Coherence of technology and regulation: The case of electricity

Professor Marija Ilic

ECE and EPP Departments

Carnegie Mellon University

milic@ece.cmu.edu

University of Paris Workshop on the NGI Project
May 29, 2006

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)

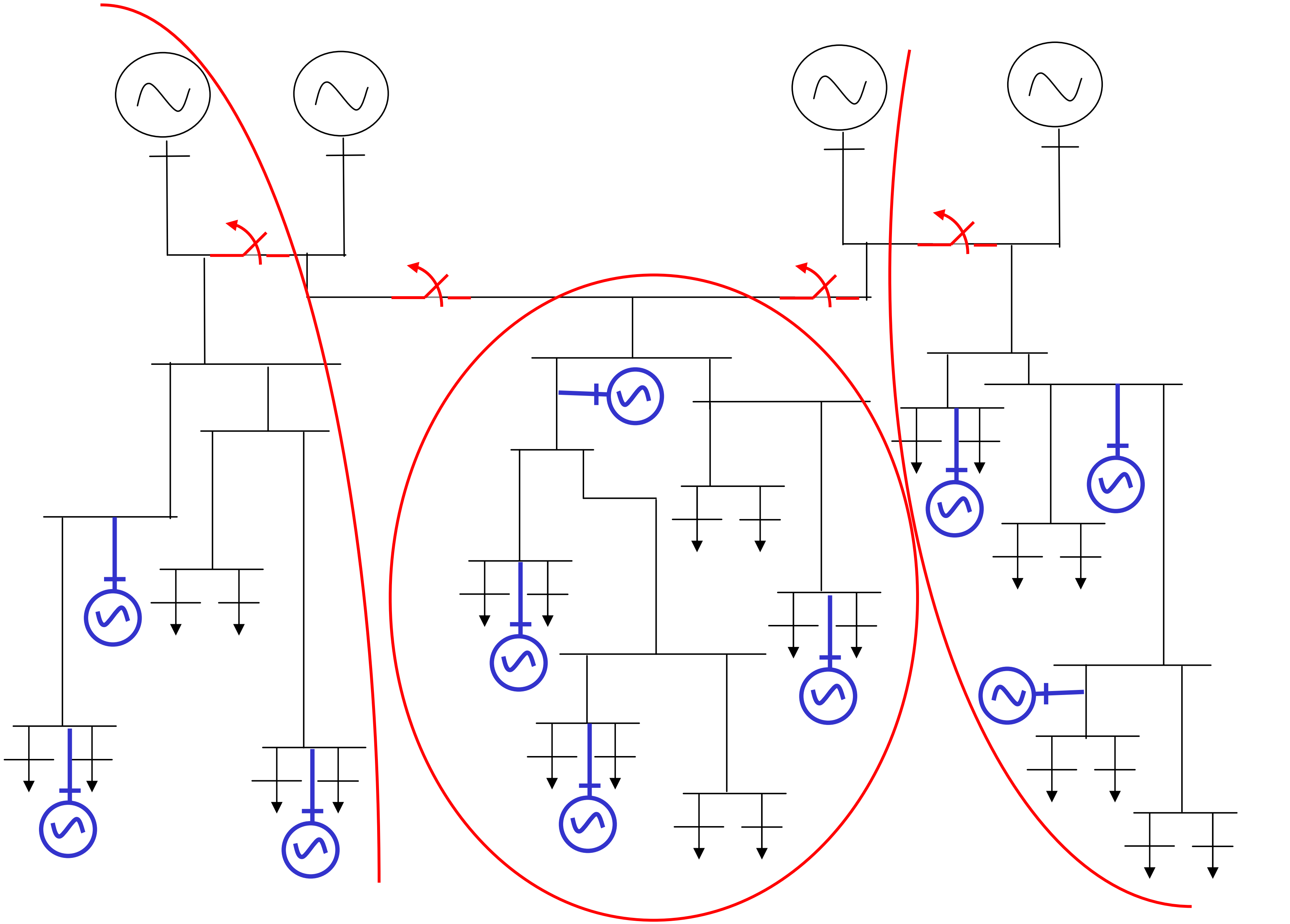
The challenge of managing change

- 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]

$$\min_{P_{i,a}^{G}, I_{i,a}^{G}, I_l^{T}} \sum_{i,a} \int_{t_0}^{T} \mathrm{e}^{-rt} \left[c_{i,a}\left(P_{i,a}(t)\right) + C_{i,a}^{G}\left(K_{i,a}^{G}(t), I_{i,a}^{G}(t), t\right)\right] dt$$

Technology

$$+\sum_{l} \int_{t_0}^{T} \mathrm{e}^{-rt} \left[C_l^{T}\left(K_l^{T}(t), I_l^{T}(t), t\right)\right] dt$$

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

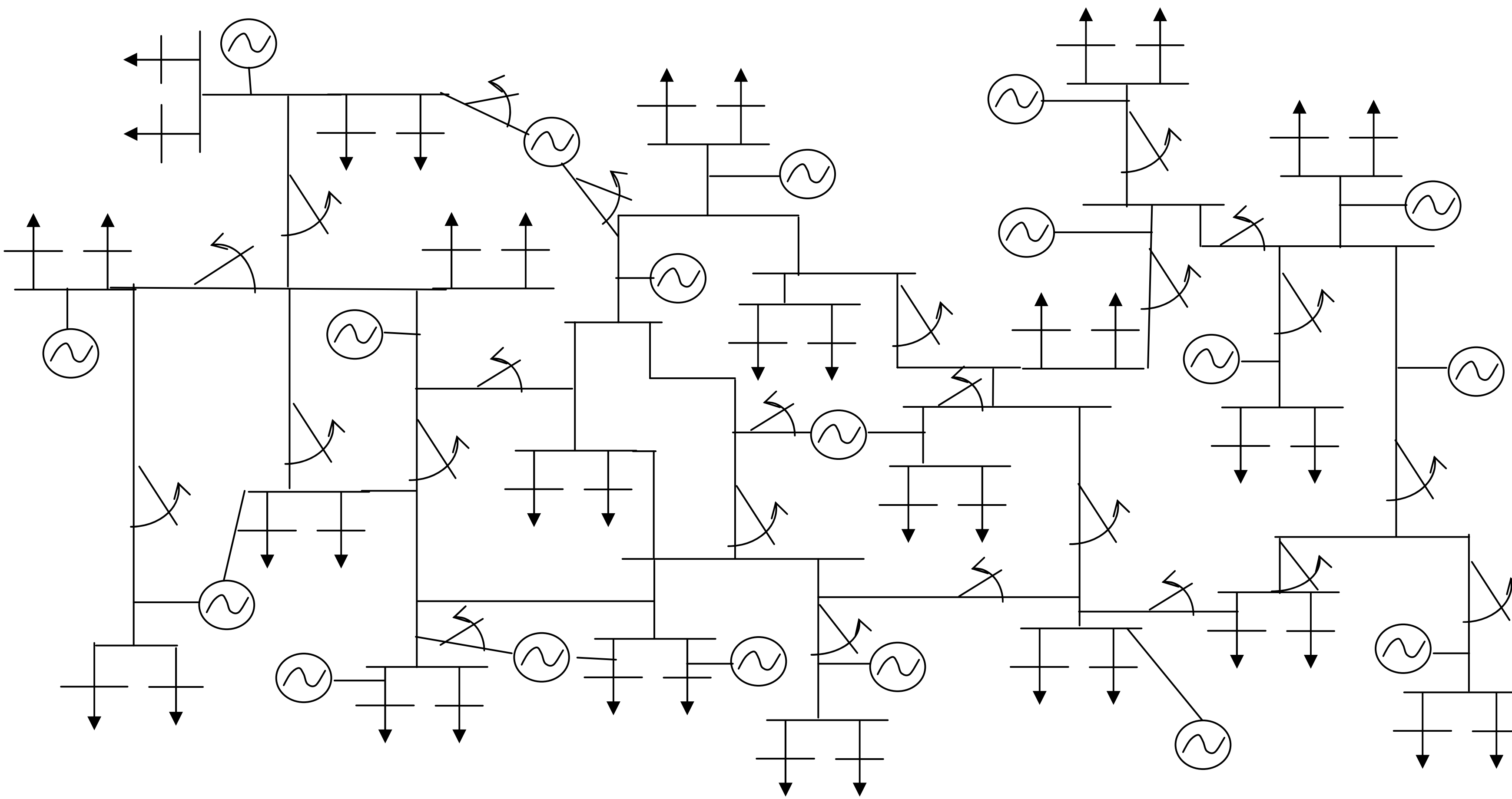
$$\frac{dK_l^{T}}{dt} = I_l^{T}(t) \; ; \; \frac{dK_{i,a}^{G}}{dt} = I_{i,a}^{G}(t) \; ; \; K_l^{T}(0),\; K_{i,a}^{G}(0); \; I_l^{T}(t),\; I_{i,a}^{G}(t) \geq 0$$

