Coherence of technology and regulation: The case of electricity

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Talk outline

- Brief summary of the electric system infrastructure evolution
- Demand characterization as the key to architecture choice and its evolution
- The need for systemic technological and regulatory approach in the electricity sector
- Examples of several layer schemas and their technological, regulatory and economic characterization
- Layer schema as a complex dynamic system
- Hidden opportunism
- Dynamic Energy Control Protocols (DECP) as a means of managing opportunism

Brief summary of the electric system infrastructure evolution

- Historically, neither regulated nor liberalized electricity system was designed at one stage with well-defined/understood objectives.
- Technologically, the system has evolved in a mushroom-type manner driven by the load demand needs.
- Institutionally, governance has evolved to accommodate the load demand needs as well (private or publicly owned utilities governed by the local states).
- As a rule, there has not been much coordination of technological and institutional solutions (“designs”).
- N.B. NO “DESIGNS” OF LAYER SCHEMA; GRADUAL EVOLUTION, INSTEAD.

Demand characterization as the key to architecture choice and its evolution

- Two qualitatively different demand characterizations/roles and their hybrids.
- **Demand characterization I--top-down**: Demand is projected by the utilities (using macro-economic signals, temperature, climate); any deviations of total demand are managed as hard-to-predict disturbances.
- **Demand characterization II-bottom-up:** Demand is characterized by the individual loads (actors), including both expectations and bounds on deviations.
- **Hybrid demand characterizations-**-various degrees of multi-layered aggregation of the individual actors interacting with the utilities.

Needs for coherence of technology and regulation in the electricity sector

- What it is and what it might be

  -The challenge of managing change (invalid technological and regulatory assumptions and complexities, and their relations)

  -The evolving architectures over longer-time horizons (examples of traditional and evolving system goals)

  -Relationships between goals and qualitative (and quantifiable) system characteristics

  -Possible architectures (schema) for internalizing externalities (multi-layered architectures) (CMU research)

MAJOR QUESTION: HOW TO CATALYZE THE CHANGE (BY MEANS OF TECHNOLOGY AND REGULATION DESIGNS) ACCORDING TO WELL-UNDERSTOOD OBJECTIVES ?

An example of what it is and what it might be: The case of electric power grids

- What it is (August 2003)

Grid failure caused by lack of info/incentives to the individual actors for on-line adjustments prior to becoming too late

What it might be: On-line adjustments at the system demand side (individual actors), and by the system operators to re-route remaining resources w/o losing the system as a whole

STRIKING DIFFERENCES BETWEEN TOP DOWN AND DISTRIBUTED/MULTI-LAYERED APPROACHES (TECHNOLOGICAL AND REGULATORY)

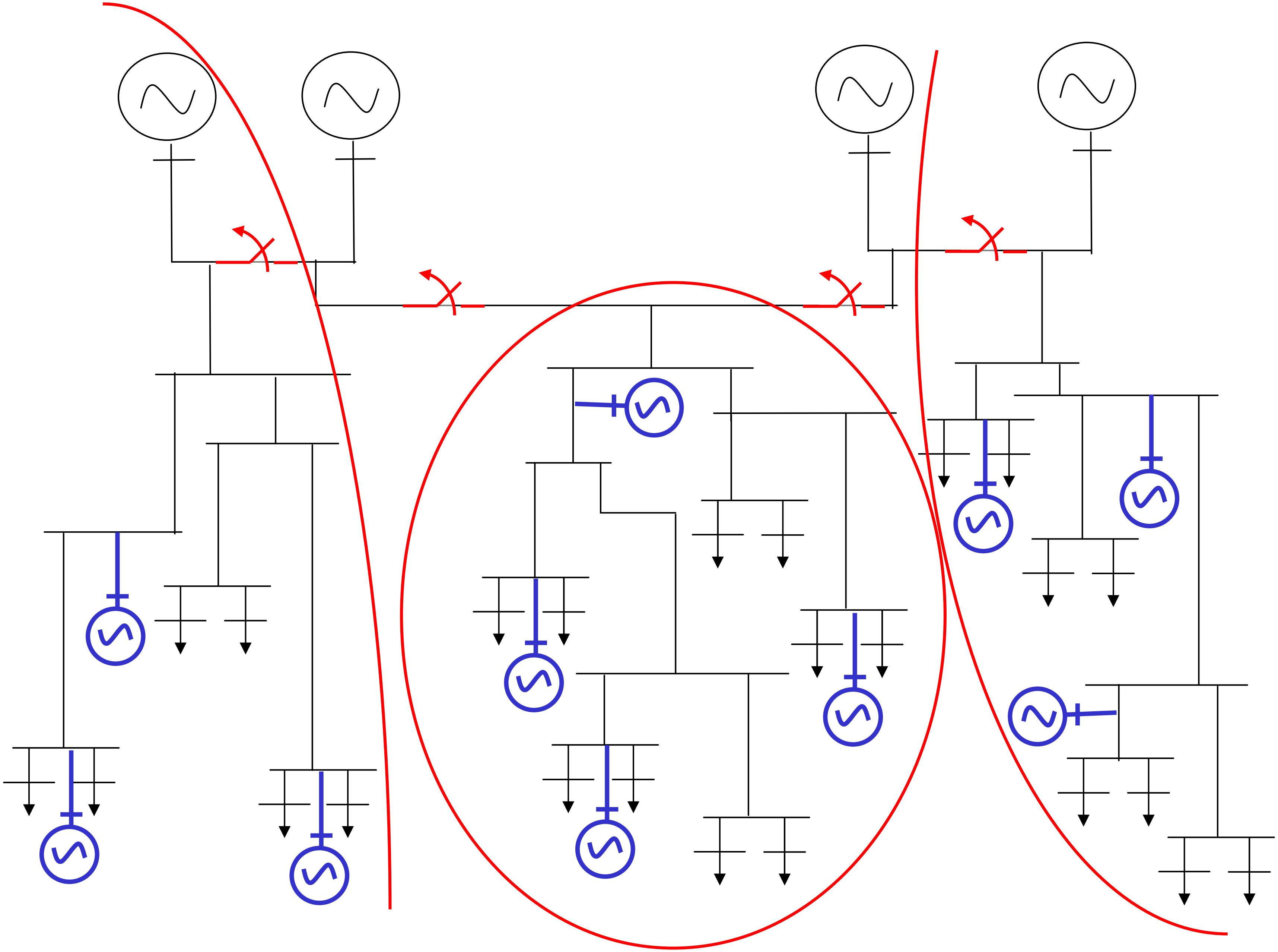
The challenge of managing change

- Network infrastructures have largely been designed assuming system characteristics that no longer hold [1,2]
- Qualitatively new system characteristics and objectives evolving as a result of regulatory changes, technological progress and unplanned component failures [3]
- No methodologies to manage this evolution

Examples of several layer schemas and their technological, regulatory and economic characterization[5,6,7,8]

- 1. Existing paradigm: Centralized, large scale; vertically integrated, horizontally distributed.
- 2. Transitional paradigm: Aggregation across non-traditional boundaries
- Likely end state paradigm : Very decentralized, large number of small scale individual actors (demand side, in particular).

Vertically integrated and hybrid layer schema



Key Features under Regulation

- Operations and planning separate tasks
- Hierarchical operations and control based on temporal and spatial separation
- Generation and transmission planning done sequentially and statically
- Average price reflecting total capital and O&M (not an actively used signal)
- Customer not an active decision maker
- No direct incentive for right technologies

Traditional objective—regulatory benchmark [4]

$$\min_{P^G_{i,a},\, I^G_{i,a},\, I^T_l} \sum_{i,a} \int_{t_0}^{T} \mathrm{e}^{-rt}\left[c_{i,a}\left(P_{i,a}(t)\right) + C^G_{i,a}\left(K^G_{i,a}(t), I^G_{i,a}(t), t\right)\right]dt$$

Technology

$$+\sum_{l} \int_{t_0}^{T} \mathrm{e}^{-rt}\left[C^T_l\left(K^T_l(t), I^T_l(t), t\right)\right]dt$$

Investment

$$-\sum_{i} \int_{t_0}^{T} \mathrm{e}^{-rt}\left[U_i\left(L_i(t), u_i(t)\right)\right]dt$$

Uncertainty in Load

subject to

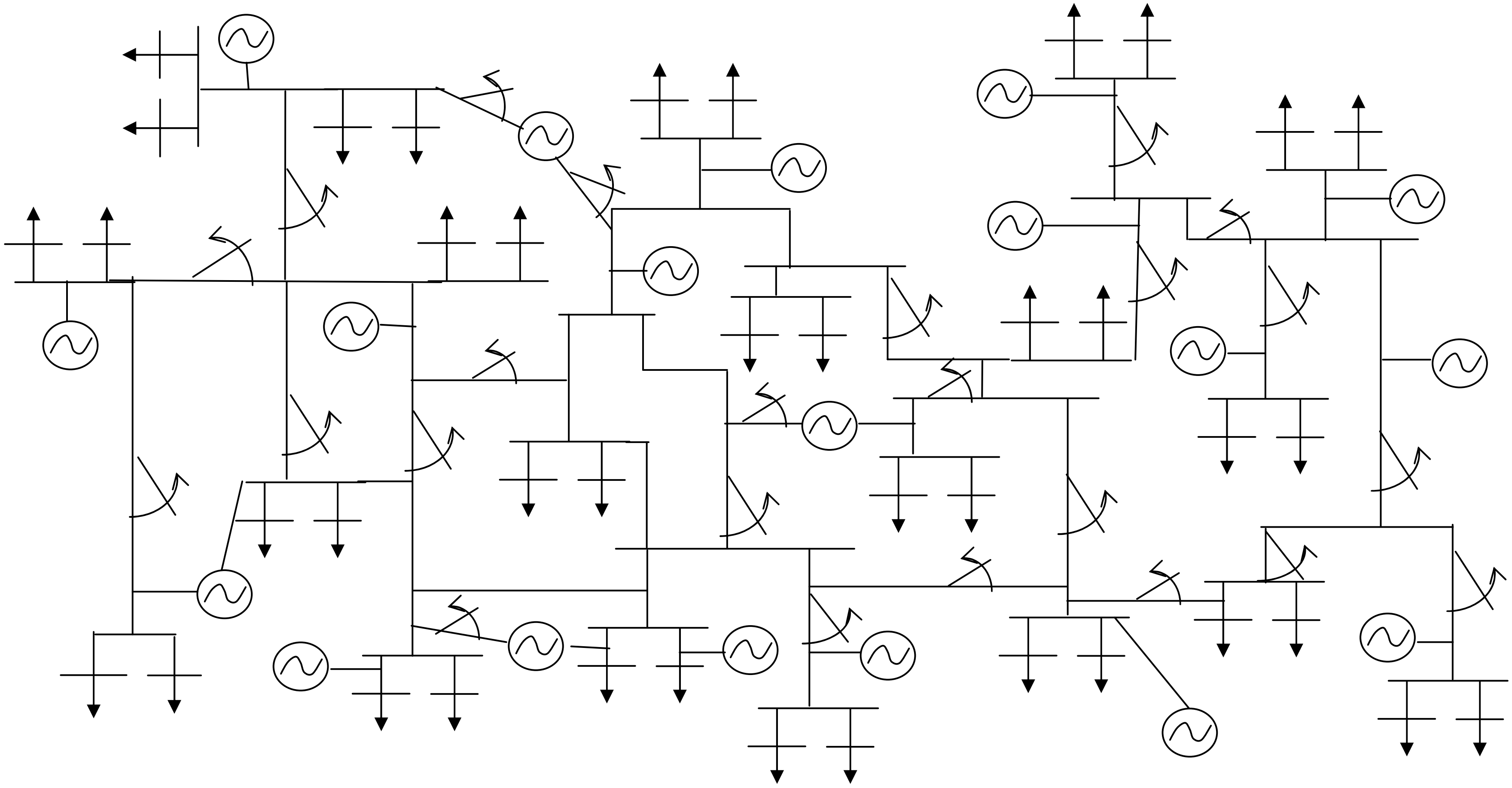
$$\frac{dK^T_l}{dt} = I^T_l(t)\ ;\ \ \frac{dK^G_{i,a}}{dt} = I^G_{i,a}(t)\ ;\ K^T_l(0),\ K^G_{i,a}(0);\ I^T_l(t),\ I^G_{i,a}(t) \geq 0$$

