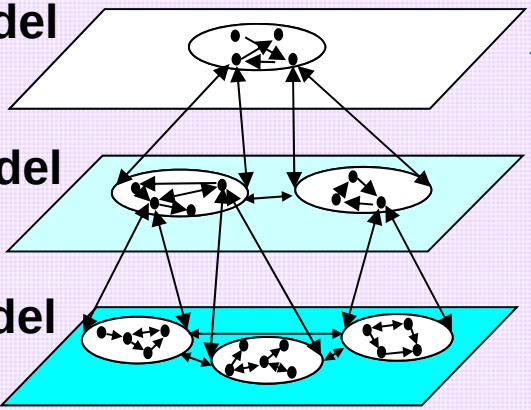
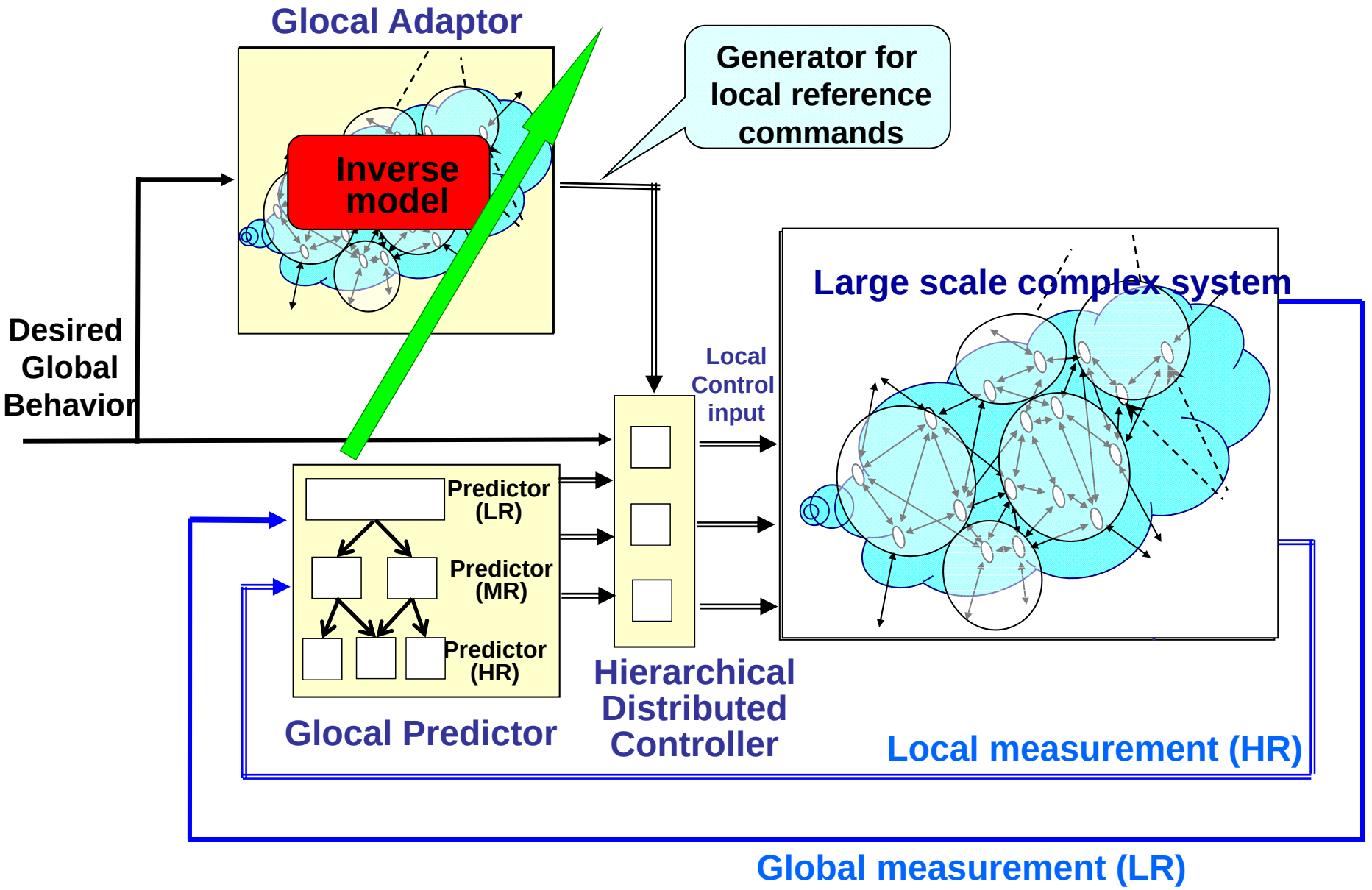


Image of Glocal Control System



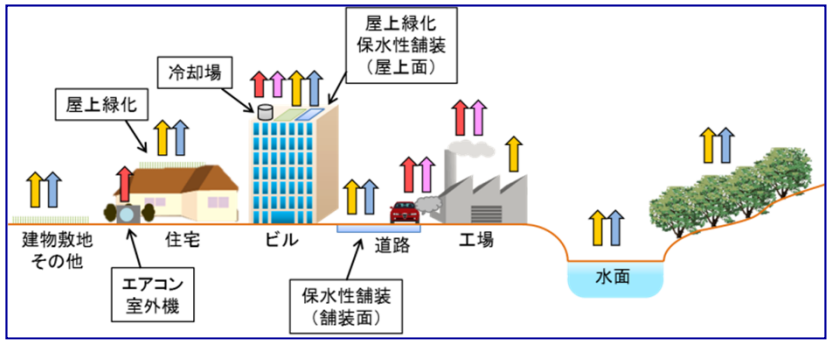
OUTLINE Part 1

1. Glocal Control & Energy Networks

- Glocal Control (background, idea, goal)
- **Urban Heat Island Problem**
- Integrated Energy Networks

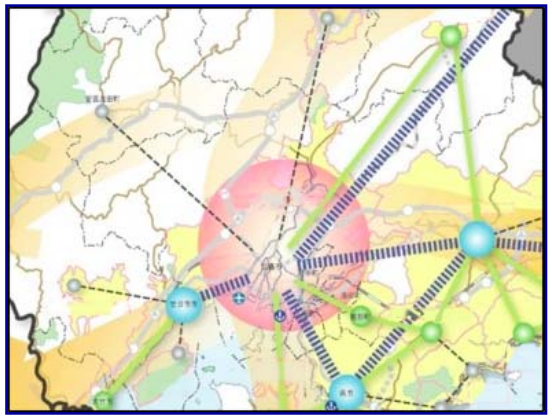
Urban Heat Island Problem

Local Actions of Measurement & Control

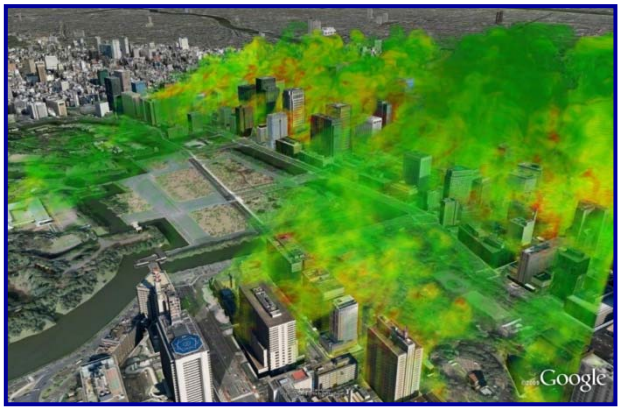


Scale of buildings and roads

Realization of Global Desired Environment of a Whole City



Glocal Control



Scale of residential and business areas

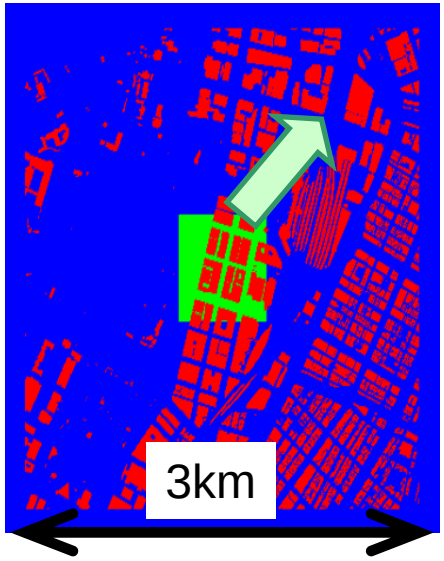
Scale of districts/towns

Possibility by Glocal Control

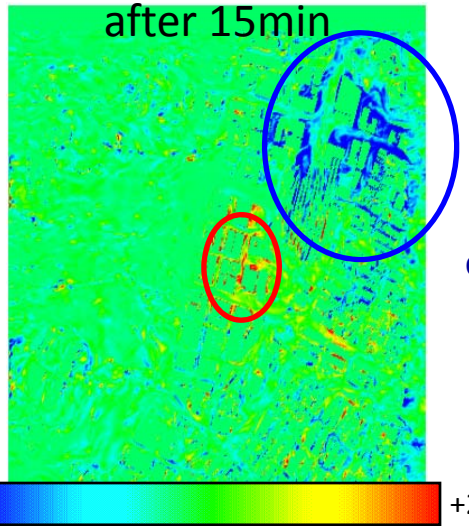
Fix

VS

Shift actively



Temperature Difference:
15m above the surface
after 15min



Much cooling affect

-3C° +2C°

Control

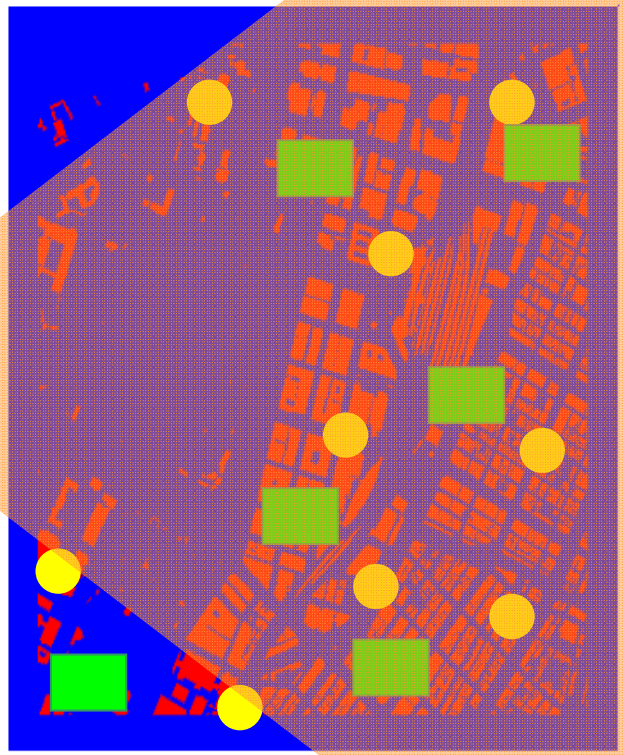
Distributed local actuators

Prediction

Global Prediction by model

Measurement

Distributed local sensors



Hierarchical Air Conditioning (1/3)

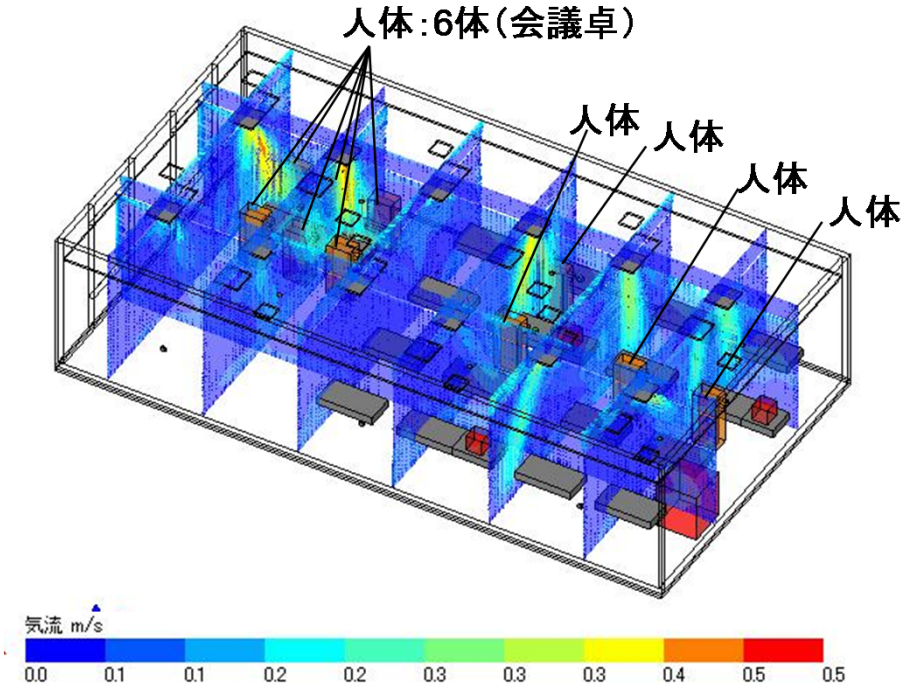
Hierarchical Air Conditioning System

Area: Group of buildings
Building: Set of floors
Floor: Set of rooms

(with Azbil)