$$\sum_{i} H_{li}\left(P_{i,a}(t) - L_i(t)\right) \leq K_l^{T}, \; P_{i,a}(t) \leq K_{i,a}^{G}, \; \sum_{i,a} P_{i,a} = \sum_{i} L_i$$

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

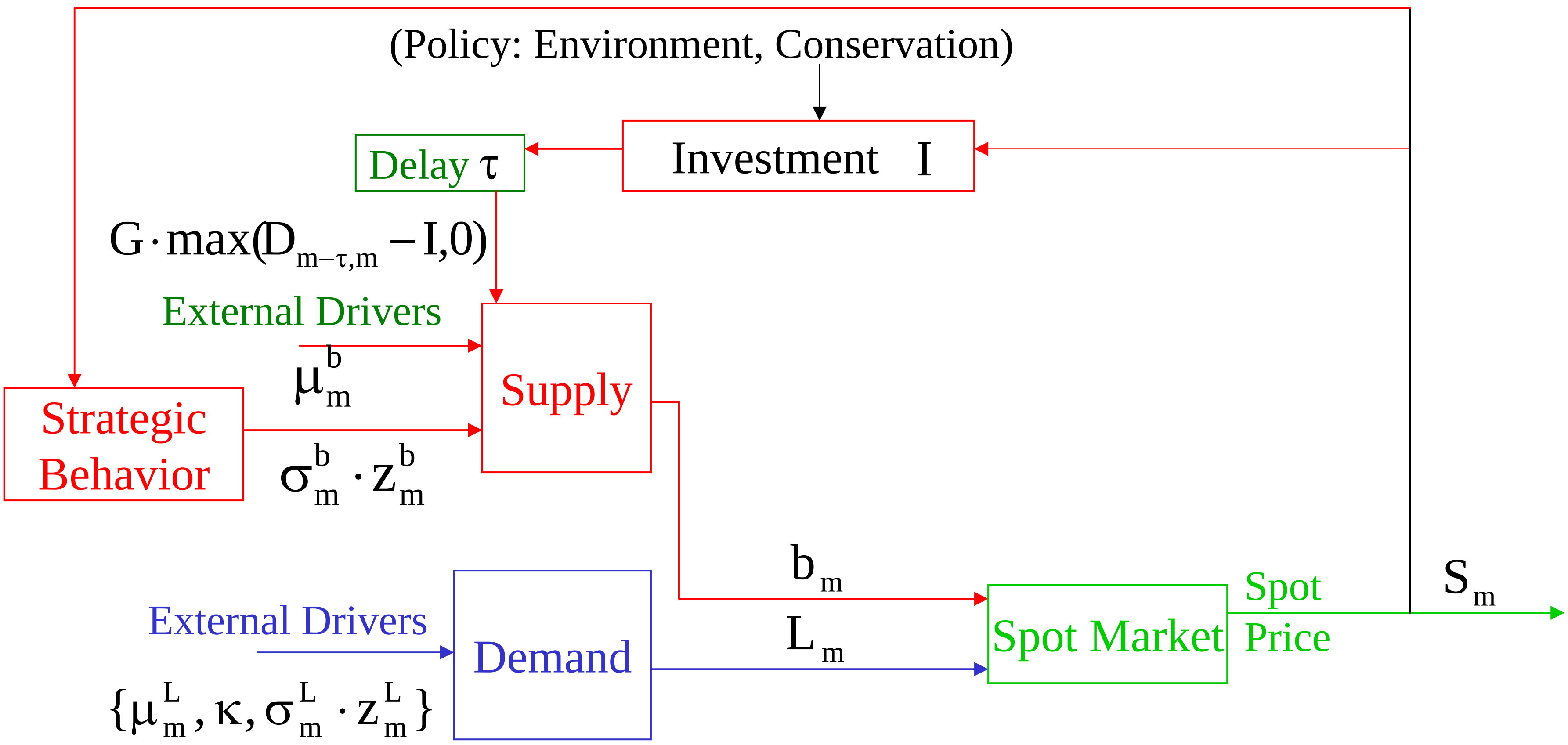
$$\min_{P_{i,a}^G, I_{i,a}^G} \int_{t_0}^{T} \Big[c_{i,a}(t) P_{i,a}(t) + C_{i,a}^G\left(K_{i,a}^G(t), I_{i,a}^G(t), t\right)$$

$$- \underbrace{\lambda(t)}_{\text{Energy Market Price}} P_{i,a}(t) + \sum_l \underbrace{\mu_l(t)}_{\text{Transmission Market Price}} H_{li} P_{i,a}(t) \Big] dt$$