$$\sum_i H_{li}\left(P_{i,a}(t) - L_i(t)\right) \leq K^T_l,\ P_{i,a}(t) \leq K^G_{i,a},\ \sum_{i,a} P_{i,a} = \sum_i L_i$$

Evolving architectures—(partially) distributed

- Customers beginning to respond to the market forces (considering alternatives--user syndicates, customer choice, DG, etc)
- DGs forming portfolios (syndicates)
- Distribution companies (wire owners) designing for synergies, MINIGRIDS
- Manufactures providing equipment /design
- An overall problem: Signals for change weak

Decentralized Paradigm— Individual actors'-driven schema



Decision making by the individual actors

- Electricity Supply from System Side

$$\min_{P^G_{i,a},\, I^G_{i,a}} \int_{t_0}^{T} \Big[c_{i,a}(t)P_{i,a}(t) + C^G_{i,a}\big(K^G_{i,a}(t), I^G_{i,a}(t), t\big)$$

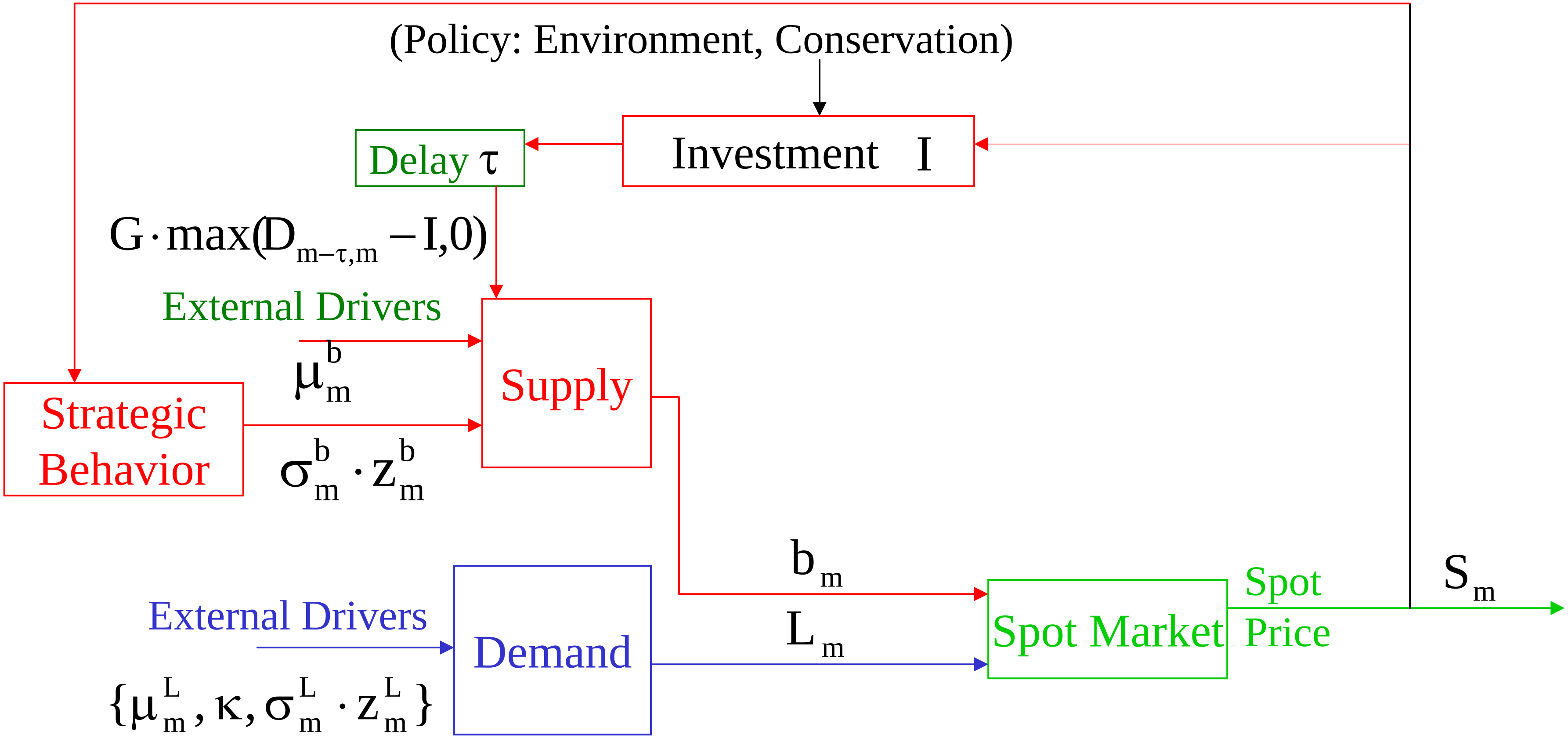
$$- \lambda(t)P_{i,a}(t) + \sum_{l} \mu_l(t) H_{li} P_{i,a}(t) \Big] dt$$

Energy Market Price **Transmission Market Price**

subject to

$$\frac{dK^G_{i,a}}{dt} = I^G_{i,a}(t) \ , \ I^G_{i,a}(t) \geq 0 \ , \ P_{i,a}(t) \leq K^G_{i,a}$$

A Long-term Electricity Price Model – HIDDEN OPPORTUNISM



(Policy: Environment, Conservation)