Energy saving (40%)
Heat island problem

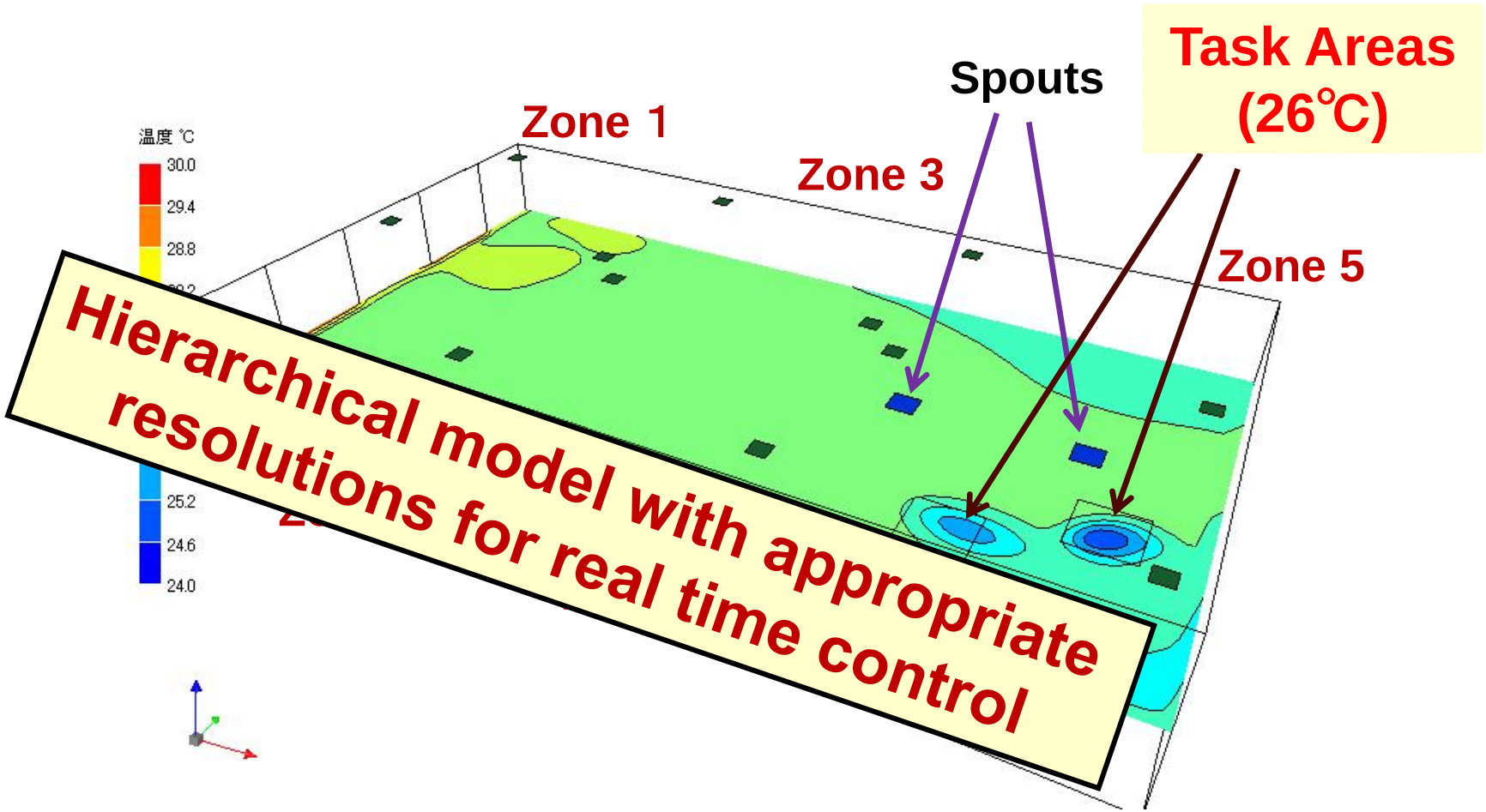
Scalability



Hierarchical Air Conditioning (2/3)

(with Azbil)

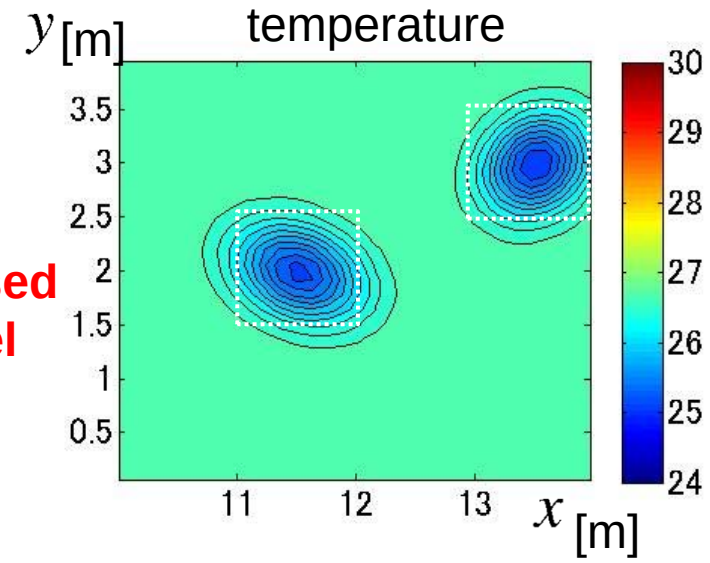
Upper Layer : Energy Saving
Lower Layer : Comfortableness

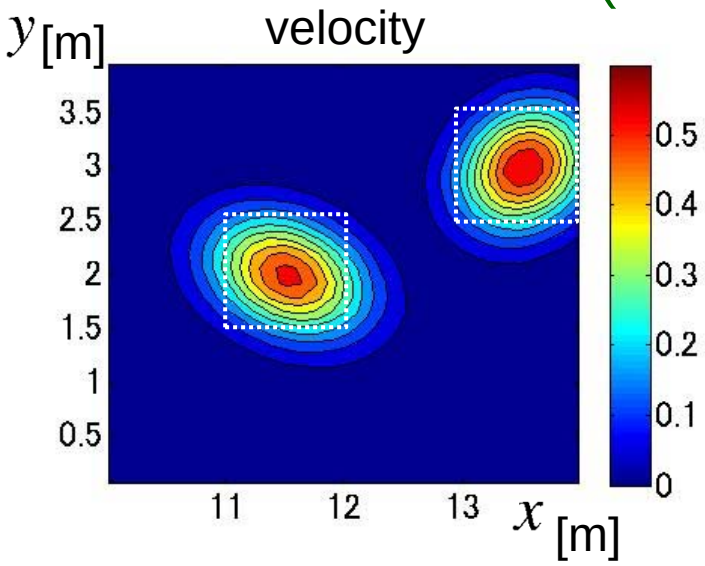


Hierarchical Air Conditioning (3/3)

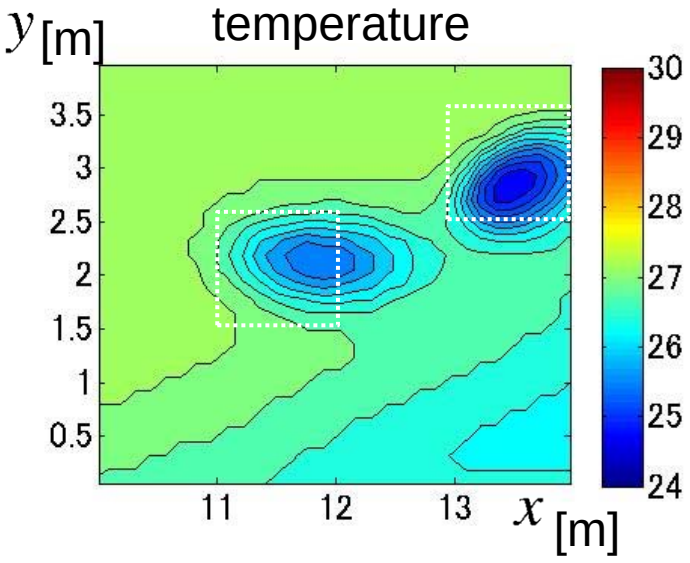
(with Azbil)

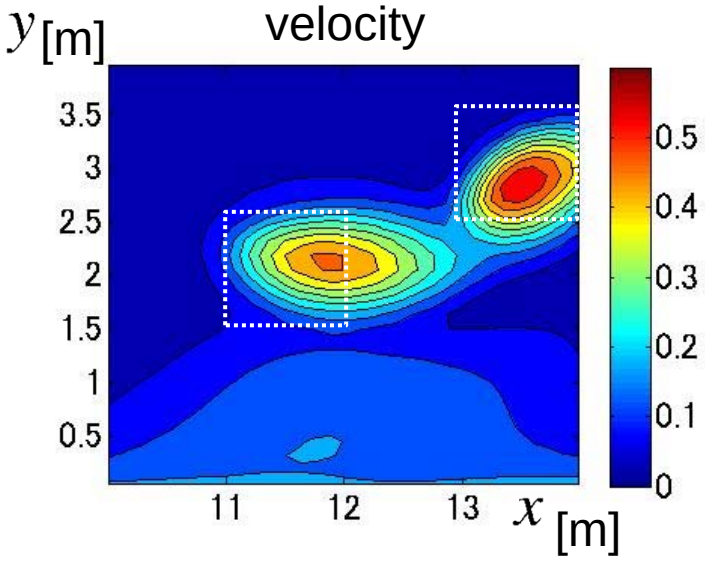
Proposed Model



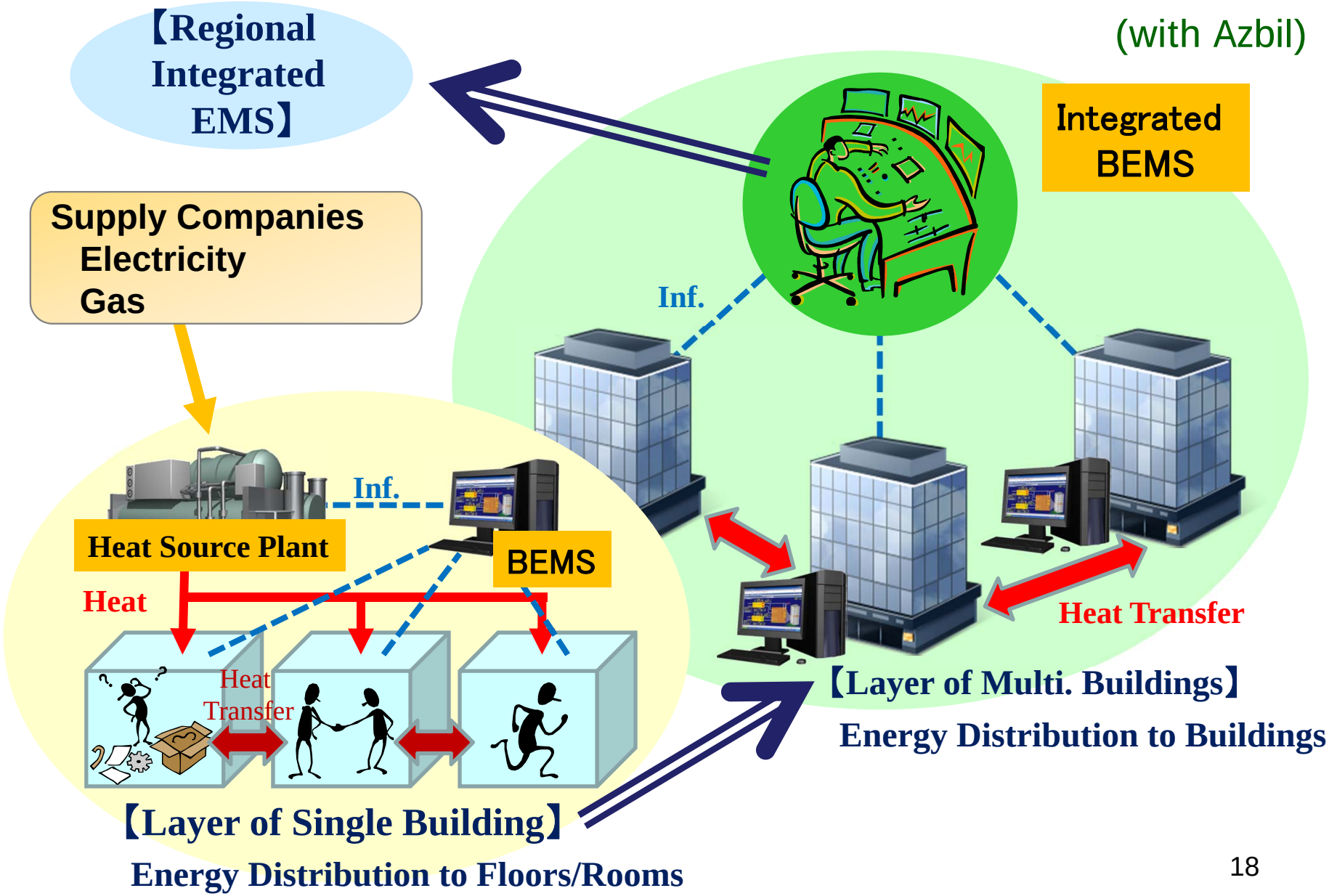


CFD Model





Towards Regional Integrated EMS



OUTLINE : Part 1

1. Glocal Control & Energy Networks

- Glocal Control (background, idea, goal)
- Urban Heat Island Problem
- **Integrated Energy Networks**