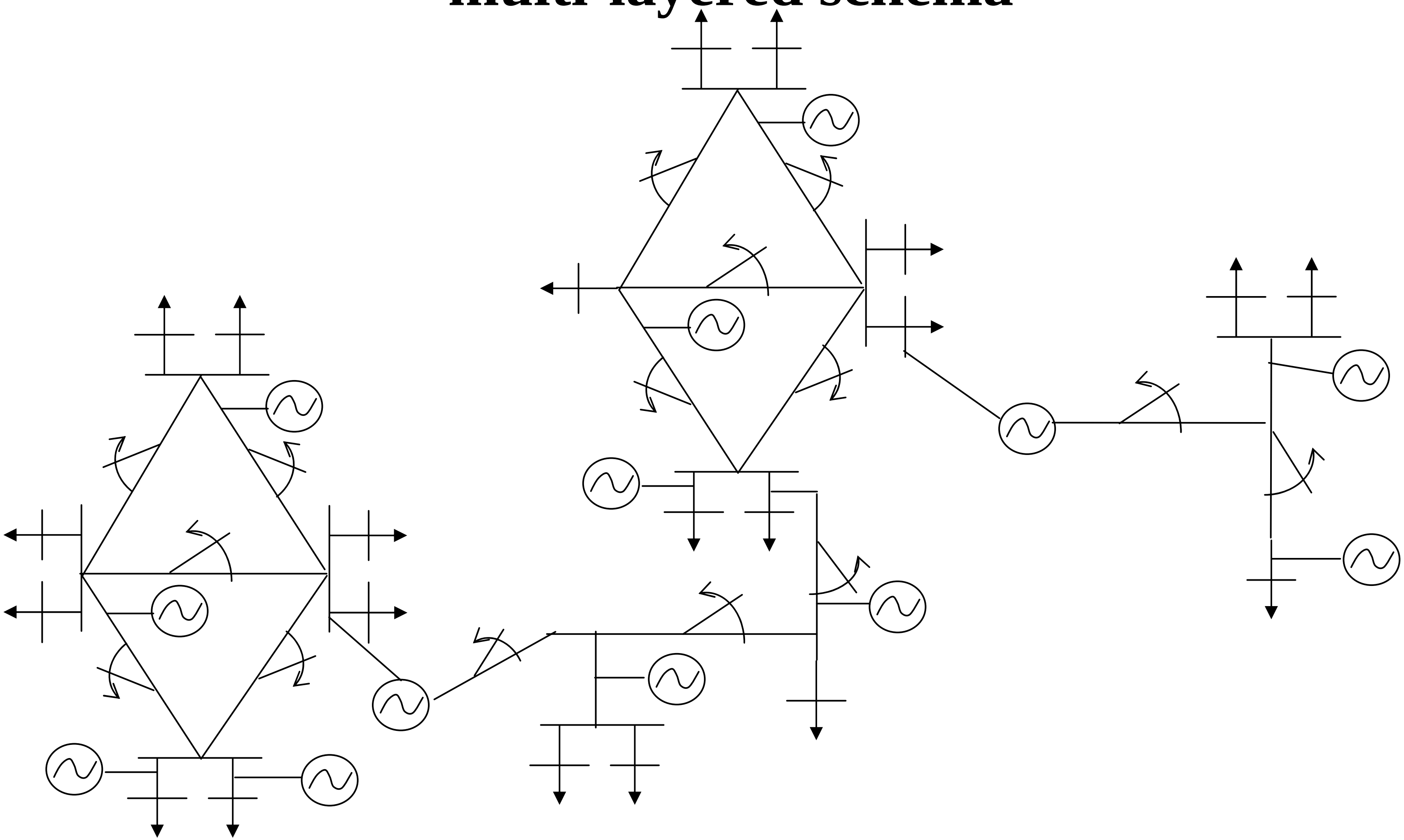
subject to

$$\frac{dK_{i,a}^G}{dt} = I_{i,a}^G(t) \;,\; I_{i,a}^G(t) \geq 0 \;,\; P_{i,a}(t) \leq K_{i,a}^G$$