Investment I

Delay τ

$G \cdot \max(D_{m-\tau,m} - I, 0)$

External Drivers

μ_m^b

Supply

Strategic Behavior

$\sigma_m^b \cdot z_m^b$

b_m

S_m

Spot Market

Spot Price

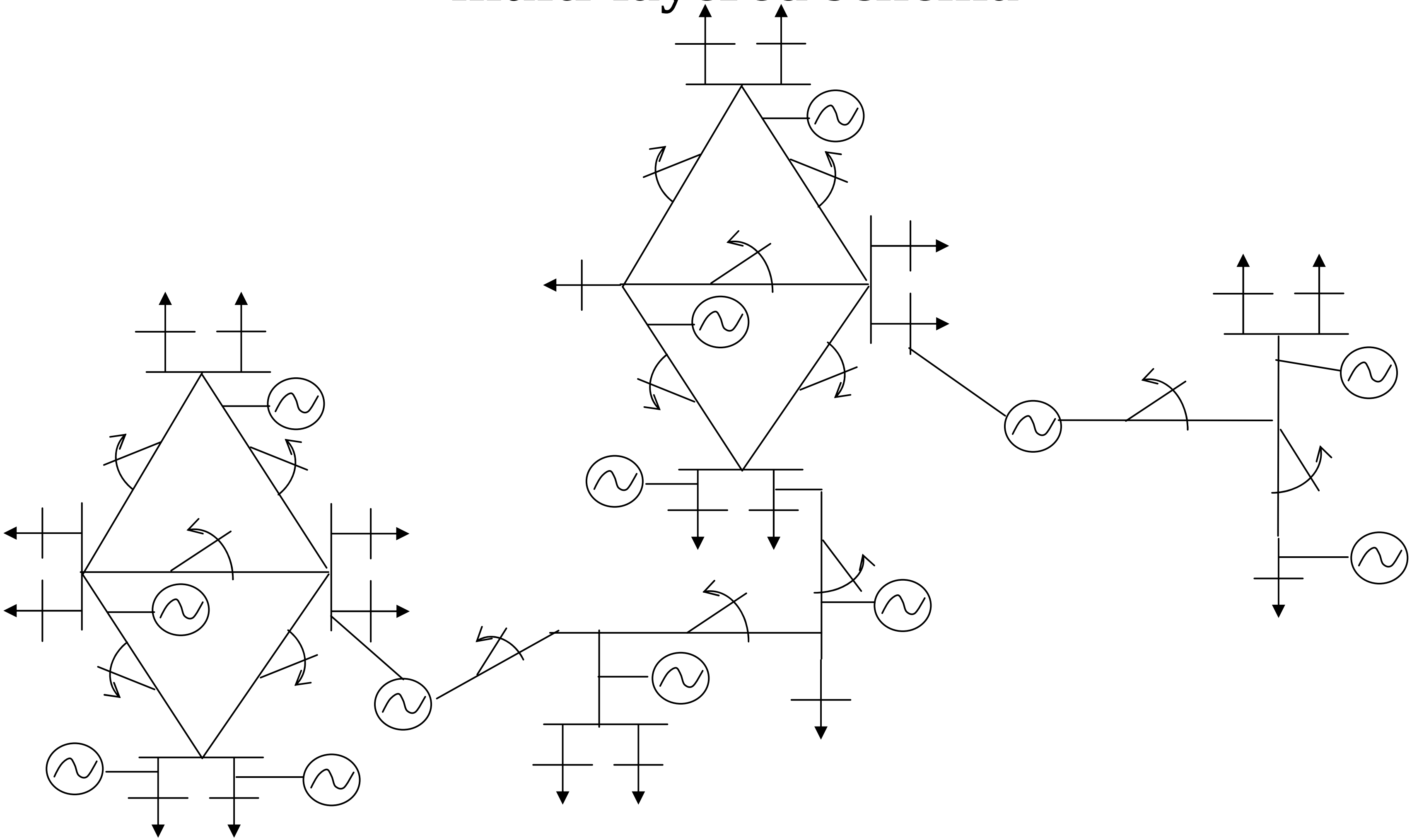
L_m

External Drivers

Demand

$\{\mu_m^L, \kappa, \sigma_m^L \cdot z_m^L\}$

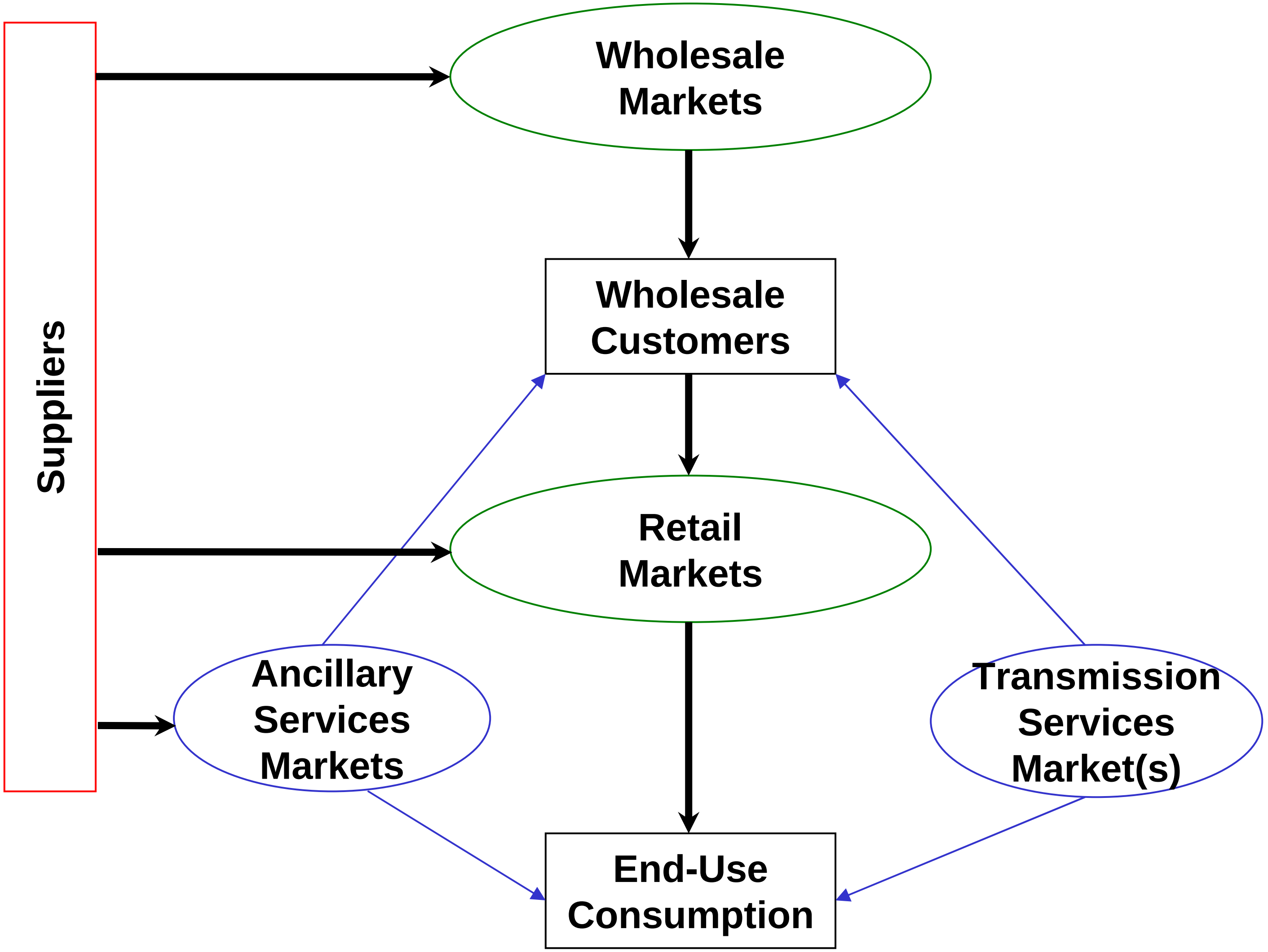
Re-aggregation—multi-layered schema



Ongoing Changes

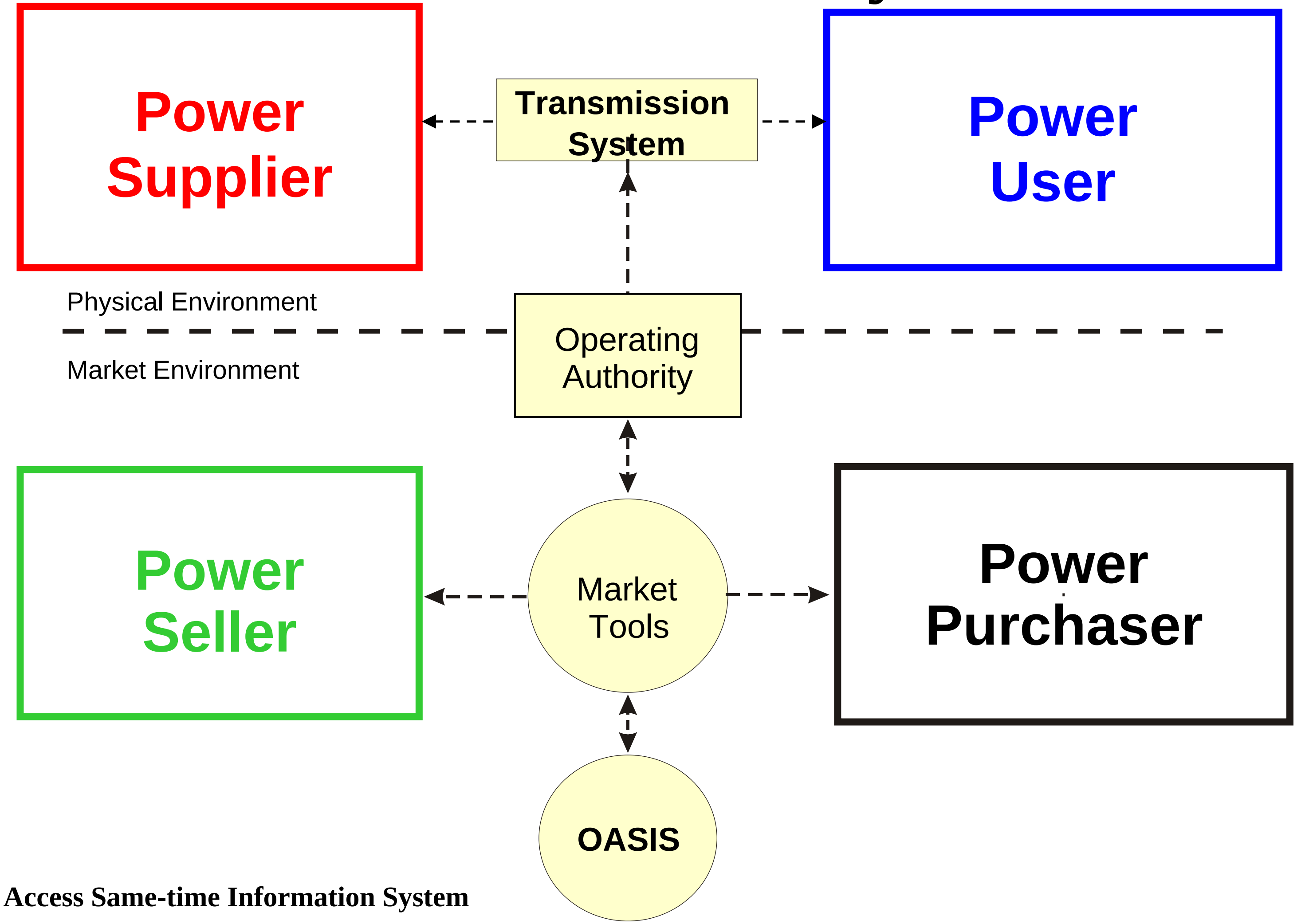
- Technological (cost-effective small and smart power supply, direct line flow control devices (FACTS), Internet, customer automation)
- Organizational (competitive power generation, electricity markets, customer choice, potential for PBR-based transmission businesses; open access)

Regional Electric Markets



Source: DOE Electricity 2002 Conceptual Design

Functional/Corporate Unbundling of Regulated Utilities—From traditional to individual actors-driven layer schemas



Power Supplier

Transmission System

Power User

Physical Environment

Operating Authority

Market Environment

Power Seller

Market Tools

Power Purchaser

OASIS

OASIS: Open Access Same-time Information System

Key Features Under Competition

- Power supply, delivery and consumption separate functional and/or corporate entities (own objectives)
- Decentralized decision making under uncertainties
- Active use of price signals (temporal and spatial)
- Potential for valuing right technologies
- Issues with reliability and long term system evolution

Individual actors-driven decisions

- Qualitatively Different Mode
  - Multi-stage, Decentralized Decisions
- Smart Components and Smart Control
  - Supplier
  - User
  - Transmission
- Role of Information Technology (IT)

Non-traditional objectives in the evolving architectures for critical infrastructures [5,8,9] –”ilities”

- Differentiated reliable service at value
- Sustainable mid-/long-term system evolution
- Flexible response to rare events
- HIDDEN OPPORTUNISM