Features of Energy & Water NWs

★ **Energy & Water**

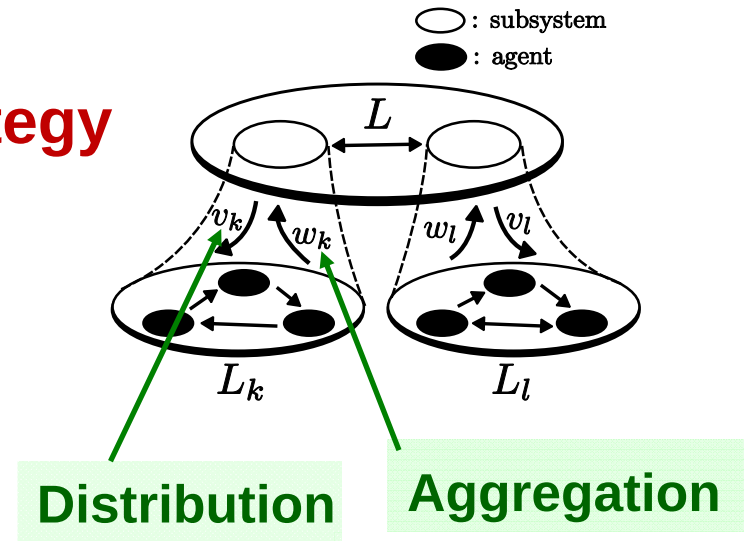
- not uniformly distributed in time/space
- unbalance between demand & supply
  - → **Control = balancing energy/water in time/space**
- but, transfer is very costly
  - → **only local actions with exchanges in neighbors are available**
  - → **shifting elements in time/space are important**

★ **To reduce total energy**

→ **Utilizing Nature & Control Strategy**

★ **Key Points**

- Hierarchical with Multi-resolution
- Aggregation & Distribution
- **Passivity**



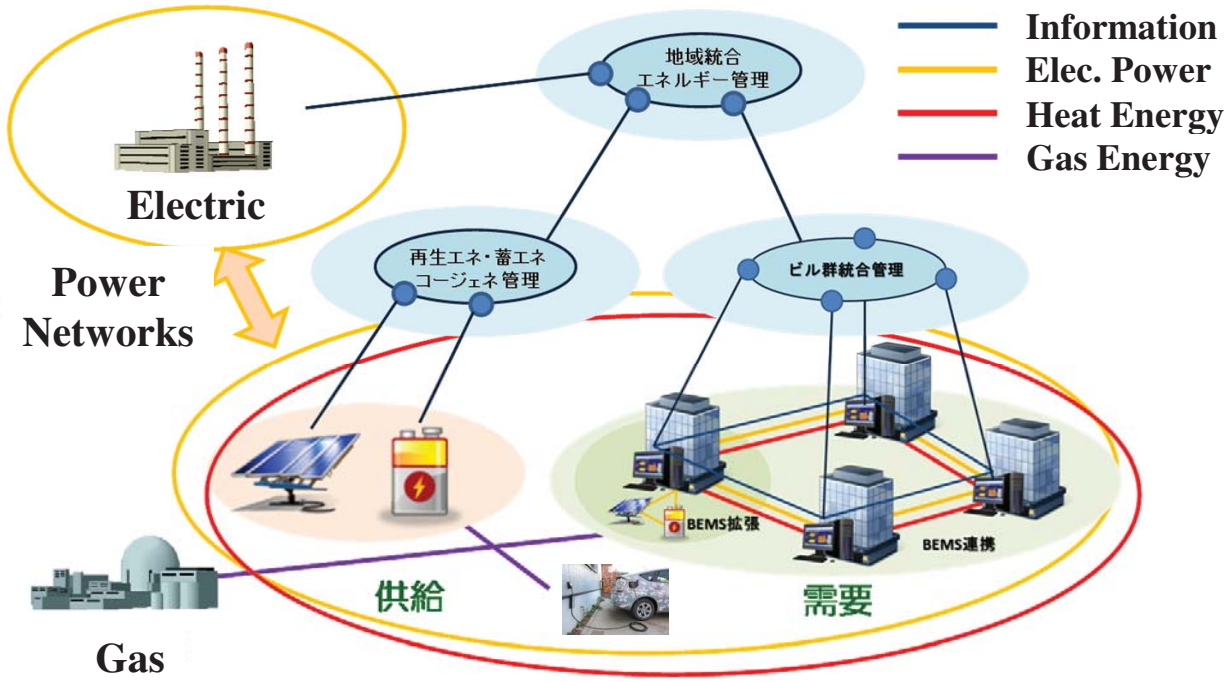
Integrated Energy Networks

Integrated Energy Network

Electric power network
+ Gas energy network
+ Heat energy network

Multi-resolved Hierarchical

ction
ralized



Regional Energy Network System

yo
Gas
u

OUTLINE

Integrated Energy Networks

with Fujitsu

with Azbil

with Tokyo-Gas

Different Target Systems

Different Shift Elements

Different Focuses

OUTLINE

Integrated Energy Networks

with Fujitsu

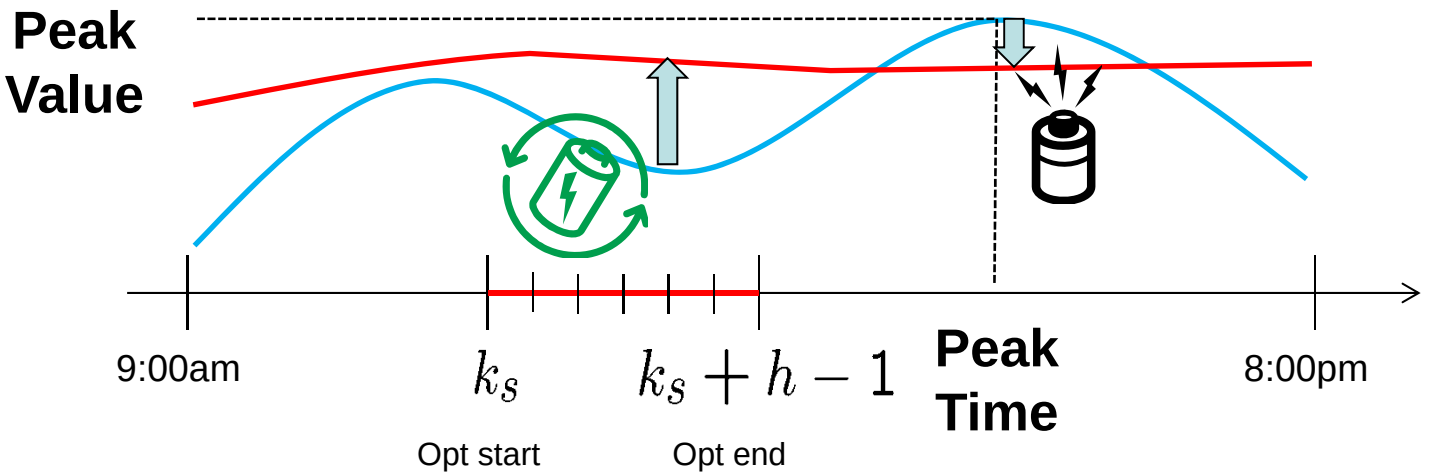
with Azbil

with Tokyo-Gas

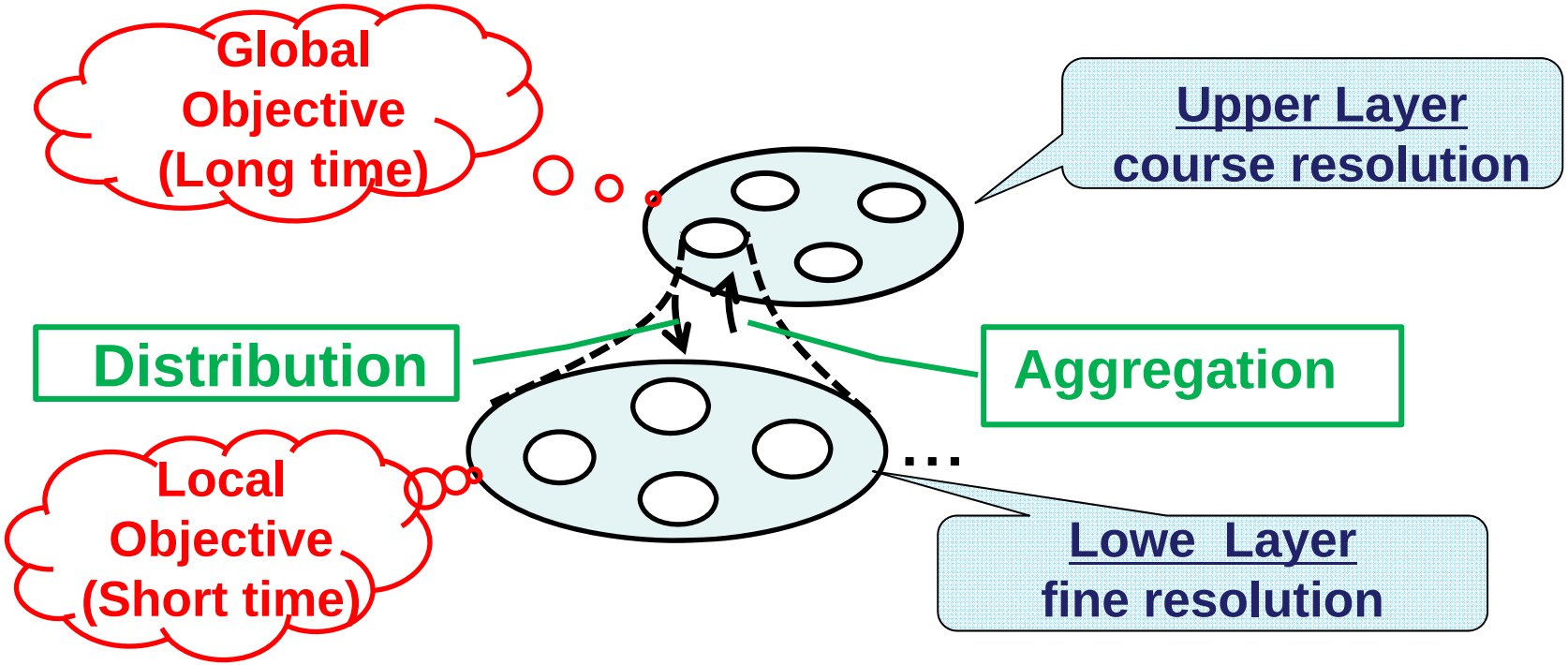
- **Electric NWs**
- **Static Storages**
- **Aggregation**

Laptop PC Battery System

(with Fujitsu)