A Long-term Electricity Price Model – HIDDEN OPPORTUNISM



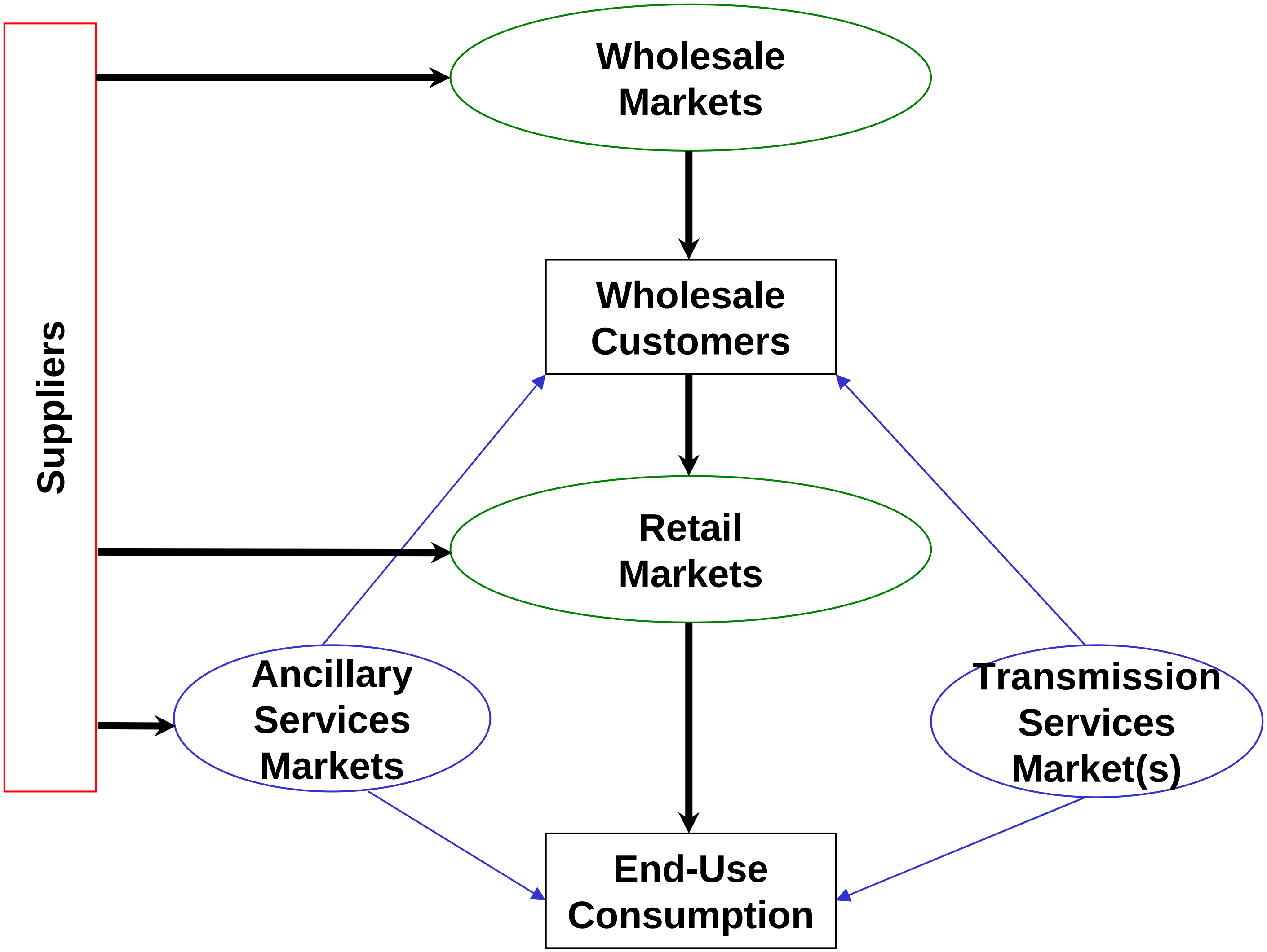
Re-aggregation—multi-layered schema



Ongoing Changes

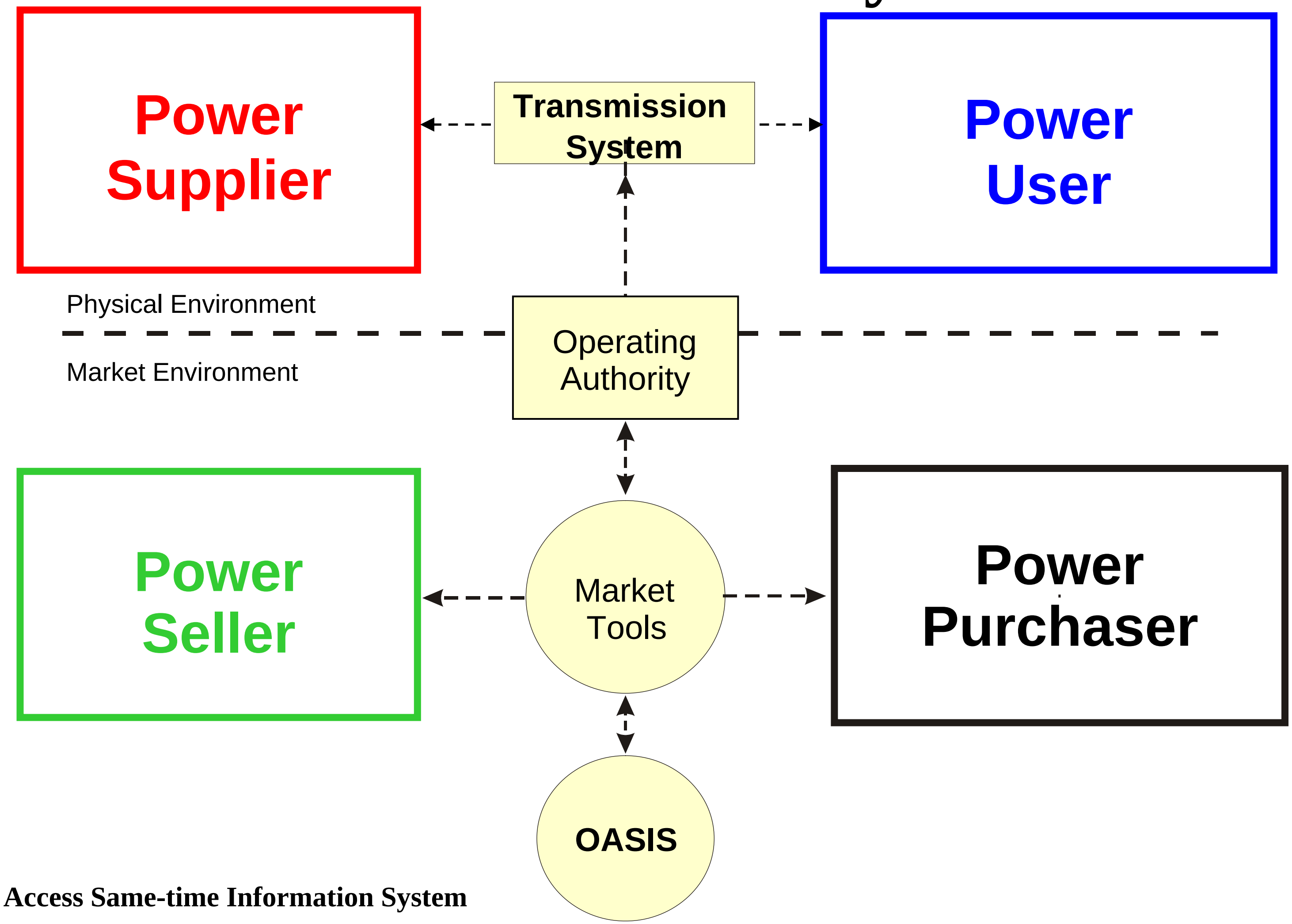
- Technological (cost-effective small and smart power supply, direct line flow control devices (FACTS), Internet, customer automation)
- Organizational (competitive power generation, electricity markets, customer choice, potential for PBR-based transmission businesses; open access)