Optimality as a function of layer schema

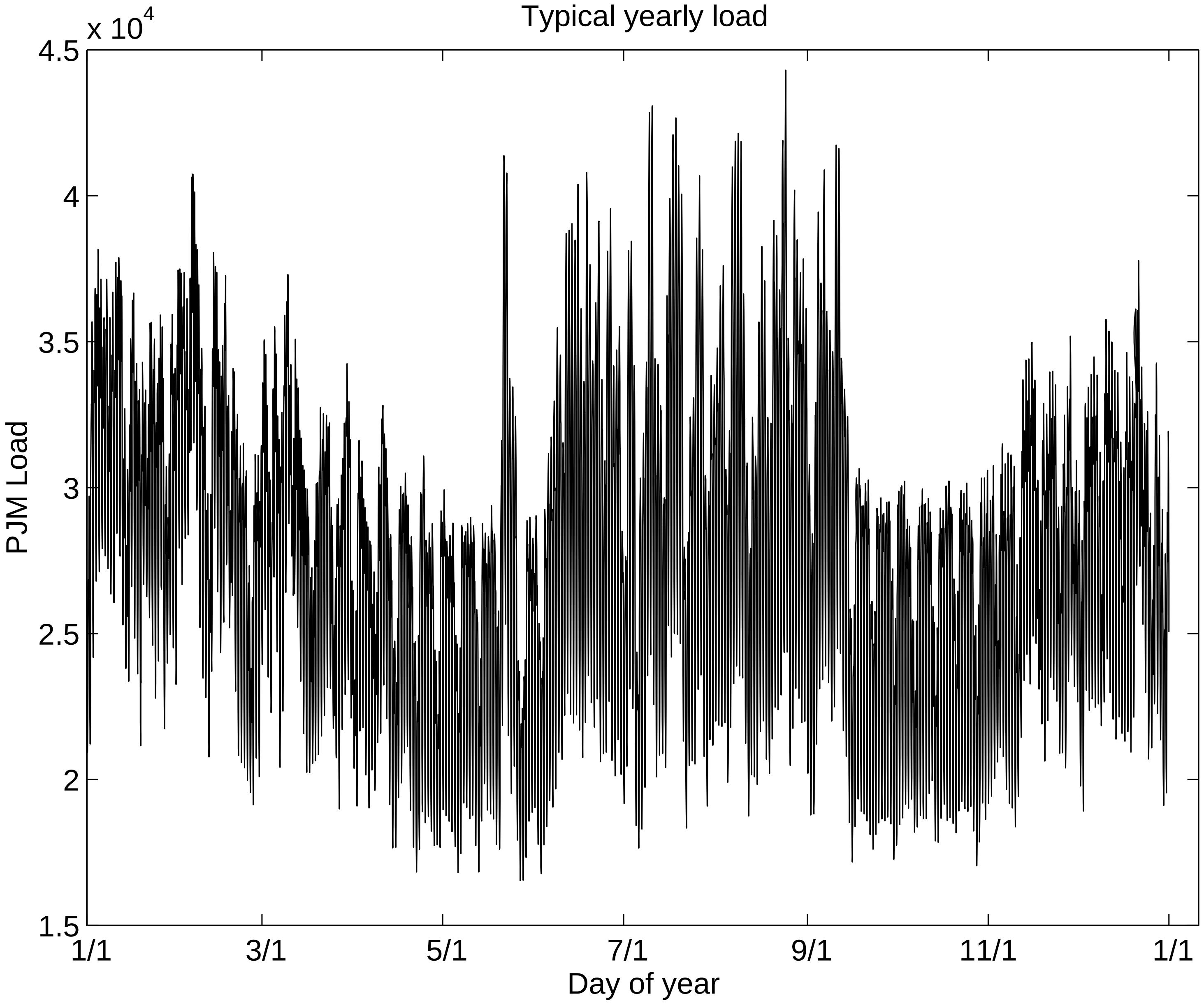
- Paradigm1-Vertically integrated layer schema : Despite the popular belief, not optimal long-term under uncertainties (much more remains to be done if dynamic social welfare is to be optimized in a coordinated way)
- Paradigm 2—Individual actors-driven layer schema: Performance very sensitive to the smartness of switches and aggregation
- Paradigm 3—Multi-layered schema: Feasible, near optimal under uncertainties; switching to implement differential reliability

Layer schema as a complex dynamic system

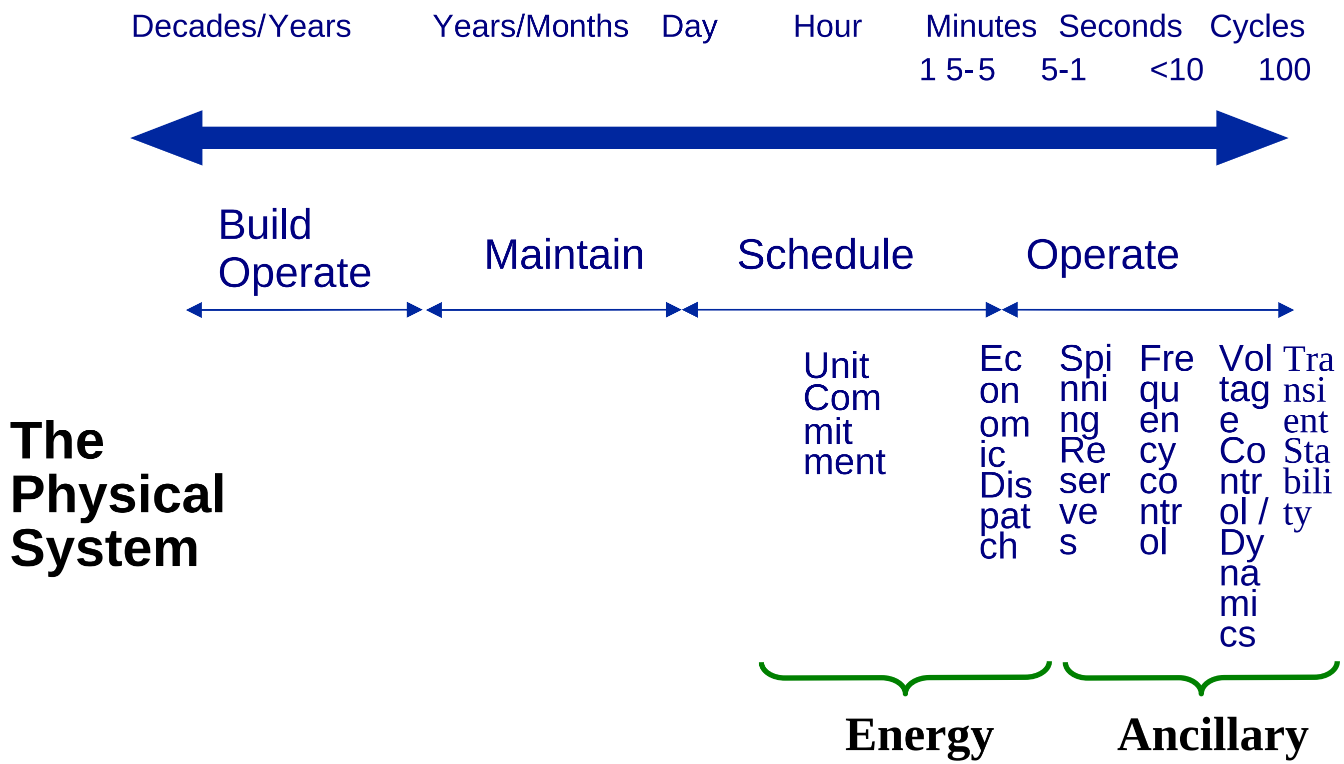
- **The need for engineering systems thinking in man-made infrastructures: Complexities**
- Heterogeneous signals defining system architecture (physical network driven by economic, regulatory and technical actions); evolving architectures
- Wide range of spatial and temporal inter-dependencies
- Architecture-dependent objectives and uncertainties
- Fundamental irrelevance of root-causes [1]
- Fundamental need for completeness [3]
- Fundamental need for embedded on-line information monitoring and use for decision making [2]

Inter-temporal dependencies

- Typical demand profile
- Need to balance power instantaneously
- Could be supplied either on the spot, or through long-term contracts
- Depending on how are uncertainties managed, very different effects on system-wide performance (in particular on “ilities”)
- RESULTS VERY DIFFERENT DEPENDING ON HOW IS SYSTEM MANAGED UNDER TOPOLOGICAL CHANGES (HIDDEN OPPORTUNISM)


Typical yearly load
x 10^4
4.5
4
3.5
3
2.5
2
1.5
PJM Load
1/1
3/1
5/1
7/1
9/1
11/1
1/1
Day of year