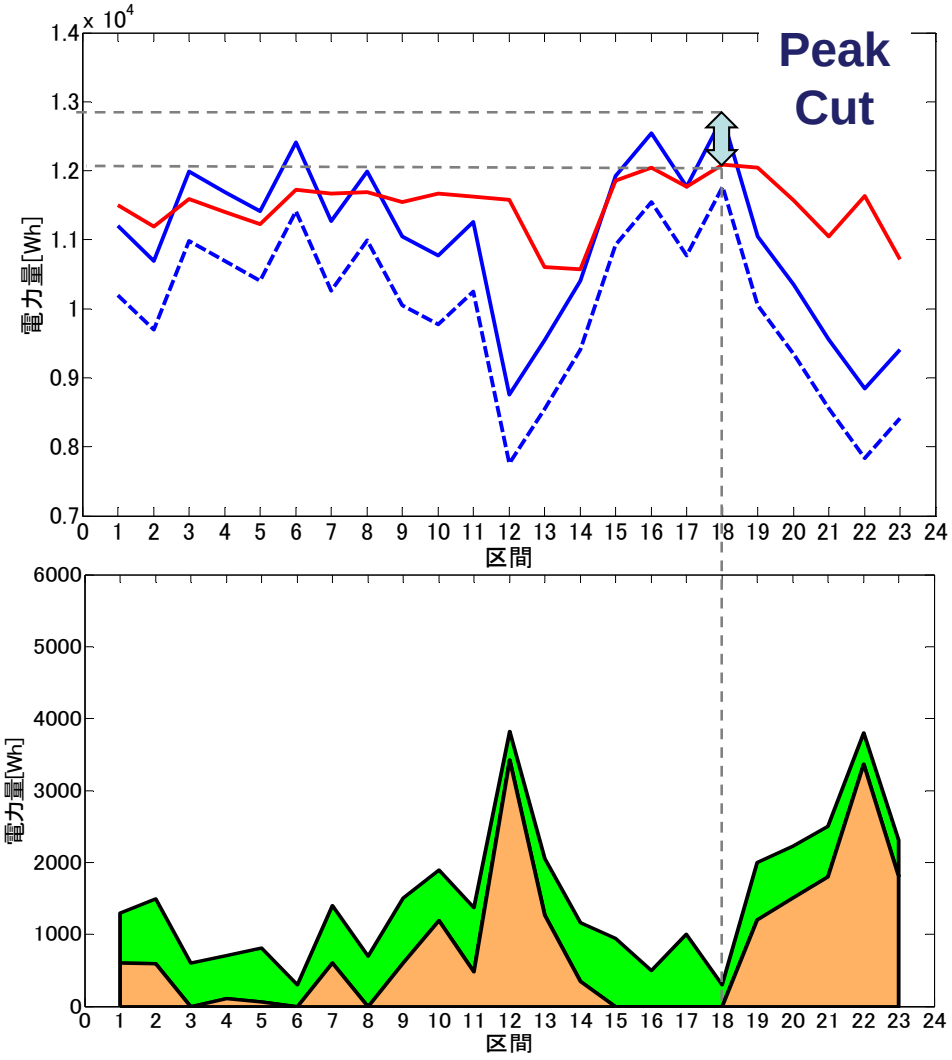


Three modes:
- AC driven
- B. driven
- B. charge



Hierarchical Model Predictive Control for Laptop PC Battery Systems

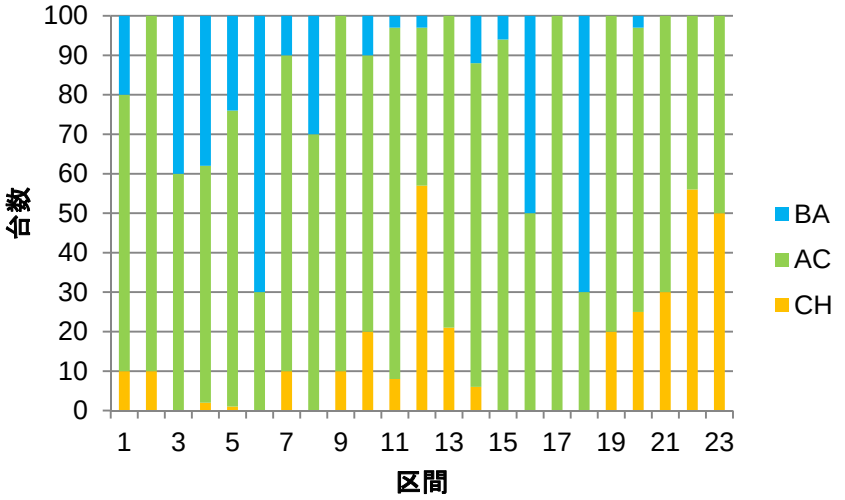
(with Fujitsu)



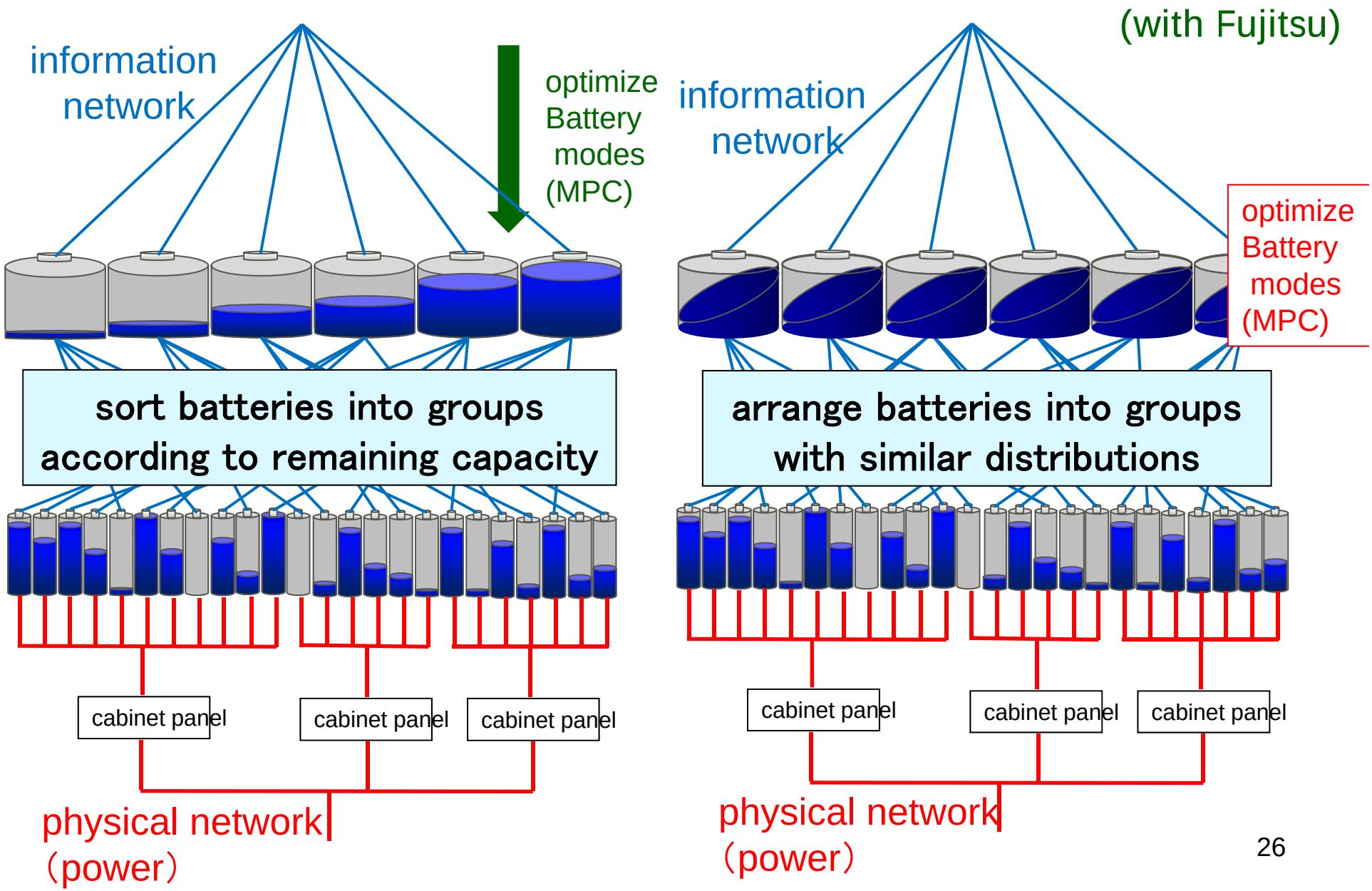
100 PCs → 10 PCs x 10 G

Upper Layer Horizon: 8

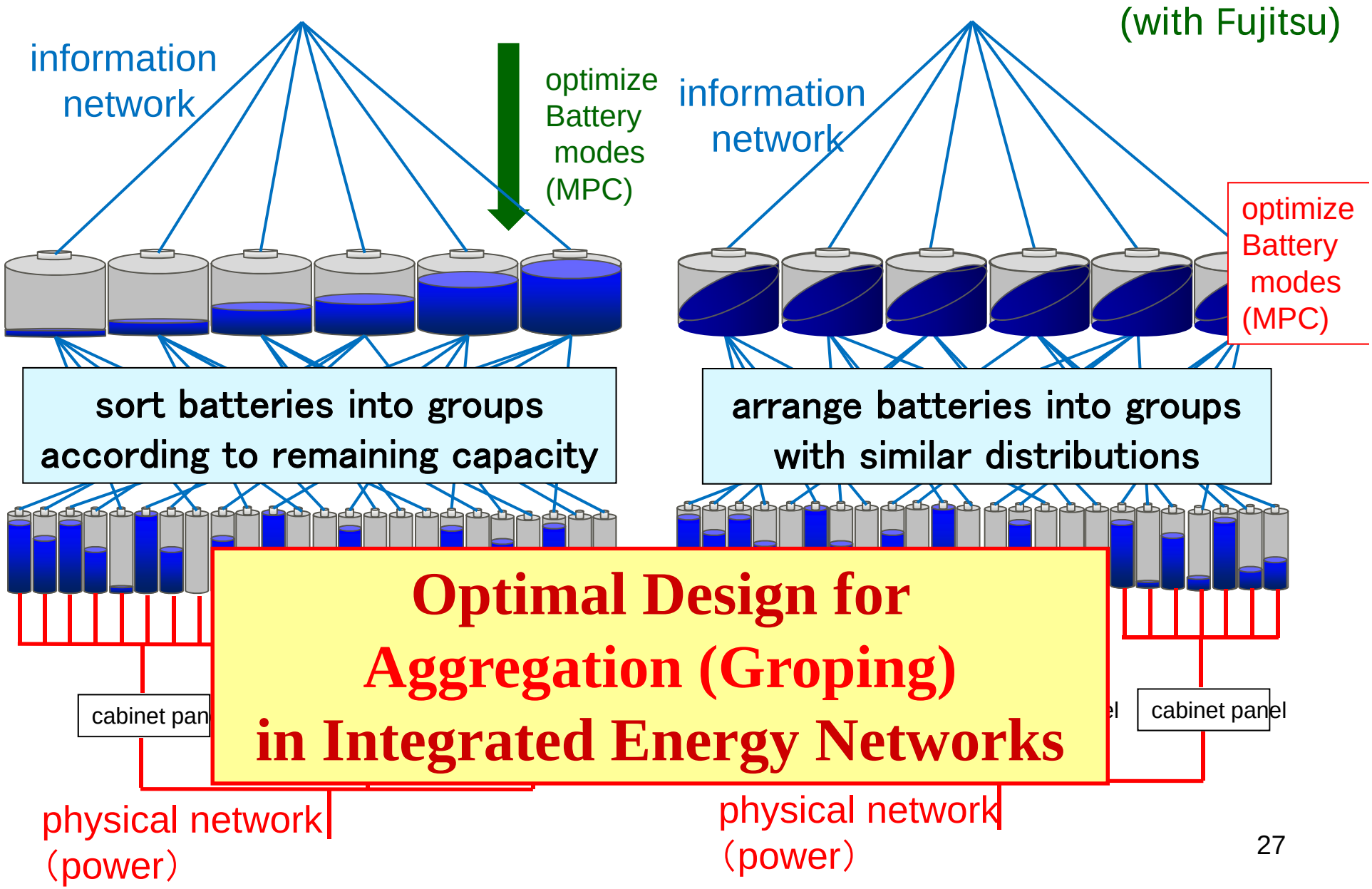
Lower Layer Horizon: 3



Two Types of Aggregation



Two Types of Aggregation



OUTLINE

Integrated Energy Networks

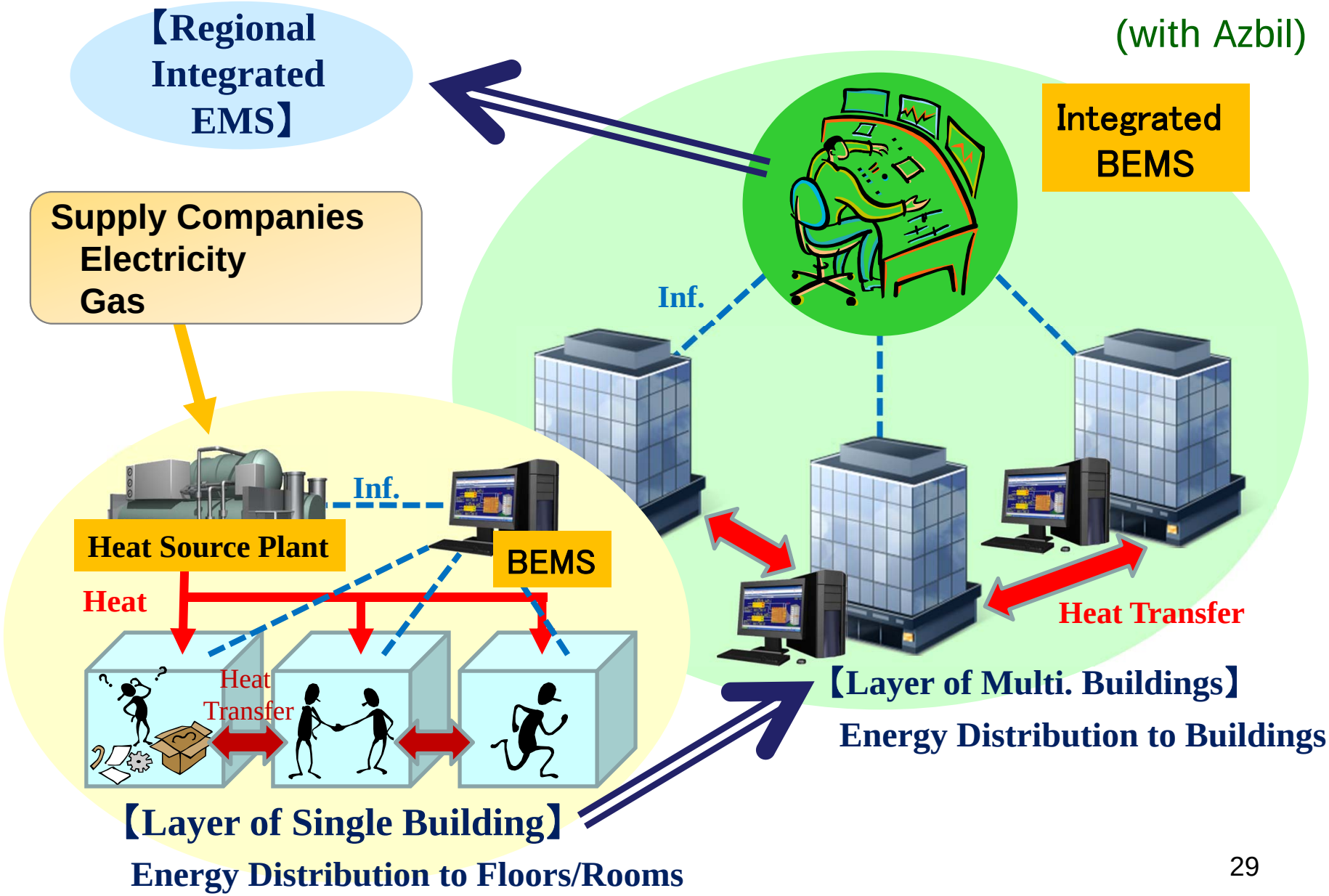
with Fujitsu

with Azbil

with Tokyo-Gas

- **Air Conditioning Systems**
- **Thermal Energy Transfer/Storage**
- **Decentralized Control**