Regional Electric Markets



Source: DOE Electricity 2002 Conceptual Design

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



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

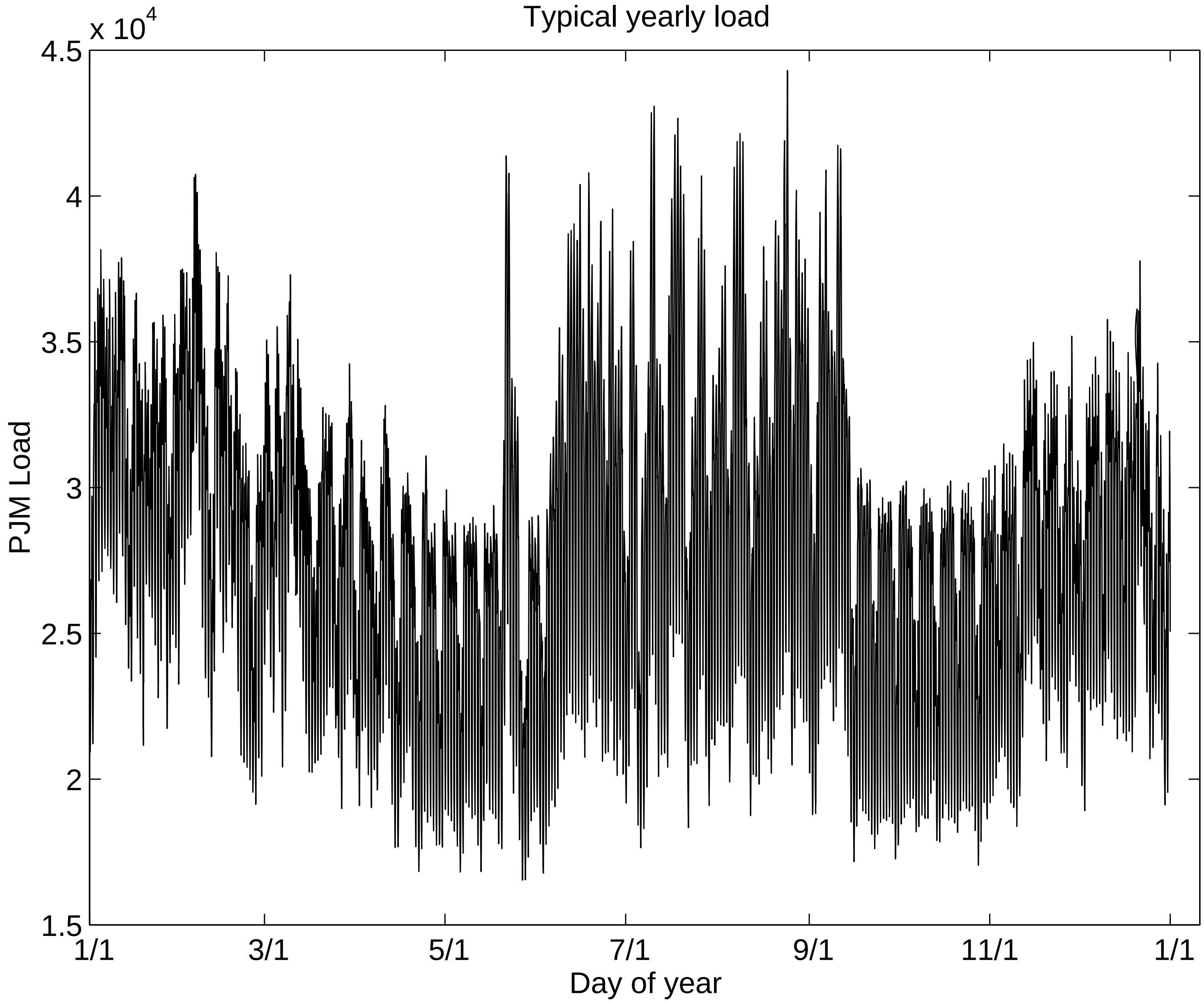
- Paradigm1-Vertically integrated layer schema : Despite the popular belief, not optimal long-term under uncertainties (much more remains to be done if dynamic social welfare is to be optimized in a coordinated way)
- Paradigm 2—Individual actors-driven layer schema: Performance very sensitive to the 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
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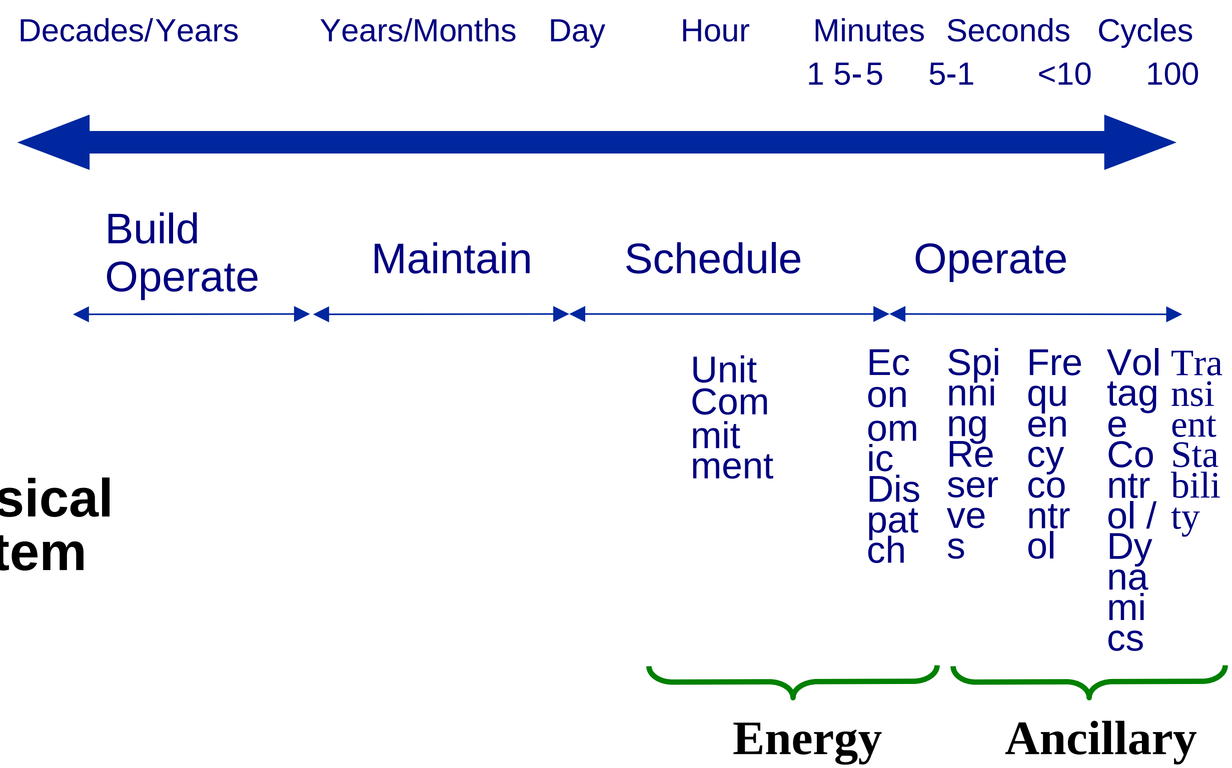
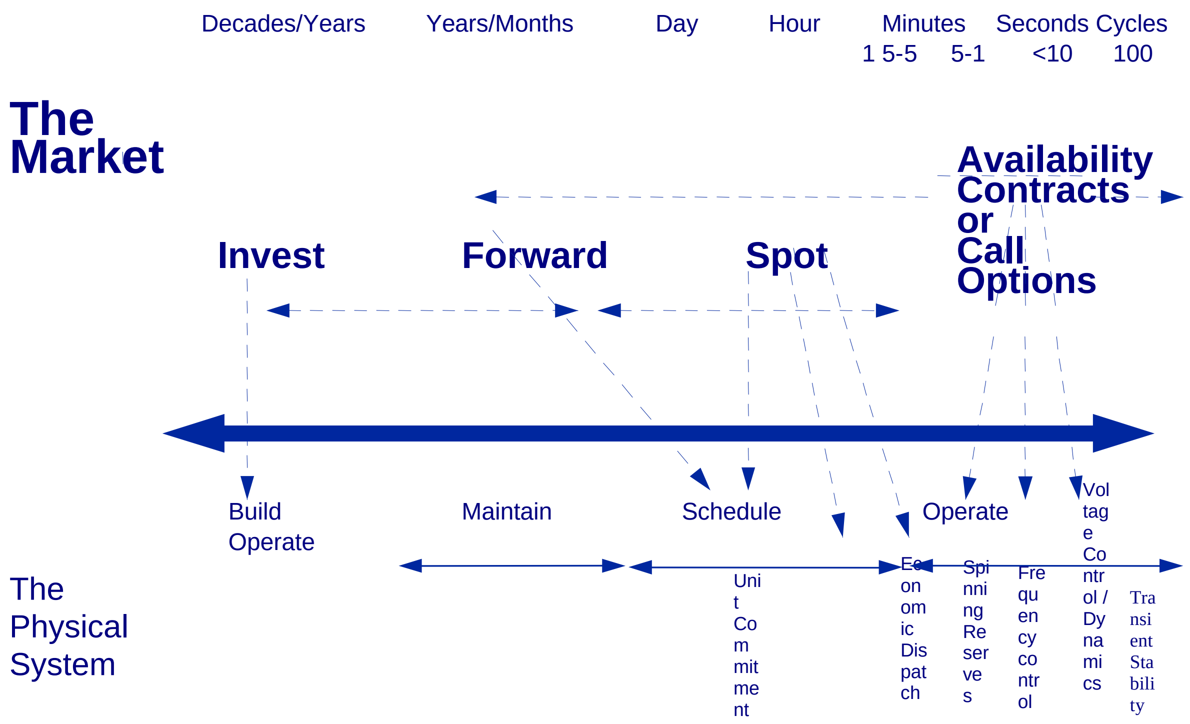
3/1
5/1
7/1
9/1
11/1
1/1
Day of year