Engineering time-line: Relevance of long-term for architecture evolution



Decades/Years Years/Months Day Hour Minutes Seconds Cycles

1 5-5 5-1 <10 100

Build Operate

Maintain

Schedule

Operate

The Physical System

Unit Commitment

Economic Dispatch

Spinning Reserves

Frequency control

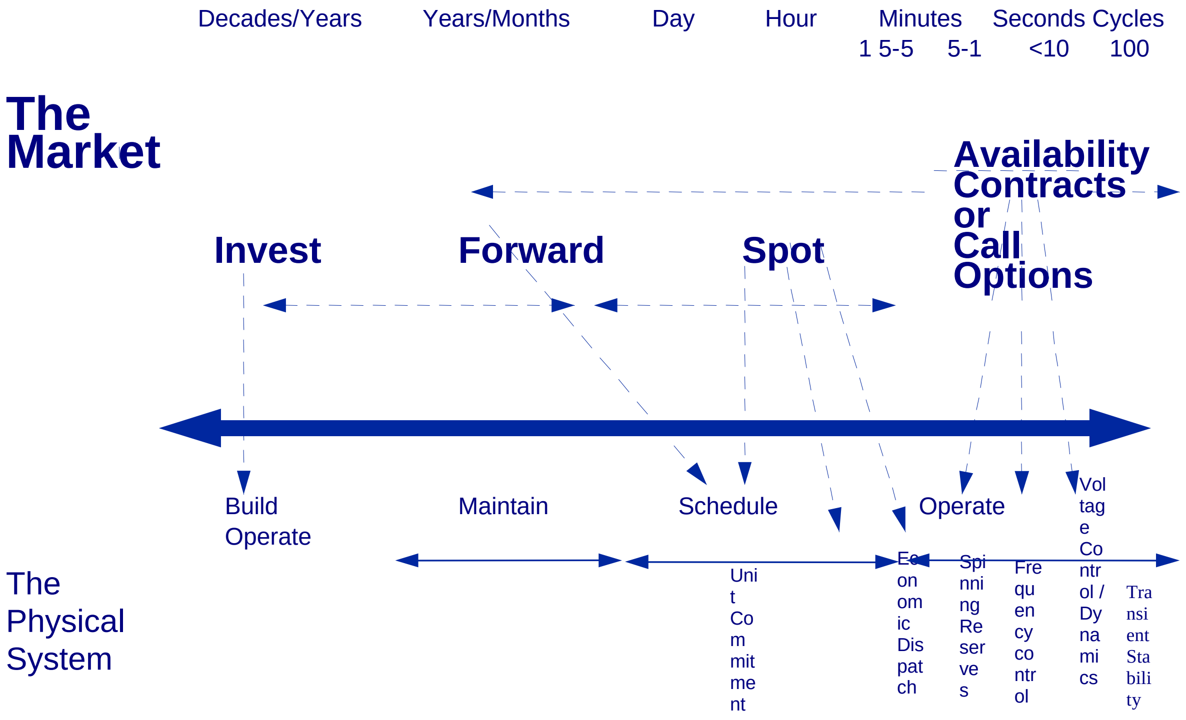
Voltage Control / Dynamics

Transient Stability

Energy

Ancillary

Market and Physical Inter-temporal Complexities



Decades/Years Years/Months Day Hour Minutes Seconds Cycles

1 5-5 5-1 <10 100

The Market

Availability Contracts or Call Options

Invest

Forward

Spot

Build

Operate

Maintain

Schedule

Operate

Voltage Control / Dynamics

Unit Commitment

Economic Dispatch

Spinning Reserves

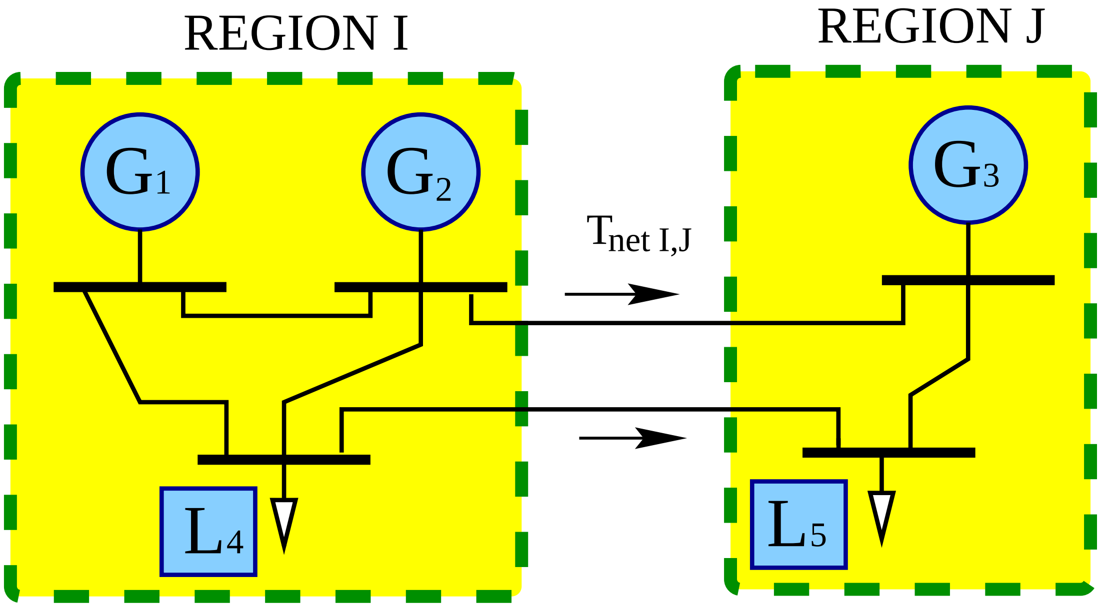
Frequency control

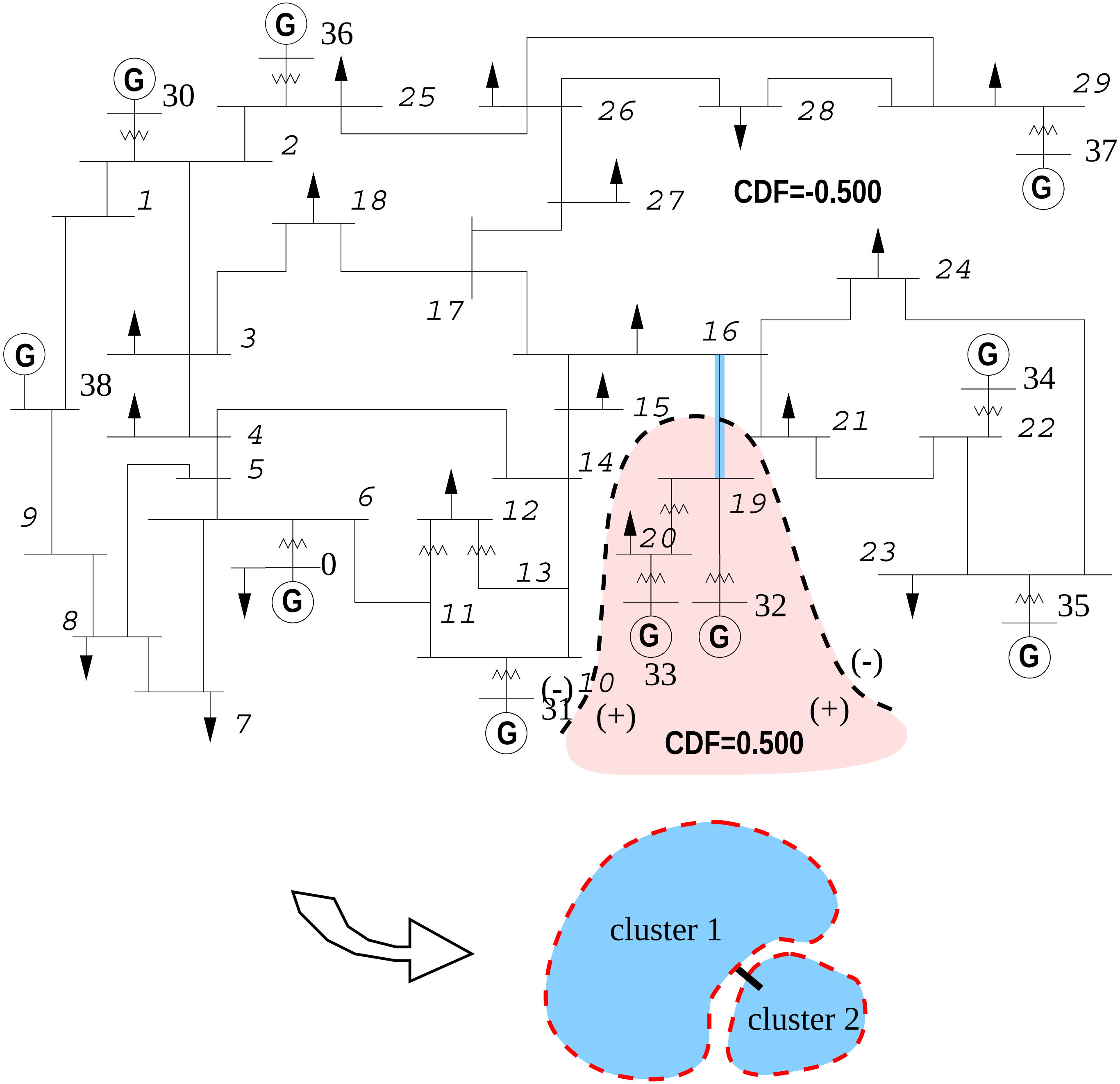
Transient Stability

The Physical System

Spatial complexities

- Very large networks
- Often no direct control of power flows between the sub-networks
- Regulatory requirements for “open access”
- Various levels of granularity: Nodes, zones, administrative boundaries (utilities, control areas) (HIDDEN OPPORTUNISM)
- Without aggregation it is impossible to “learn” how to use the network in a bottom-up way (too combinatorial)