Towards Regional Integrated EMS

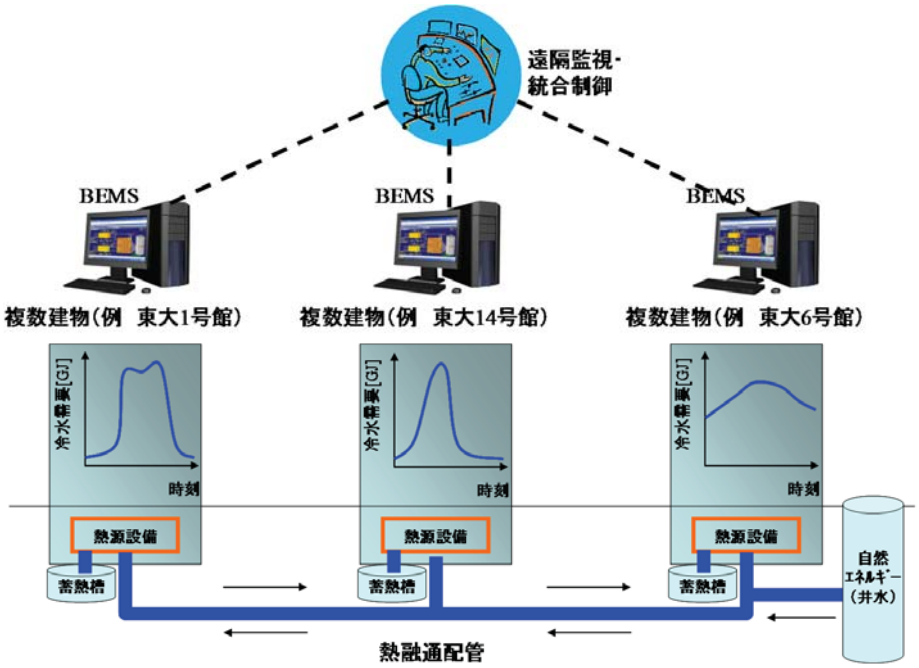


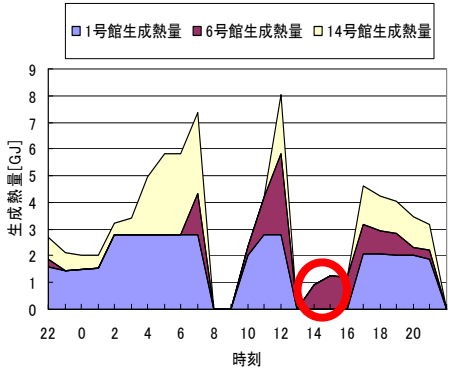
Integrated BEMS by Heat Transfer

(with Azbil)

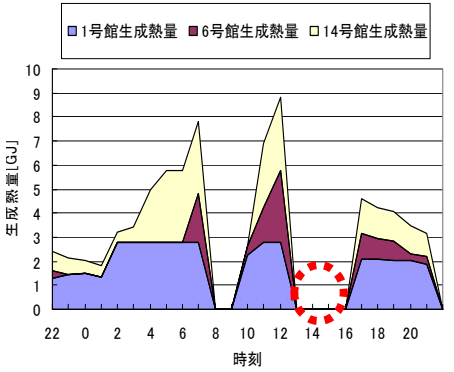
Purpose

Energy Management Control by Heat Transfer with Thermal Energy Storages





Without Heat Transfer

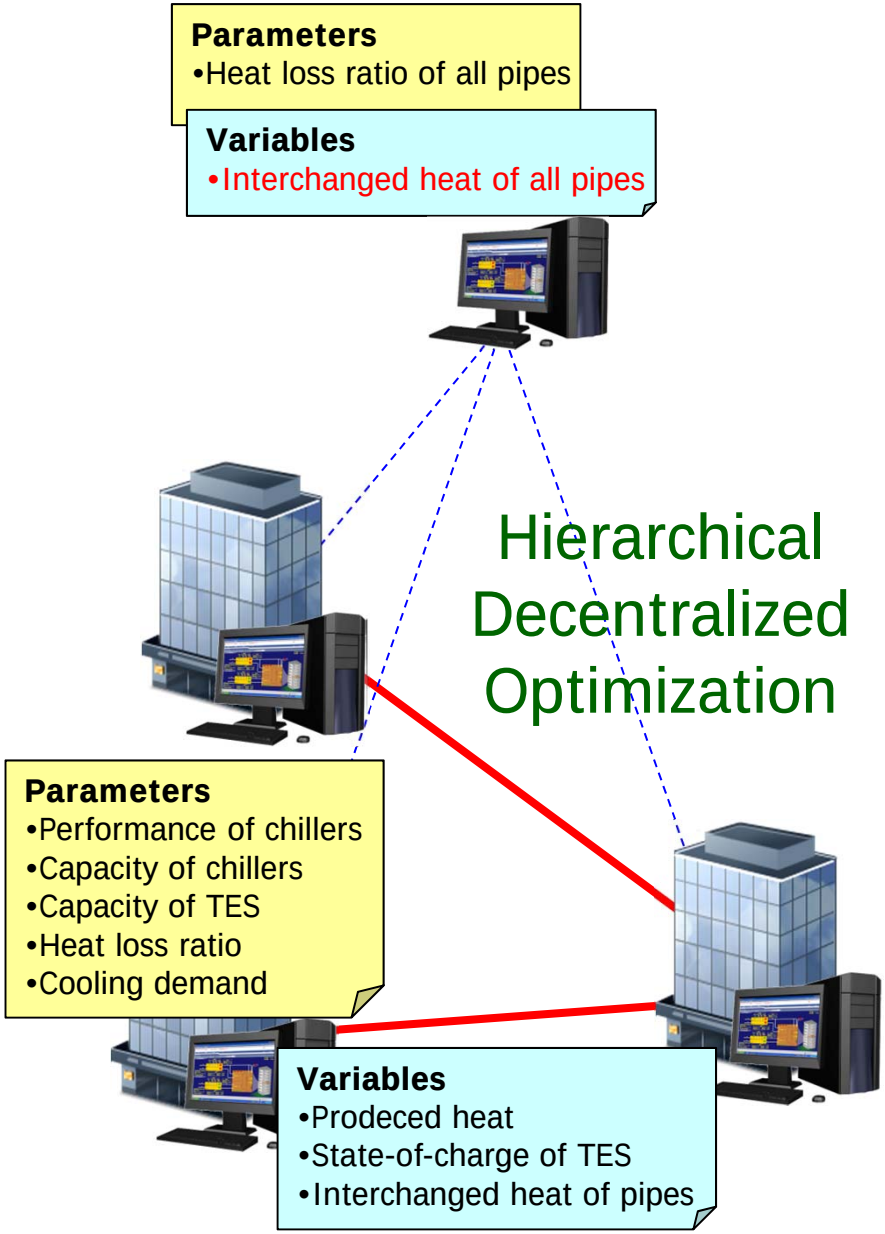


With Heat Transfer

On Going Work

1) **Hierarchical Modeling & Decentralized Control**
2) **Design Guideline for NWs (TESs, GEs)**

Features of Decentralized Control

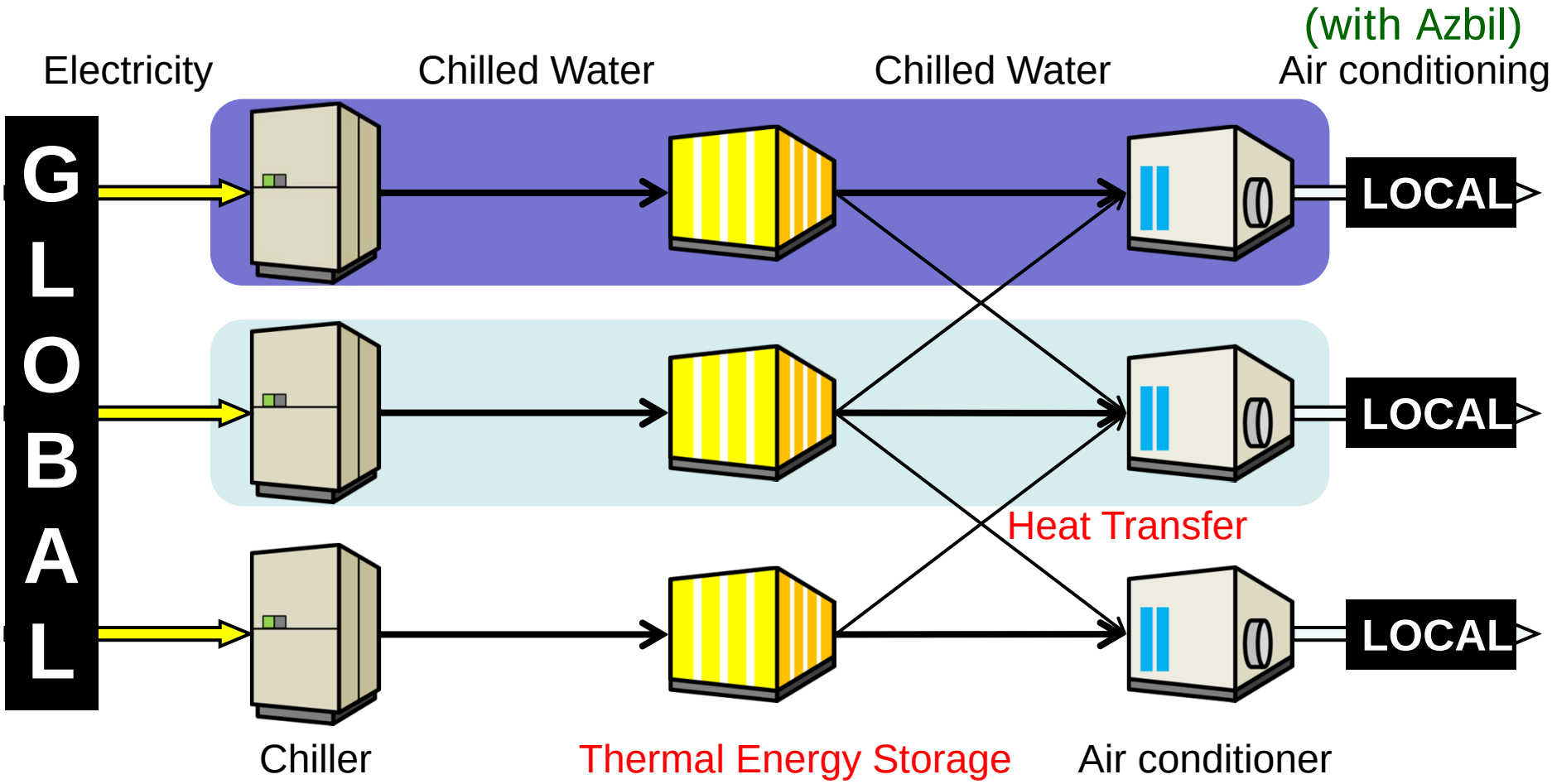


(with Azbil)

Advantages

- *Reduction of computation load* in each control device
- *Localization of confidential information*(e.g. facility information, energy consumption)
- *Adaptation capability* for facility replacement and performance degradation with updating of subsystems