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



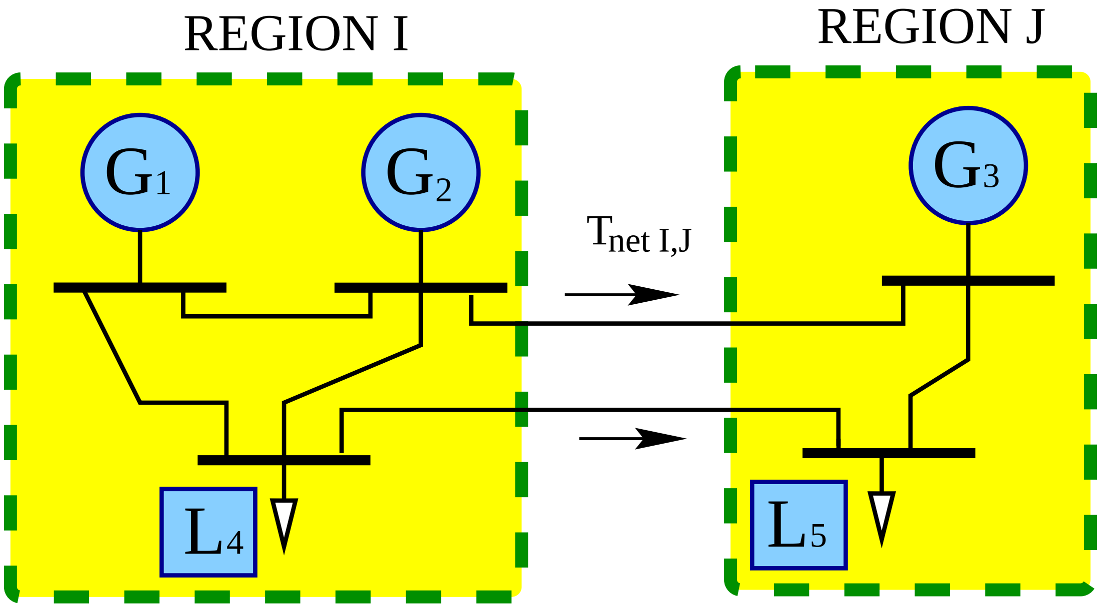
The Physical System

Market and Physical Inter-temporal Complexities



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)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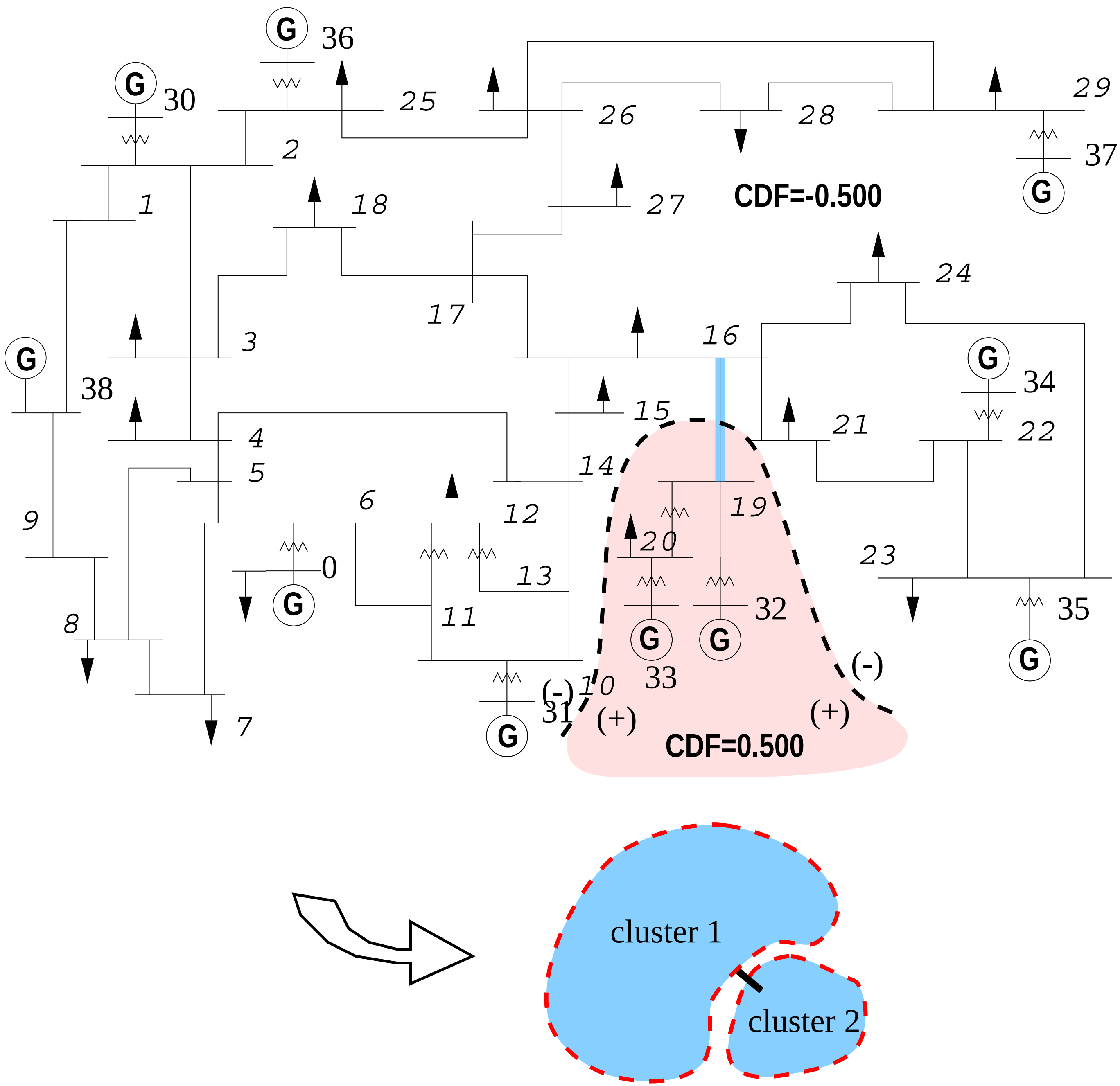