REGION I
REGION J
G1
G2
G3
$T_{net\ I,J}$
L4
L5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38
15
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6
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9
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13
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G
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32
35
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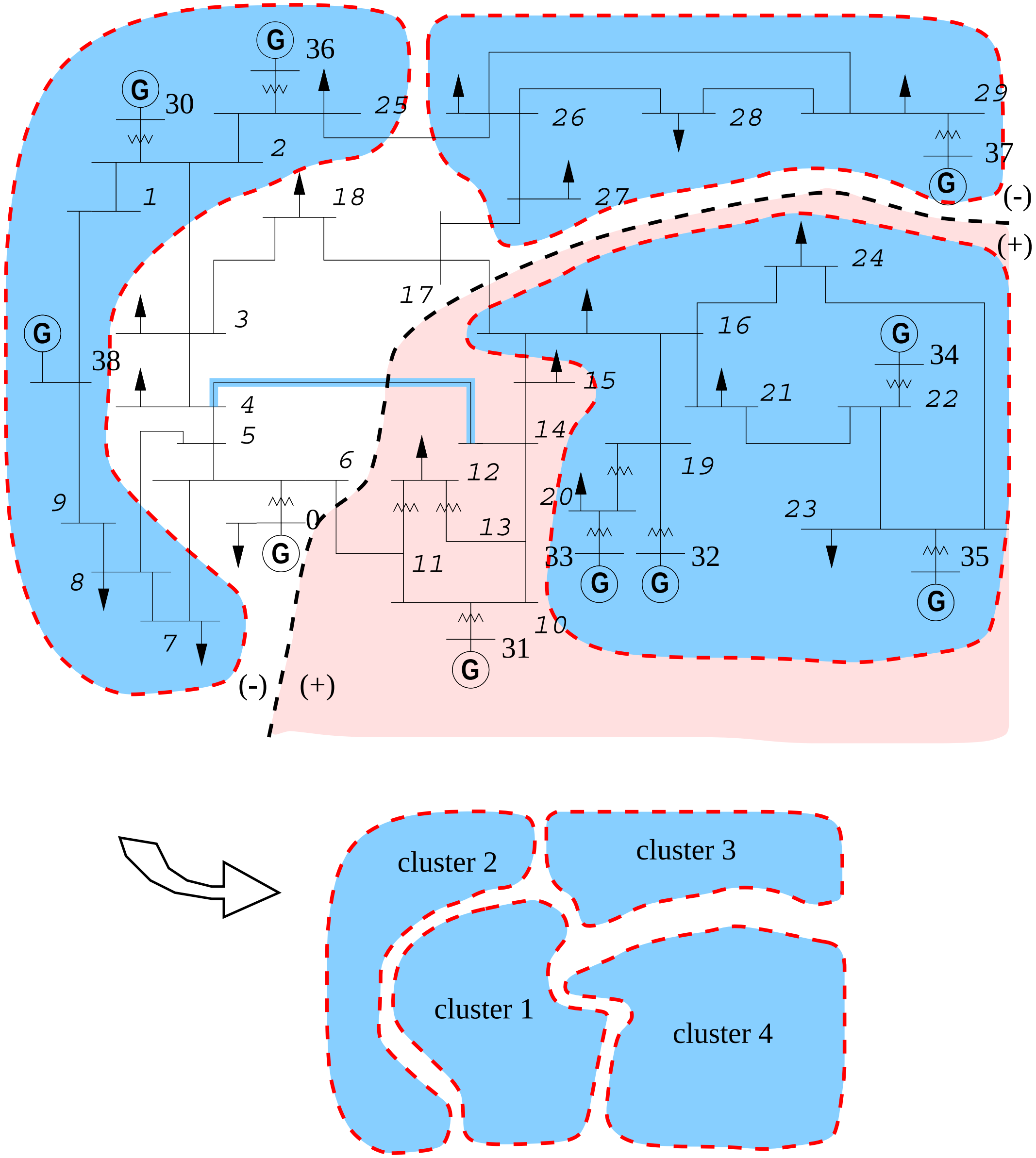
31
(+)
(+)
7
G
CDF=0.500
cluster 1
cluster 2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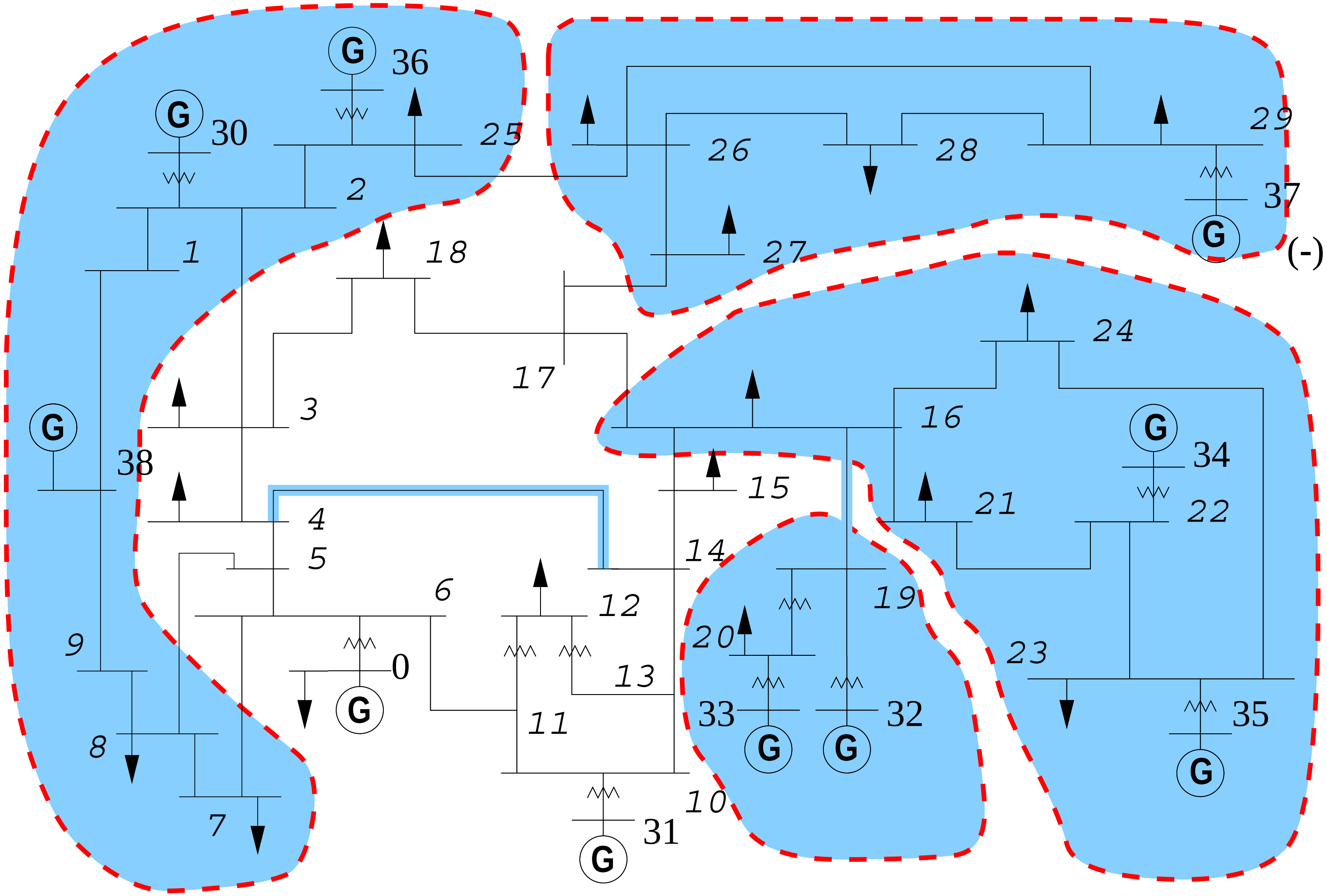
cluster 3
cluster 1
cluster 4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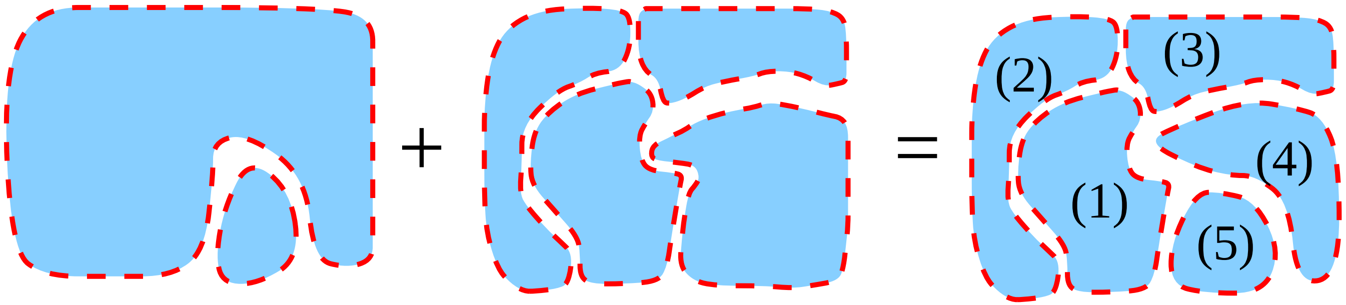
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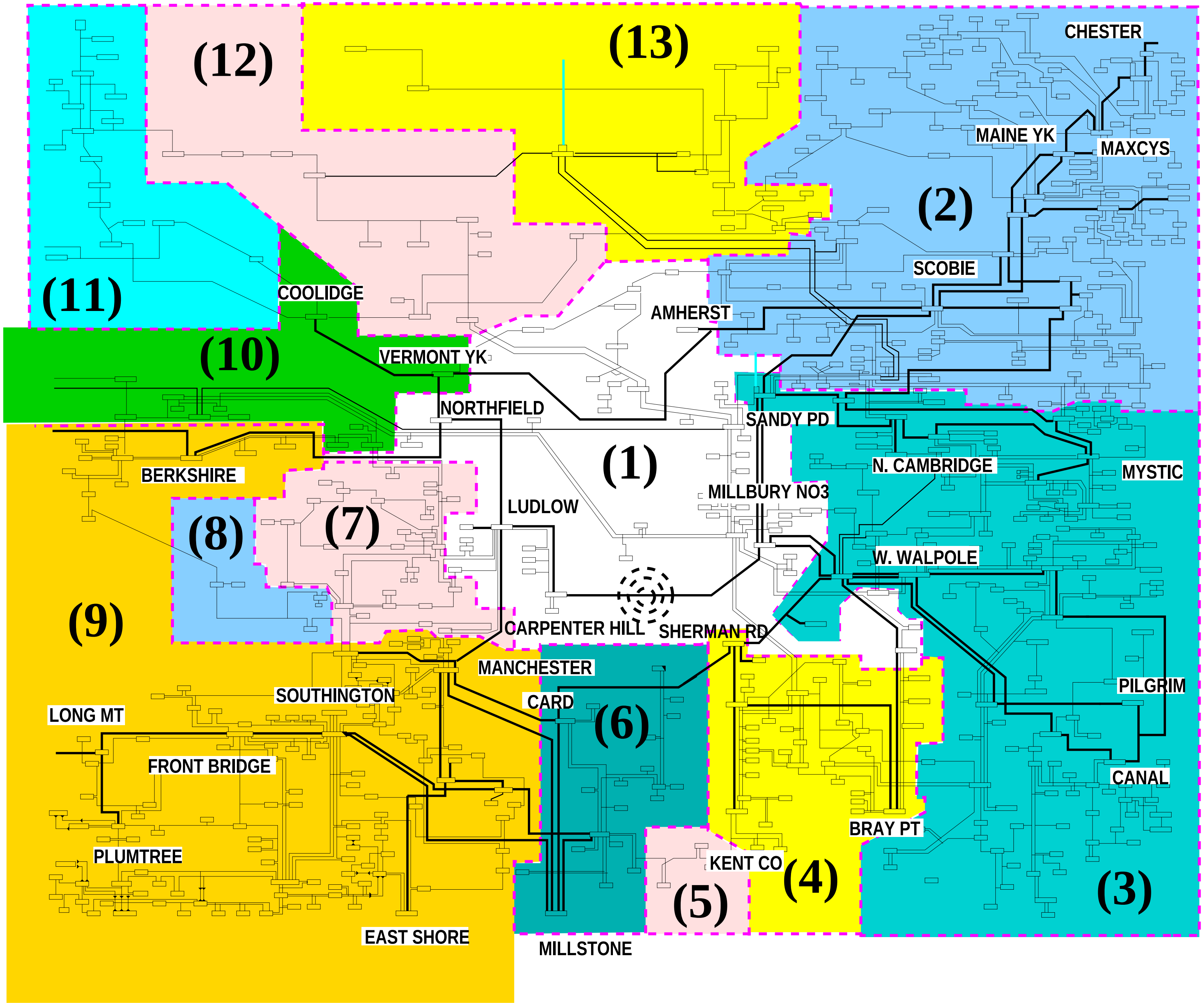
(1)
(5)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MAXCYS
(2)
(11)
COOLIDGE
SCOBIE
AMHERST
(10)
VERMONT YK
NORTHFIELD
SANDY PD
(1)
BERKSHIRE
N. CAMBRIDGE
MYSTIC
MILLBURY NO3
LUDLOW
(8)
(7)
W. WALPOLE
(9)
CARPENTER HILL
SHERMAN RD
MANCHESTER
PILGRIM
SOUTHINGTON
LONG MT
CARD
(6)
FRONT BRIDGE
CANAL
BRAY PT
PLUMTREE
KENT CO
(4)
(5)
(3)
EAST SHORE
MILLSTONE

Dynamic aggregation

- Zones—sub-groups of end-users which contribute to the line flow constraint of interest the same way (Zone 1—the largest effect; Zone 2-smaller effect, ..)
- Could be used for spatial simplifications; extremely relevant for architecture transparency and market liquidity;
- Open questions: Coordination of zones and/or control areas to implement “open access” delivery [3] (HIDDEN OPPORTUNISM)

Multi-layered architectures for flexible and reliable operation over the wide range of system conditions

- Multi-directional signals replacing top-down info flows (a means of internalizing externalities)
- Embedded modeling and dynamic decision making tools for defining multi-directional info flows (translating complex inter-temporal dependencies into useful, transparent info; Managing spatial complexities through dynamic data compression into useful info for various layers)
- The paper [9] provides theoretical foundations for this as well as a conceptual rationale for going beyond static top-down approach

Catalyzing architecture evolution—technological progress

- Computer tools for making complex data into useful info w/o losing the essential information (spatial and temporal) for the effective decision making
- Providing info dynamically at various industry layers (examples of this in the paper)
- NEED REGULATORY INCENTIVES TO SUPPORT THIS (DYNAMIC ZONE OVER TIME AND SPACE??)