Decentralized Control for Int. BEMS



Minimizing Total Energy

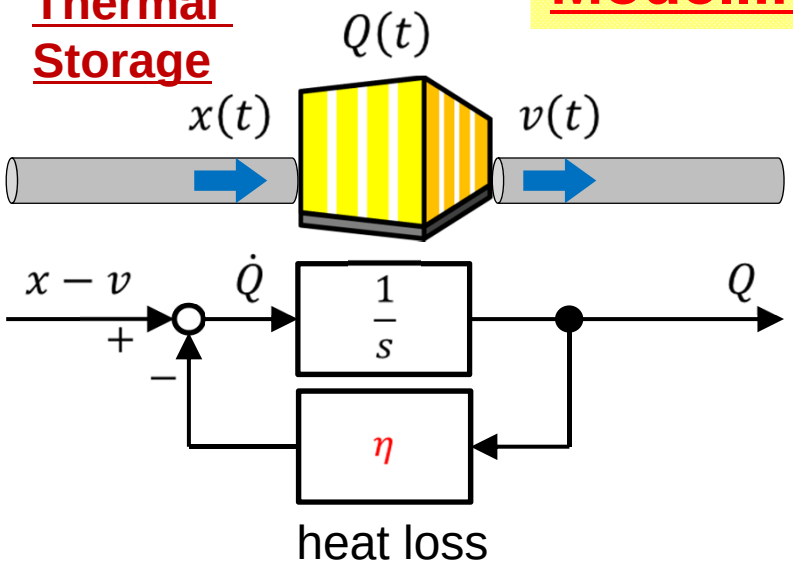
Maximizing Each Utility

Modeling of Elements and Setting of Objective Functions

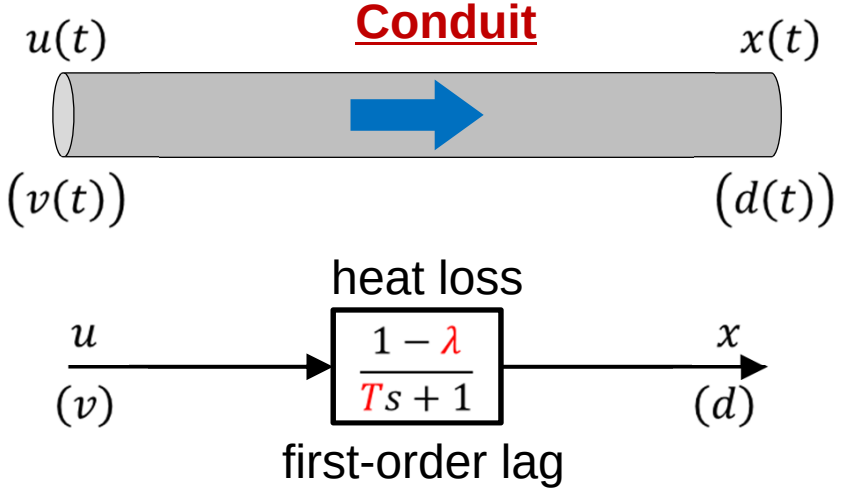
(with Azbil)

Modelling of Elements

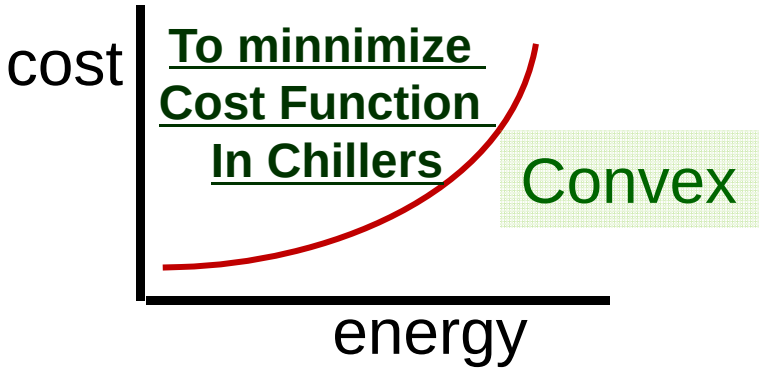
Thermal Storage

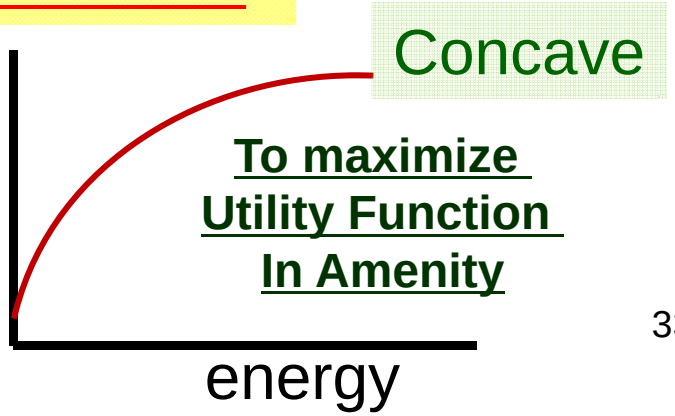


Conduit



Setting of Objective Functions





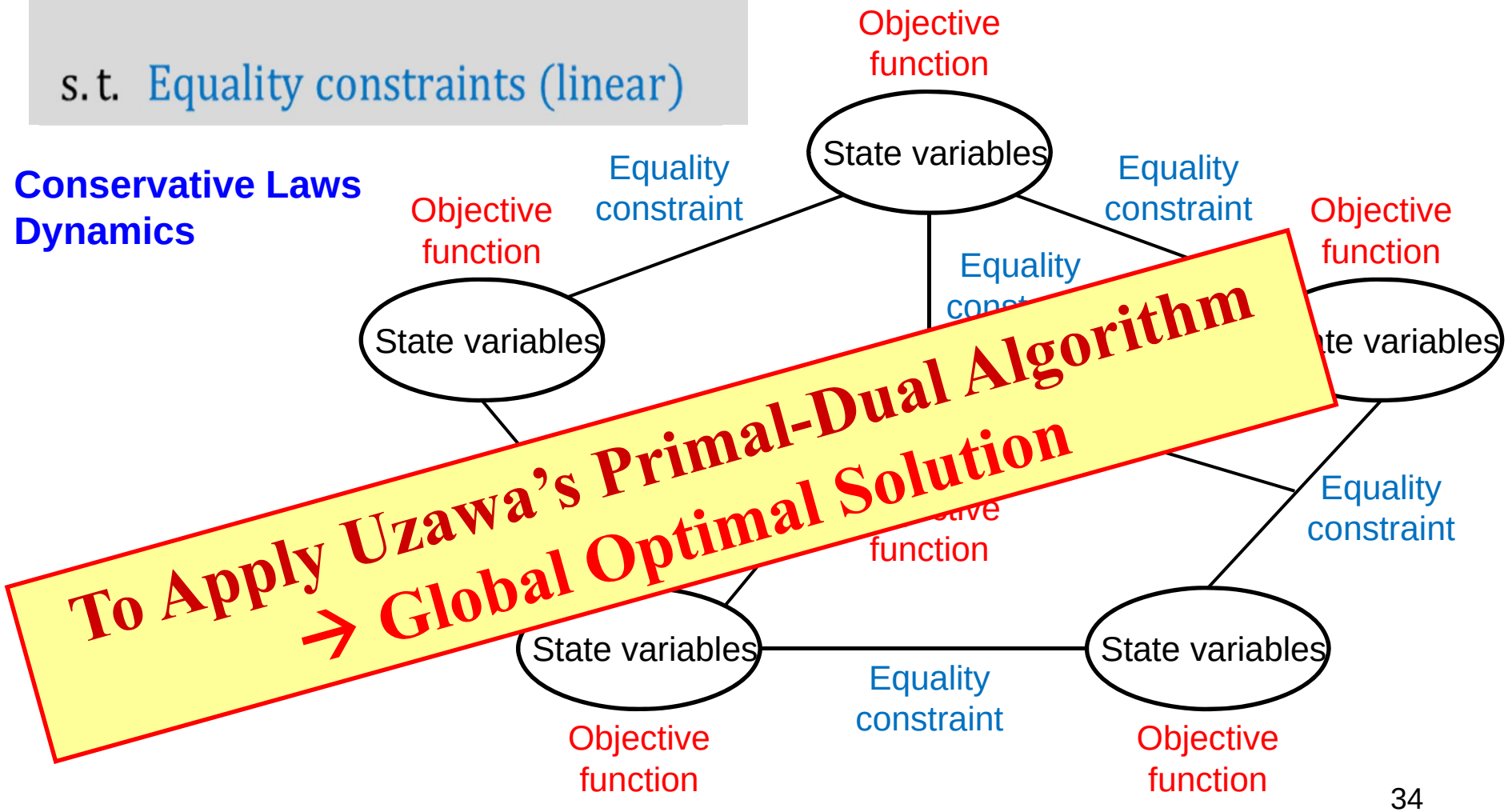
Decentralized Control : Optimization

(with Azbil)

$$\max_{\text{State variables}} \sum \text{Objective function}$$

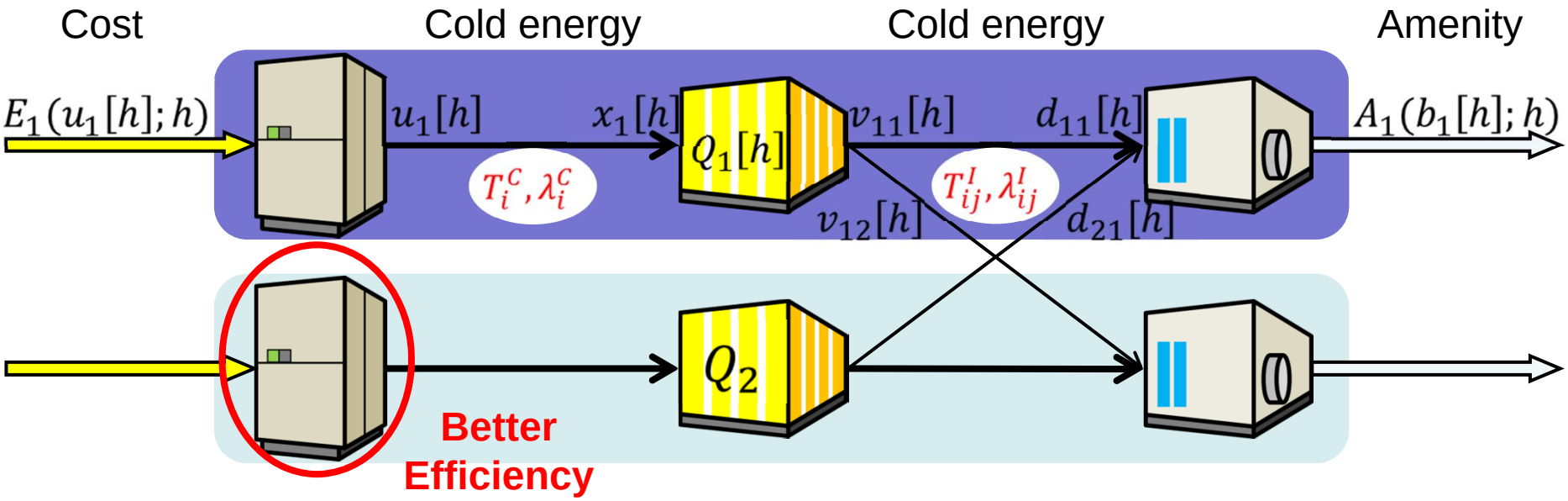
s.t. Equality constraints (linear)

Conservative Laws
Dynamics



An Example : two buildings

(with Azbil)



$$\max \sum_h \sum_i (A_i(b_i[h];h) - E_i(u_i[h];h))$$

$H = 24 \qquad \Delta t = 1.0$

$$\begin{bmatrix}0.13\\0.30\end{bmatrix} \le u[h] \le \begin{bmatrix}1.30\\3.00\end{bmatrix}$$

$$\begin{bmatrix}0 & 0\\0 & 0\end{bmatrix} \le v[h]$$

$$\begin{bmatrix}1.0\\1.0\end{bmatrix} \le Q[h] \le \begin{bmatrix}15.0\\15.0\end{bmatrix}$$