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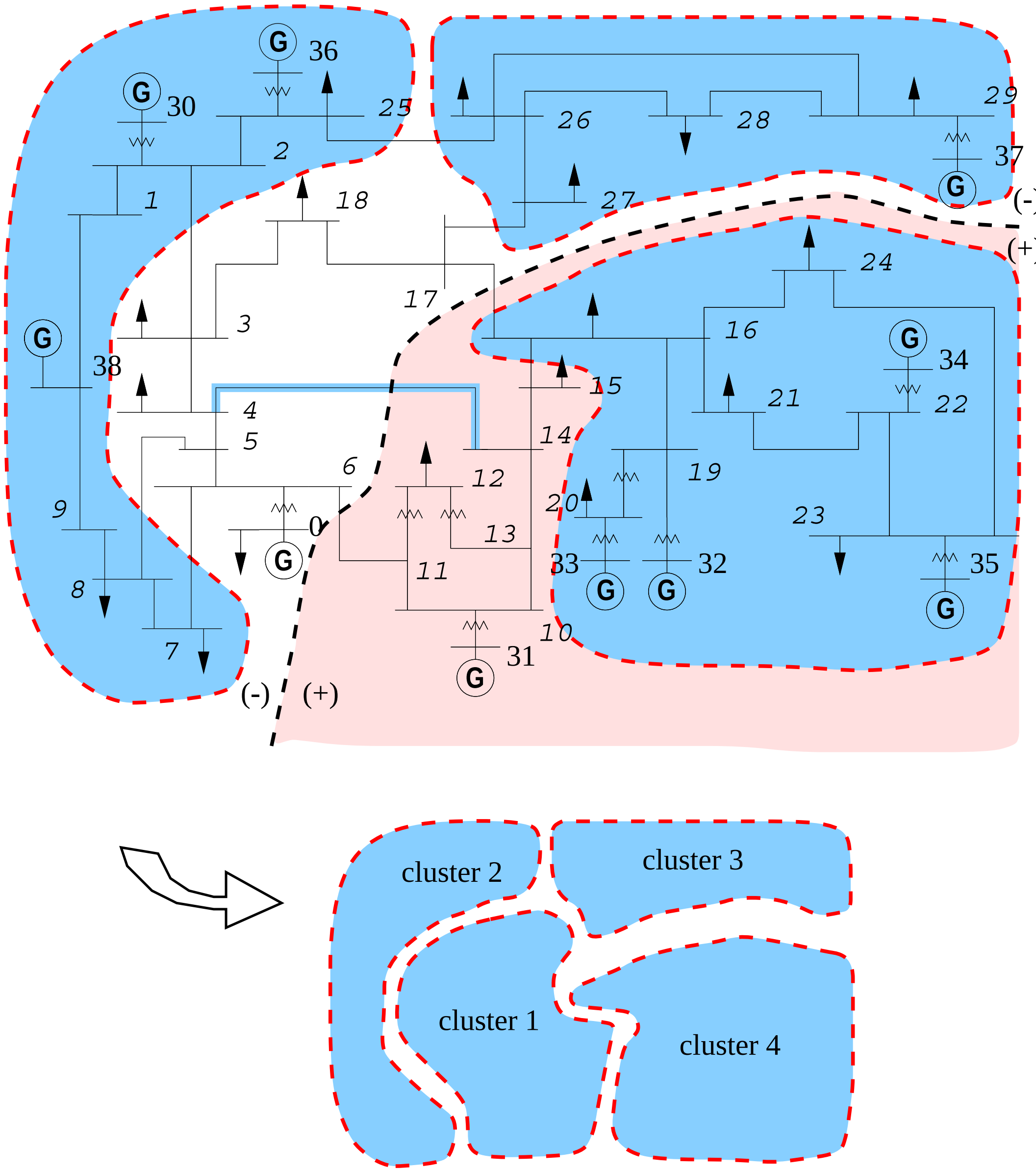

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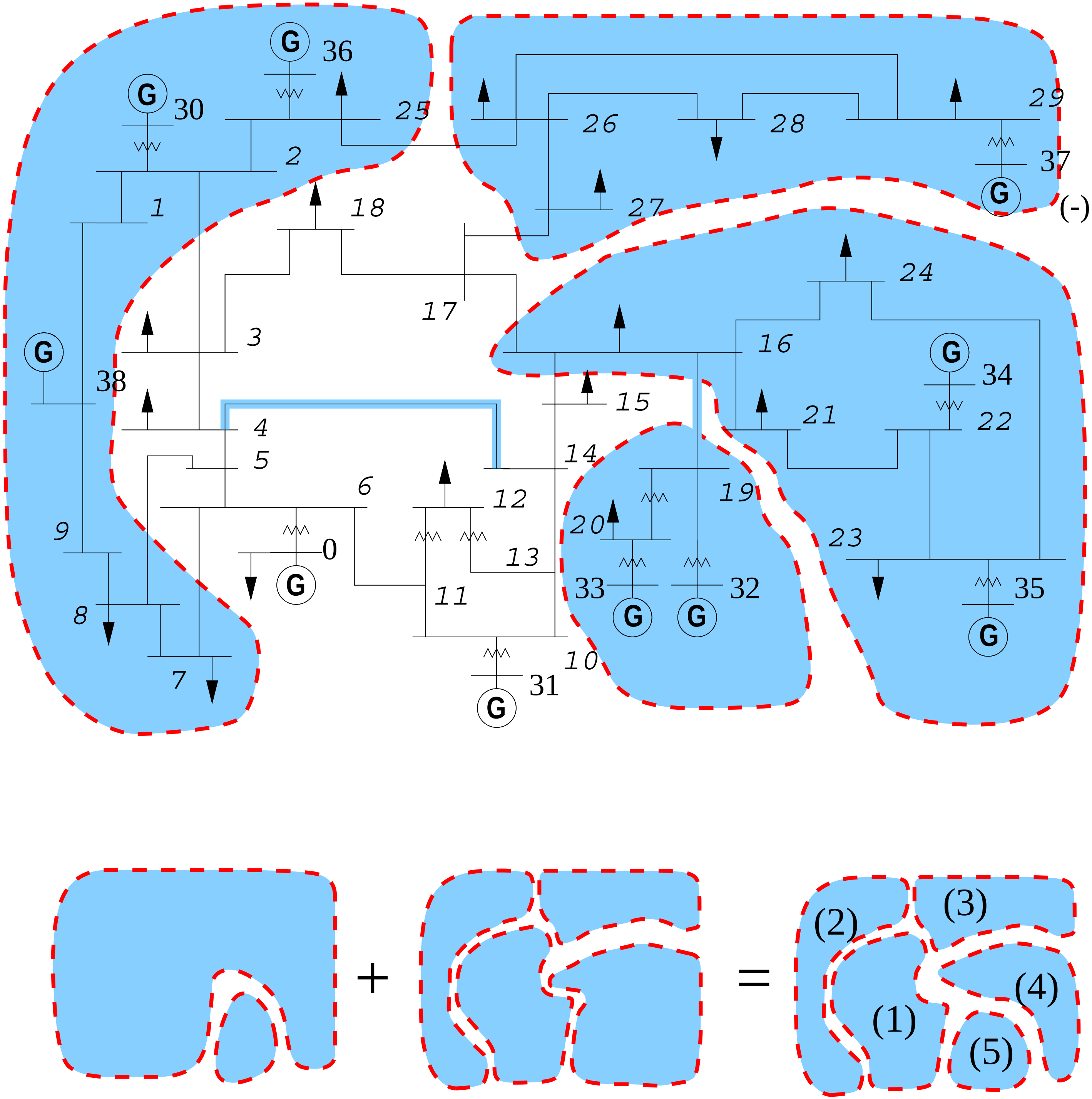