Qualitatively Different Mode

- Suboptimal operation in static sense
- Potentially optimal long-term, given uncertainties (result of distributed stochastic optimization); multi-stage decision making
- System operating closer to the acceptable operating limits for which it was designed
- Conjecture: IT tools will play critical role in facilitating iterative interplay among different entities

Some conjectures [9]

- Efficient reliability and flexibility hard to implement in a centralized architecture given today' systems engineering knowledge
- If designed right, technical, economic and regulatory signals embedded within a network infrastructure play interchangeable role in inducing desired "ilities"
- Only under strong simplifying system characteristics various architectures lead to the same performance
- Significant differences in managing uncertainties and nonlinearities (non-unique outcomes managed within a multi-layered architecture)-"ilities"
- Multi-directional flows essential for internalizing externalities

Architecture characteristics and relations to goals

- The three industry structures result in the same total system cost at equilibrium (theoretical and simulations-results) given perfect info
- Critical assumptions: Linear (DC) relations between power injections and flows; linear inequality constraints (LP problem)
- Non-linear load flow constraints do NOT lend themselves to the same result (voltage constraints cannot be handled) (NLP problem)
- Topological changes (reliability) cannot be included (DP problem)
- Common assumptions suffice traditional objectives; one must be much more careful with “ilities”

Critical open problems

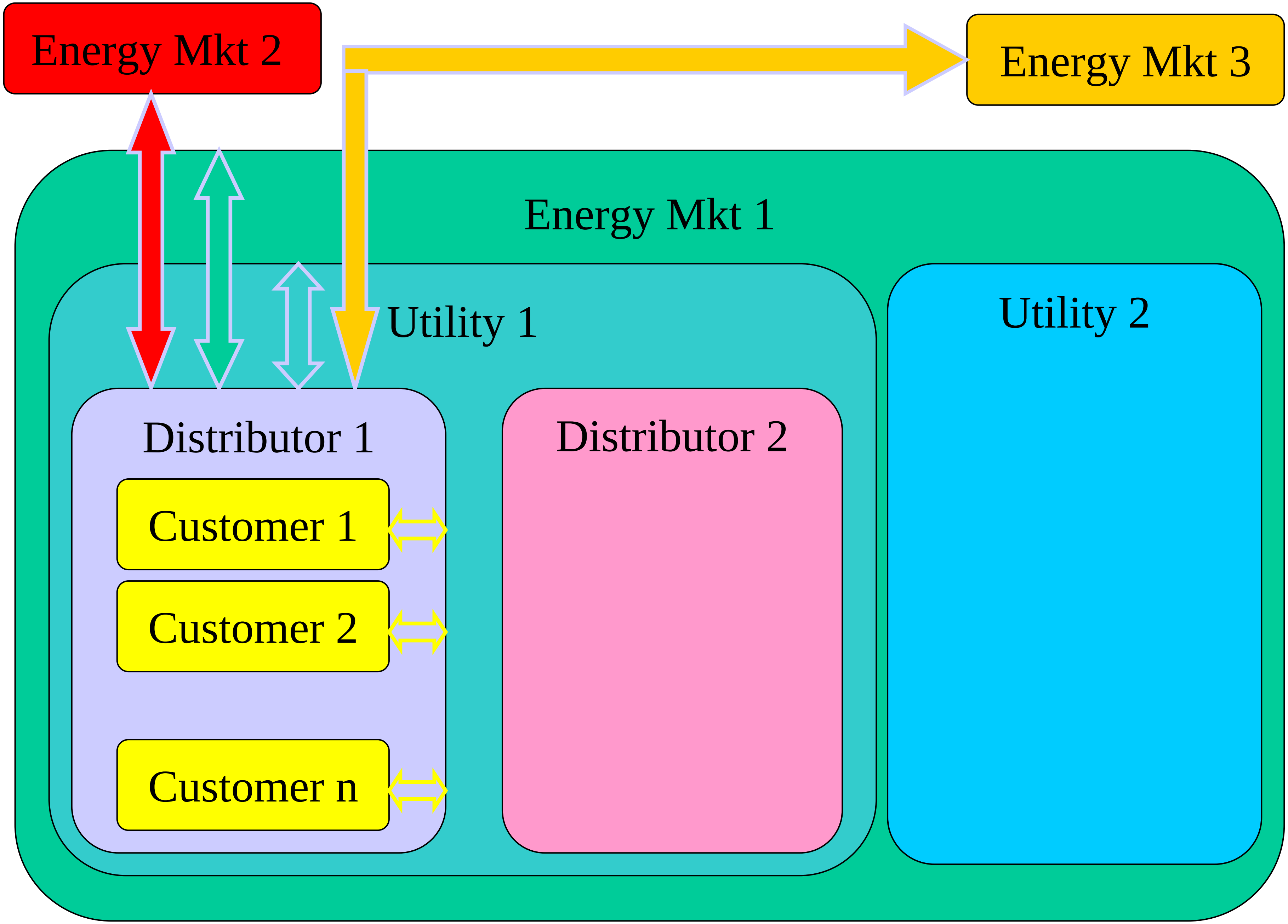
- Design of complete architectures (including markets) for managing service at value (including physical reliability-related risks) over a wide range of time horizons and their inter-temporal dependencies;
- The effect of decentralization (coordination needed for system-wide efficiency; could be through price incentives, and/or engineering rules) [3]
- Tools for re-bundling over time and space to facilitate transparent complete architectures
- Education challenges: Defining infrastructures as heterogeneous large-scale dynamic systems; re-visiting state of art large-scale systems (CMU course 18-777); aggressive development of useful computer tools [10]

The key obstacles to having a coherent approach in the electricity sector

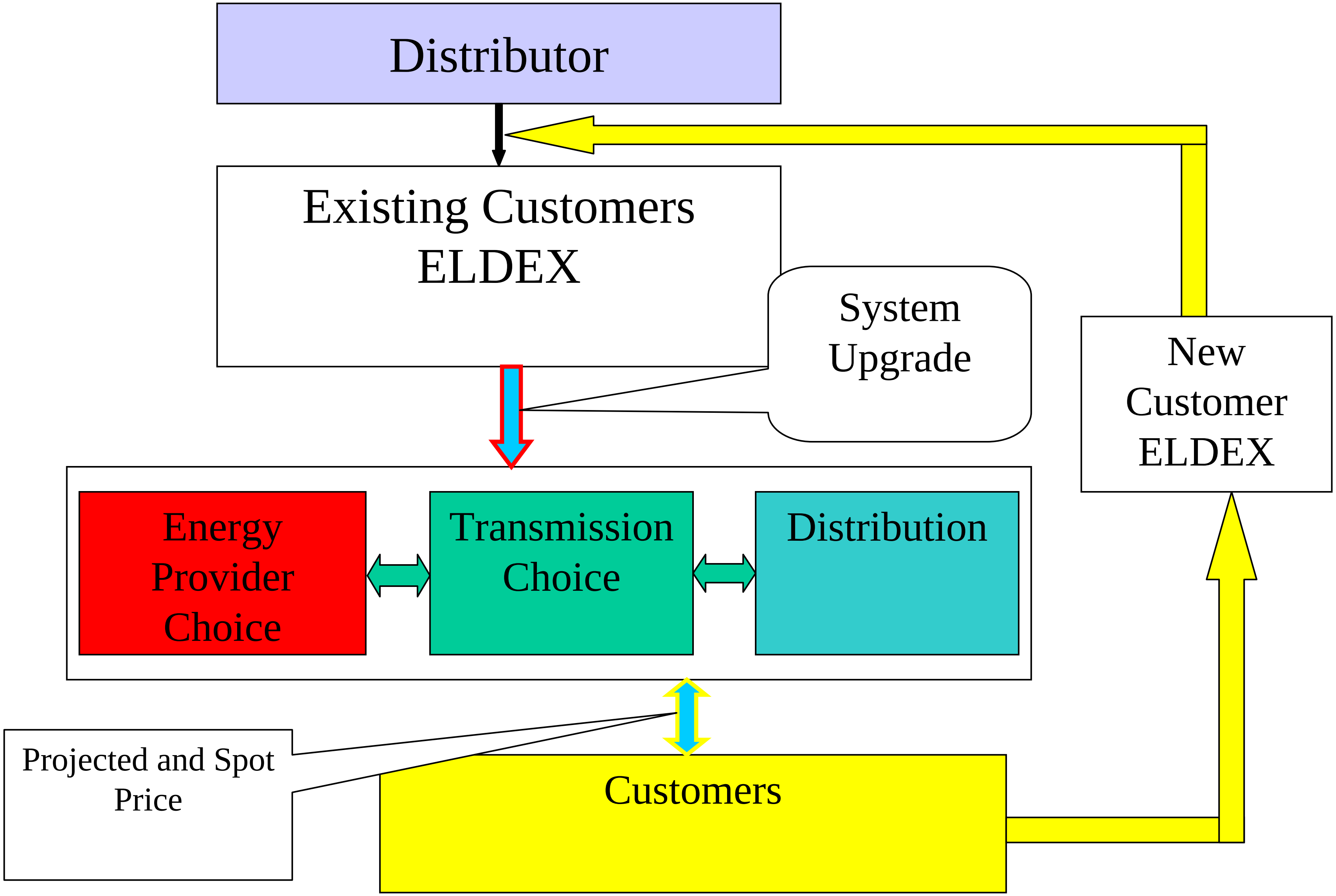
- Institutional (coexistence of obligation to serve and competitive power purchasing);
- Gap between cost-based delivery and value-based generation provision; rule-based system operations and planning
- Highly inflexible regulatory mechanisms for extracting the value of distributed “disruptive” technologies
- WE PLAN TO PROVIDE SIMULATIONS SHOWING OUTCOMES UNDER VARIOUS REGULATORY LAYER SCHEMA; TOWARD DESIGNING DECPs