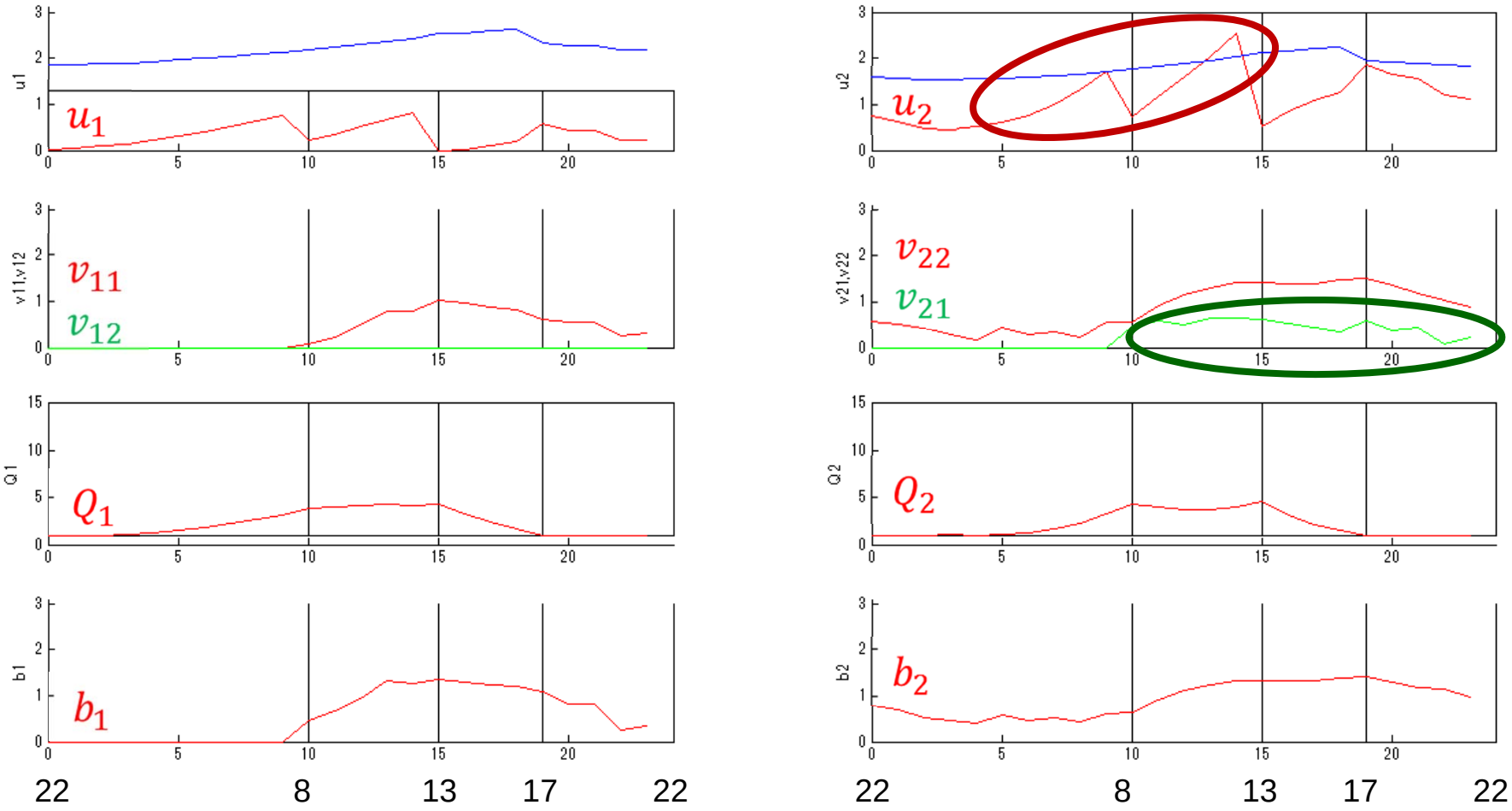
$$Q[0] = \begin{bmatrix}1.0\\1.0\end{bmatrix}$$

$$A(b[h];h) = -100(b - demand)^2$$

$$1 \leq Q_2 \leq 5$$

Enough Capacity

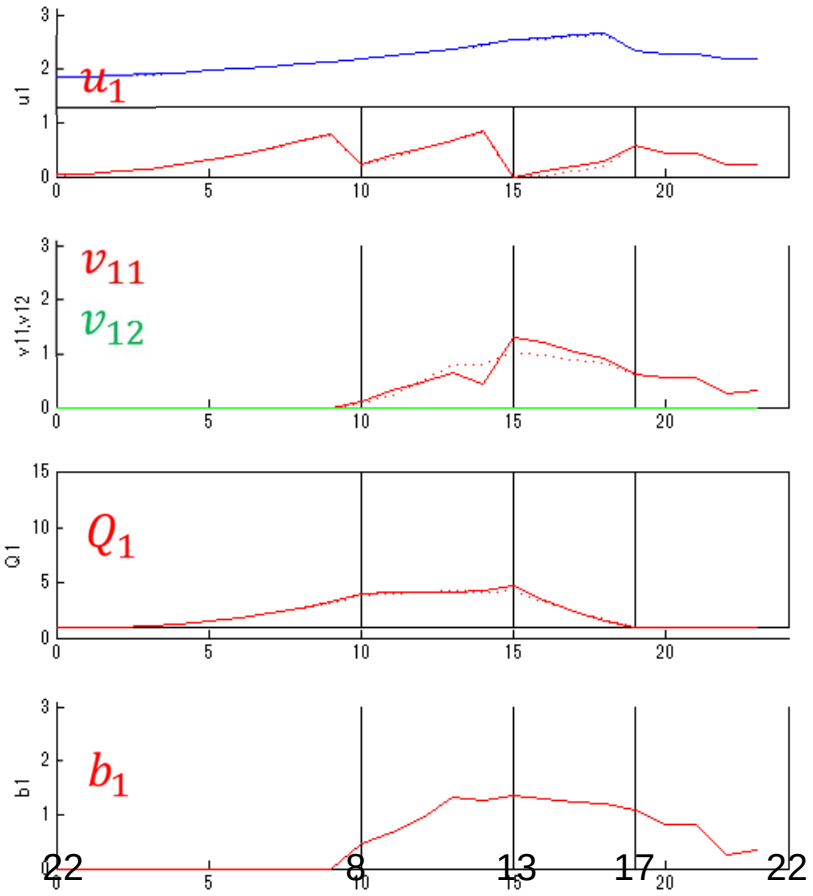
<Lowest Price> <Highest>

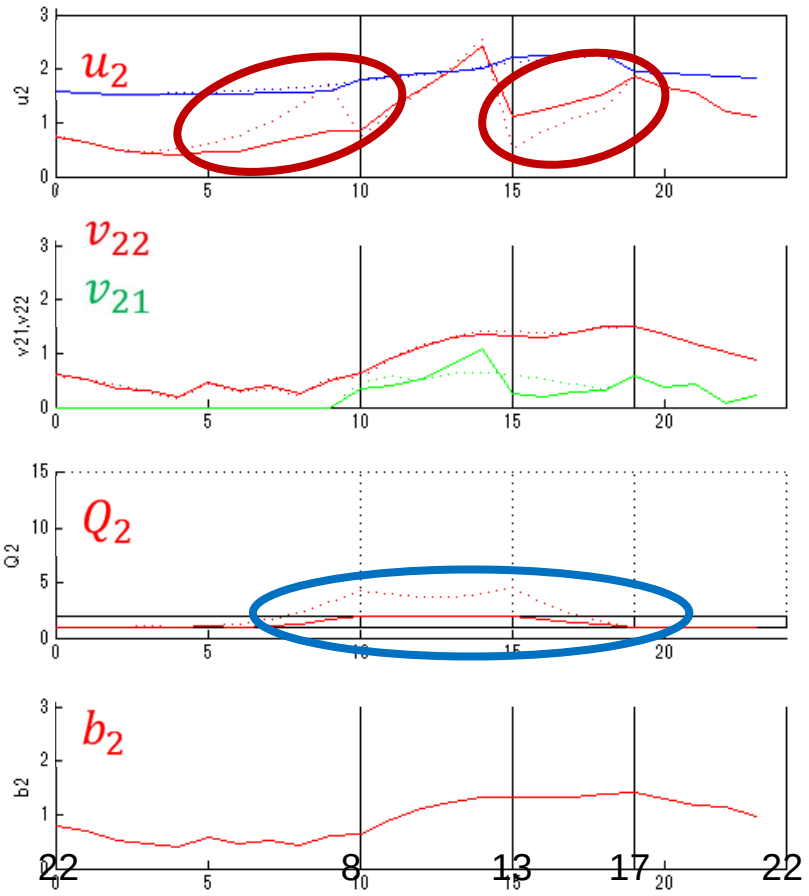


$$1 \leq Q_2 \leq 2$$

Limited Capacity

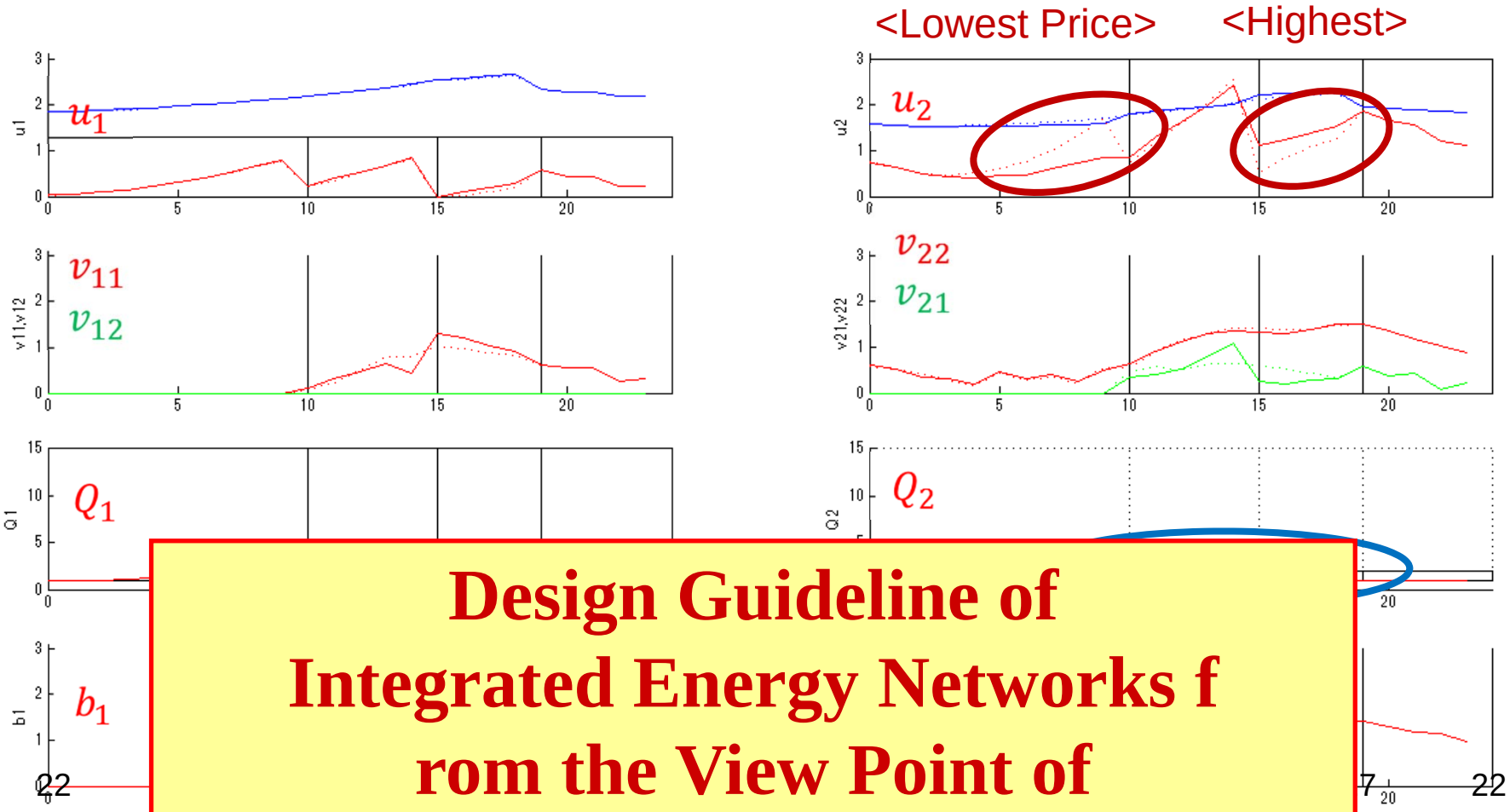
<Lowest Price> <Highest>





$$1 \leq Q_2 \leq 2$$

Limited Capacity



Design Guideline of Integrated Energy Networks f rom the View Point of Hierarchical Decentralized Control

OUTLINE

Integrated Energy Networks

with Fujitsu

with Azbil

with Tokyo-Gas

Electric NWs with PV by Gas Engines

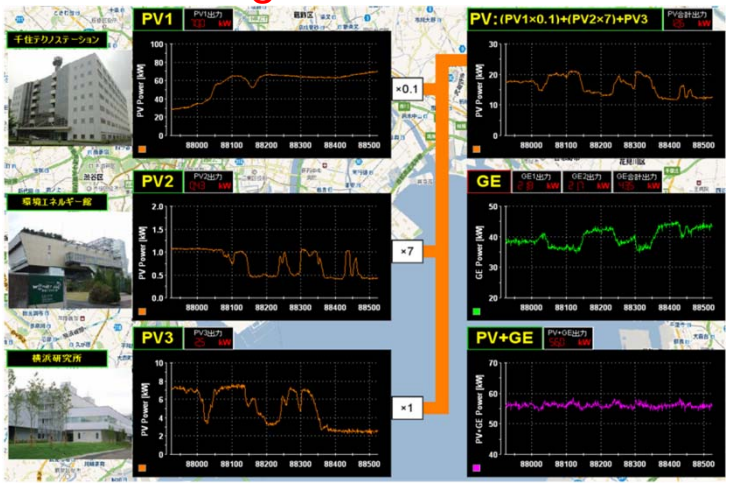
Dynamic Energy Storages

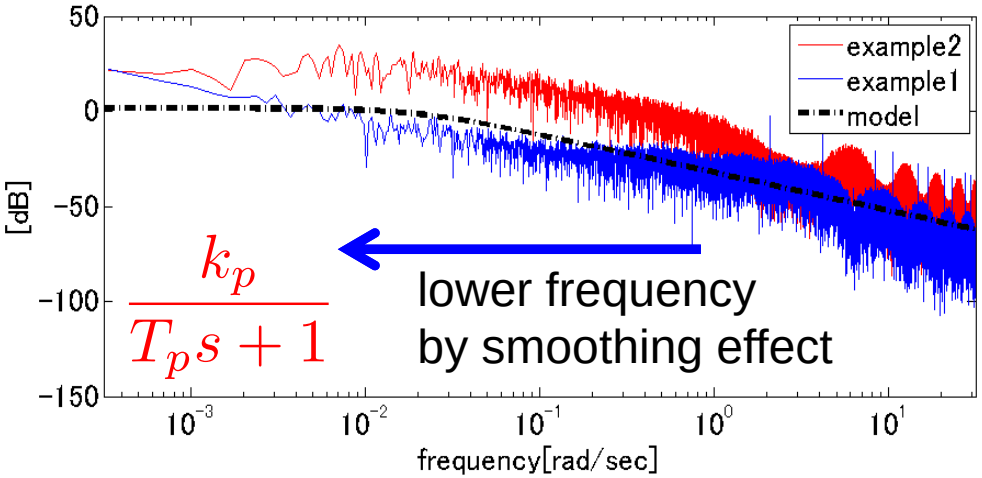
Objective in Each Layer

Hierarchical Control with Multiple Gas Turbines

(with Tokyo Gas)