Proposed enhancements-Toward Dynamic Energy Control Protocols (DECPs)

- Demand must bid (short-, mid- and long-term)
- A sequential market for forward markets to meet long-term demand specifications
- Corresponding sequential market for managing network delivery and its valuation
- Natural link between operations and investments (currently broken)
- A Stratum Energy Market (SEM) design could build on the existing market design with careful assessment of the key enhancements [11]


Energy Mkt 2
Energy Mkt 3
Energy Mkt 1
Utility 1
Utility 2
Distributor 1
Distributor 2
Customer 1
Customer 2
Customer n

Dynamic Protocol --- Distributor Level



KEY ROLE

Distributor

Existing Customers
ELDEX

System
Upgrade

New
Customer
ELDEX

Energy
Provider
Choice

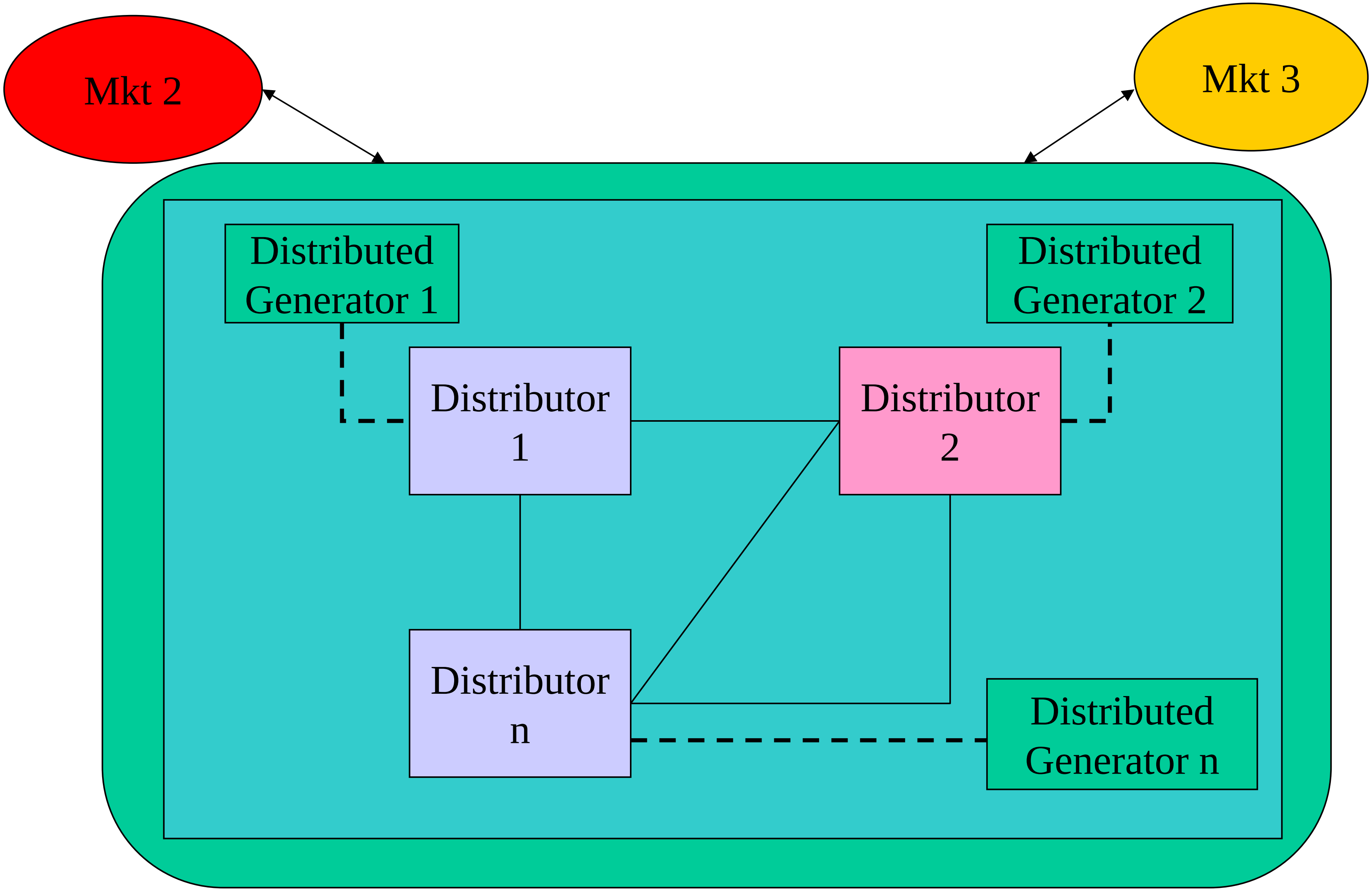
Transmission
Choice

Distribution

Projected and Spot
Price

Customers

Dynamic Protocol --- Utility Level


Mkt 2

Mkt 3

Distributed Generator 1

Distributed Generator 2

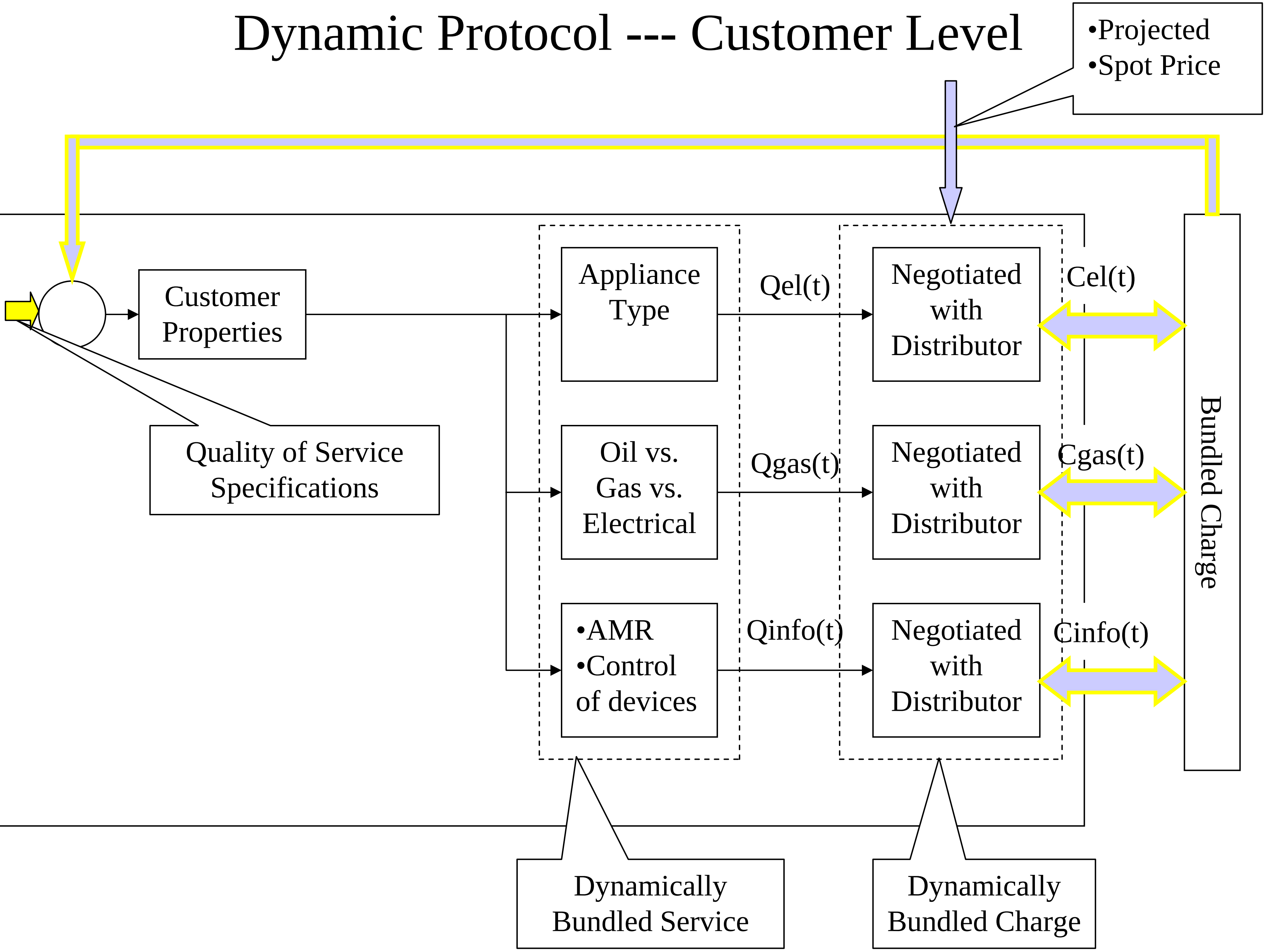
Distributor 1

Distributor 2

Distributor n

Distributed Generator n

Dynamic Protocol --- Customer Level



- Projected
- Spot Price

Customer Properties

Quality of Service Specifications

Appliance Type

Oil vs. Gas vs. Electrical

- AMR
- Control of devices

Qel(t)

Qgas(t)

Qinfo(t)

Negotiated with Distributor

Negotiated with Distributor

Negotiated with Distributor

Cel(t)

Cgas(t)

Cinfo(t)

Bundled Charge

Dynamically Bundled Service

Dynamically Bundled Charge

IT-supported Markets

- **Modeling layers at all levels of the evolving industry**
- **Modeling and learning interactions among the layers**
- **THE KEY QUESTION: WHO IS DESIGNING THESE AND ACCORDING TO WHICH THEORETICAL/PRAGMATIC APPROACHES?? AS OF NOW, IT IS LEARNING BY DOING.**

Relevant references

- [1]-[3] Three papers by Ilic at Charles River Research, Inc. www site, 2003/2004.
- [4] Yu, CN, Leotard, J-P, Ilic, M., "Dynamic Transmission Provision in Competitive Electric Power Industry", Discrete Event Dynamic Systems: Theory and Applications, 9, 351-388, Kluwer Academic Publishers, Boston, MA.
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- [6] Ilic, M., ``Change of Paradigms in Complexity and Interdependencies of Infrastructures: The Case for Flexible New Protocols'', Proceedings of the OSTP/NSF White House Meeting, June 2001.
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- [8]] Ilic, M. A Control Engineering Approach to Reliable and Flexible Infrastructure Systems, Proceedings of the MIT Internal Symposium, 2002.
- [9]] Ilic, M., Toward a Multi-Layered Architecture of Large-Scale Complex Systems: The Problem of Reliable and Efficient Man-Made Infrastructures, Proceedings of the MIT ESD Symposium, 2004.
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- [11] Wu, R., Ilic, M., NAPS’06.