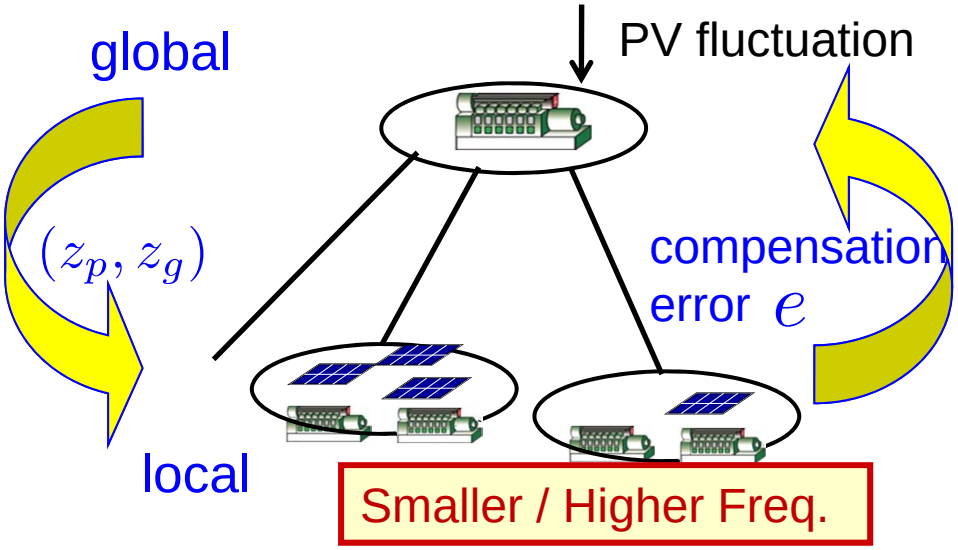
Single PV　　Sum of multiple PV



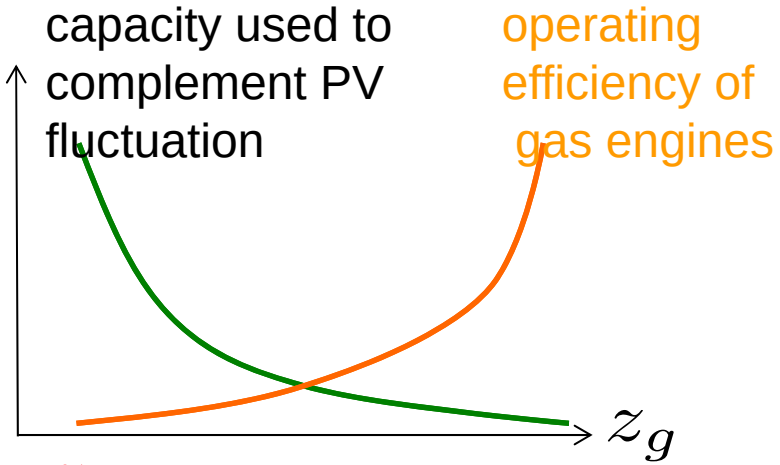


To decide optimal z_g for maximizing the efficiency

Bigger / Lower Freq.



Trade-off

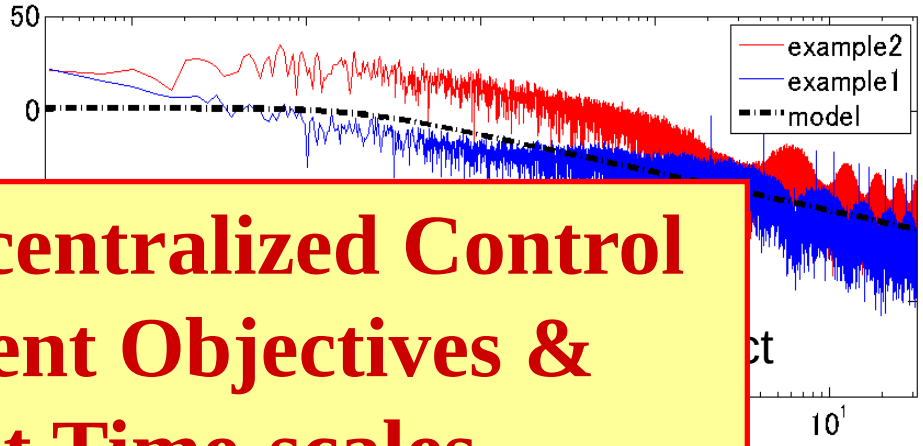


z_g : operating point

Hierarchical Control with Multiple Gas Turbines

(with Tokyo Gas)

Single PV　　Sum of multiple PV

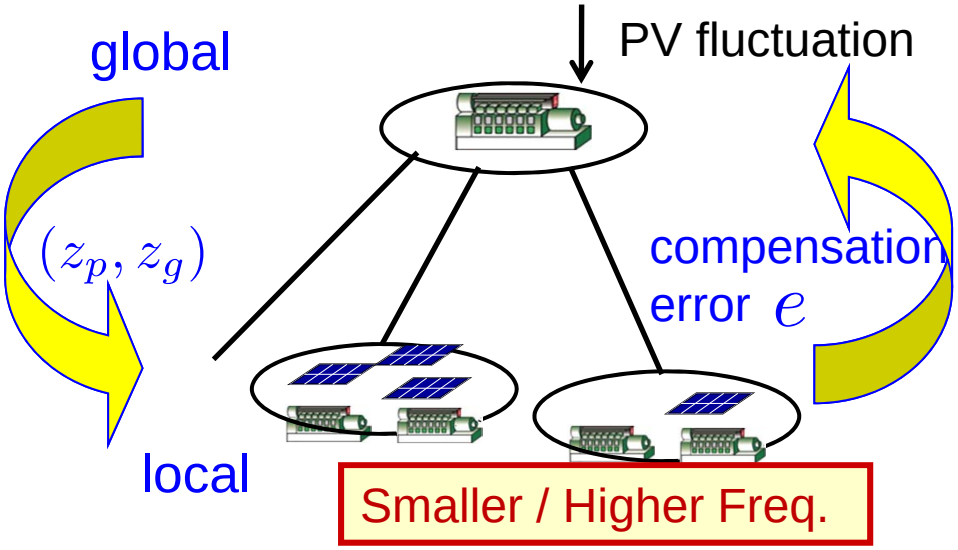


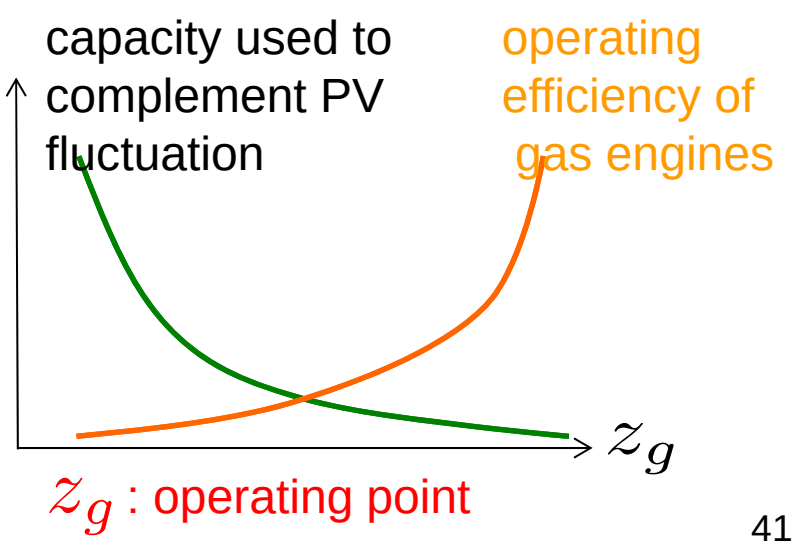
Hierarchical Decentralized Control with Different Objectives & Different Time-scales in Integrated Energy Networks

Bigger / Lower Freq.

maximizing the efficiency

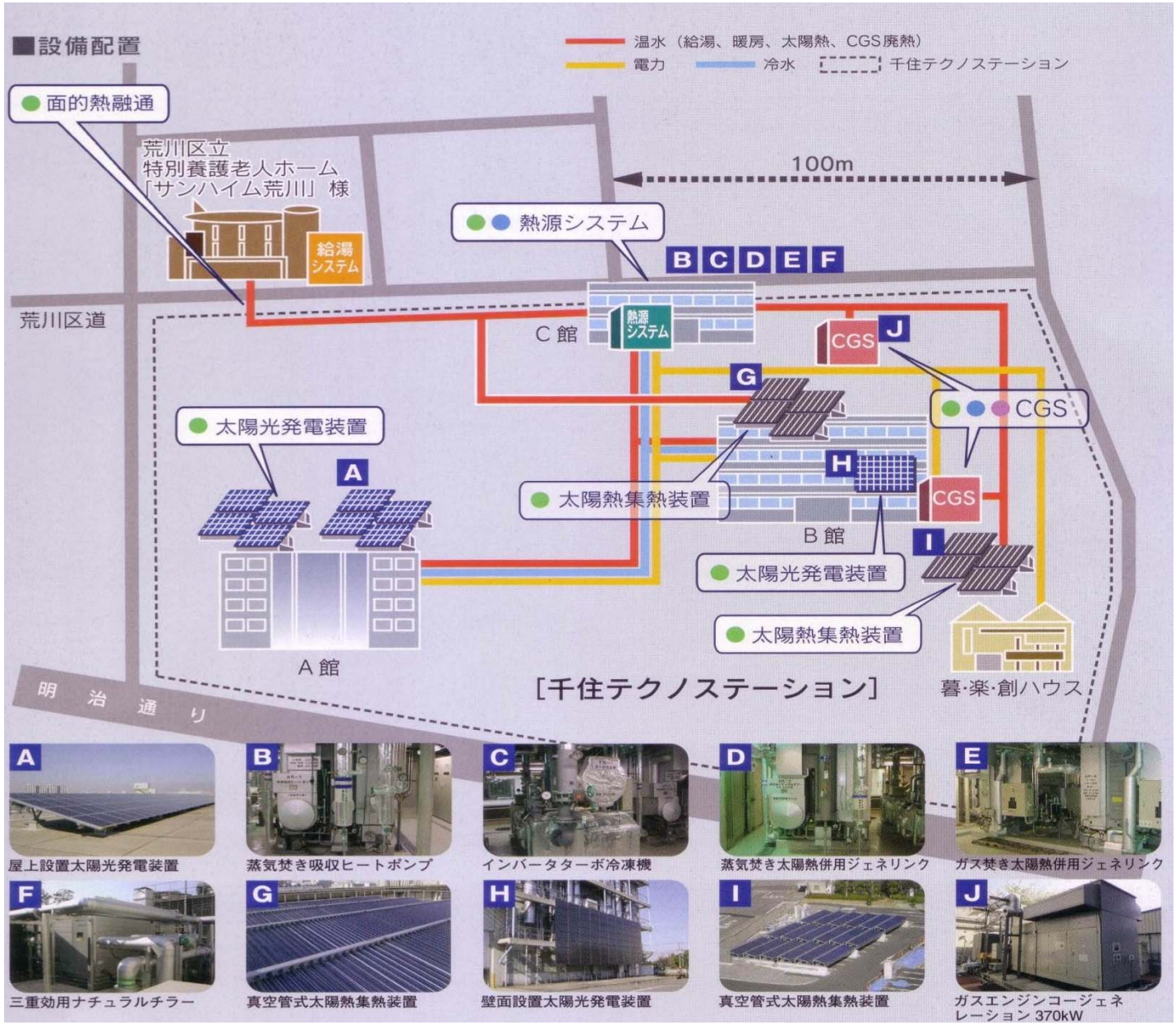
Trade-off





z_g : operating point

Experimental System for Smart Energy NW



Tokyo Gas @Senjyu