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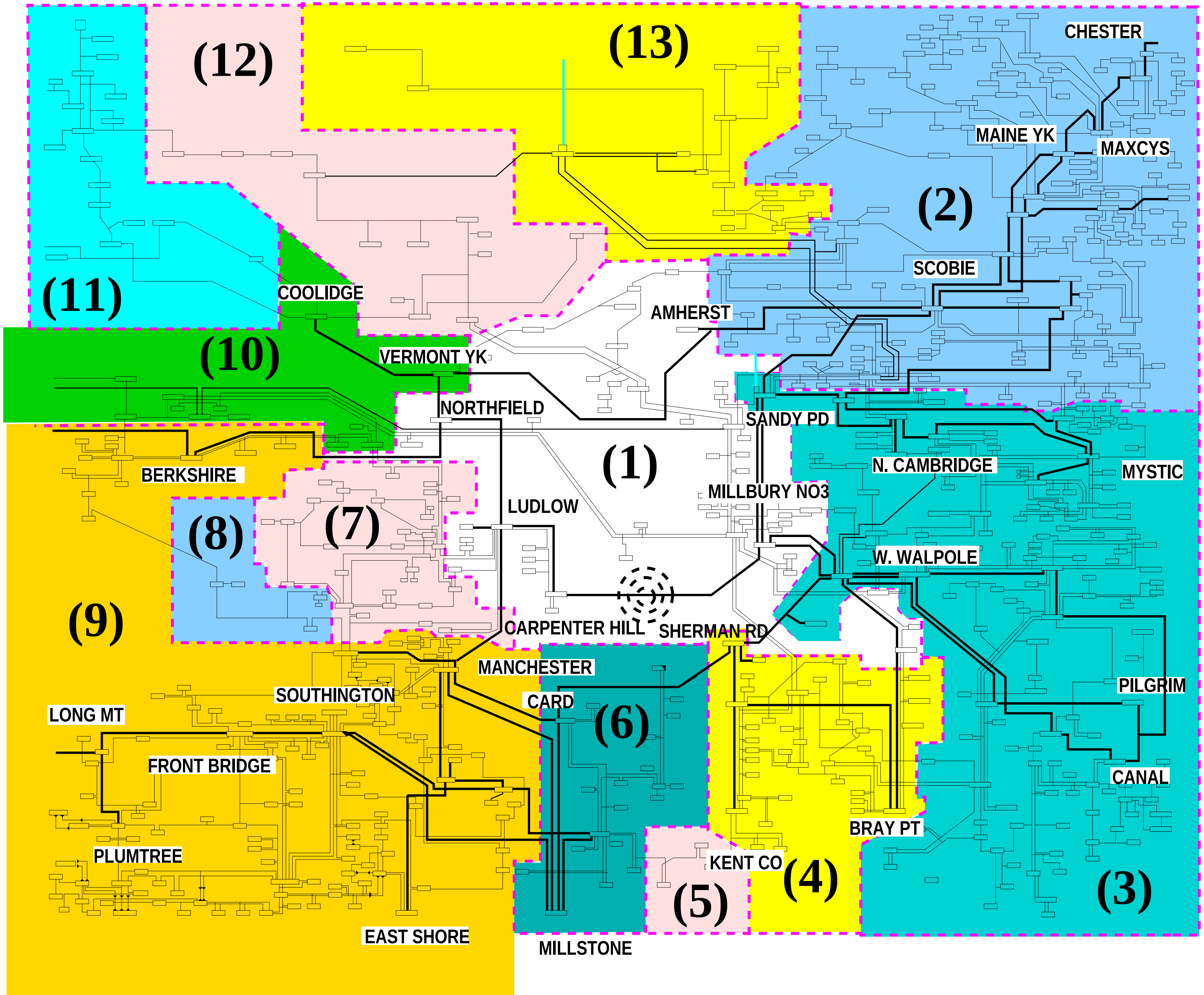
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MILLBURY NO3
BERKSHIRE
LUDLOW
W. WALPOLE
CARPENTER HILL
SHERMAN RD
MANCHESTER
SOUTHINGTON
CARD
LONG MT
FRONT BRIDGE
PILGRIM
CANAL
BRAY PT
PLUMTREE
KENT CO
EAST SHORE
MILLSTONE

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

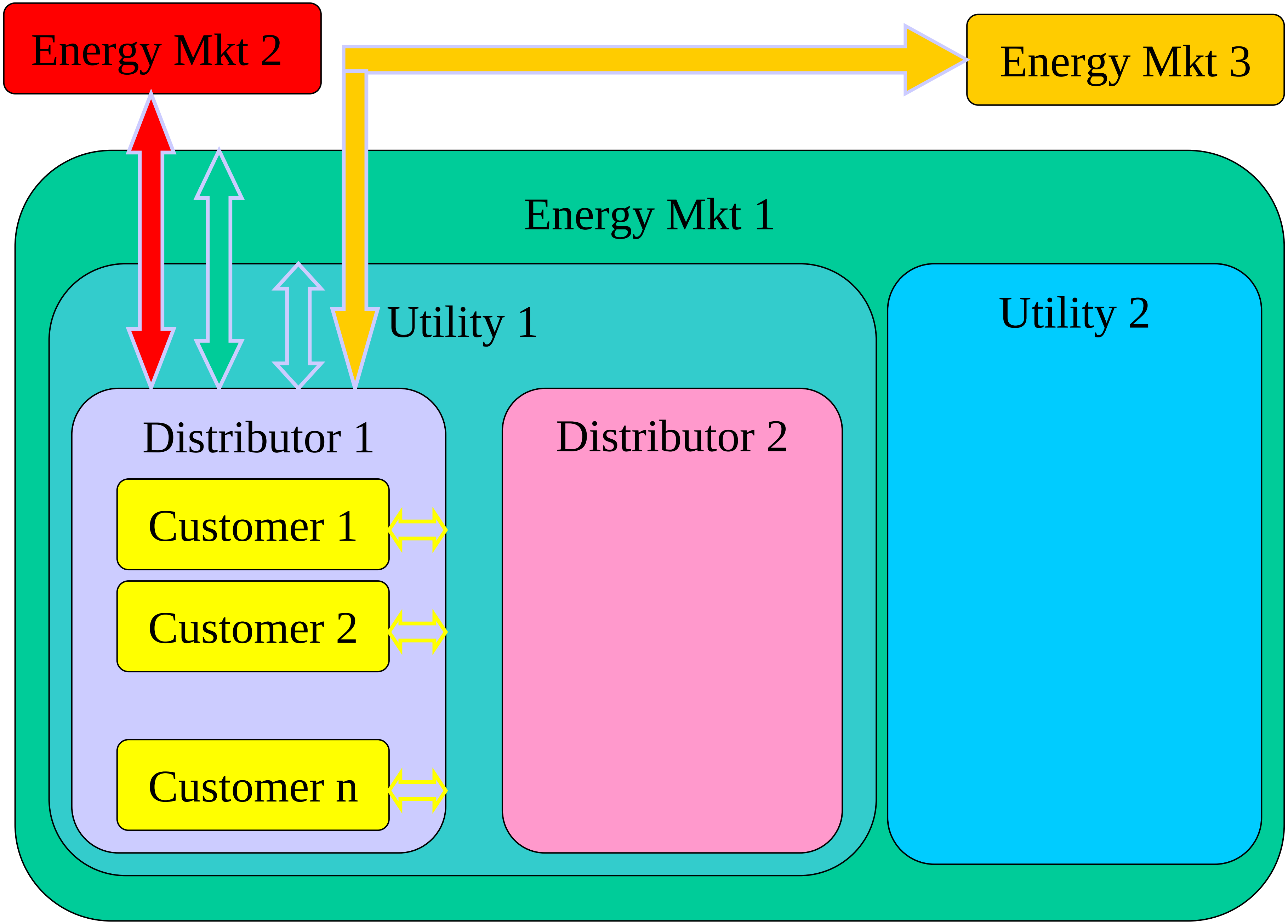
- Design of complete architectures (including markets) for managing service at value (including physical reliability-related risks) over a wide range of time horizons and their inter-temporal dependencies;
- The effect of decentralization (coordination needed for system-wide efficiency; could be through 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

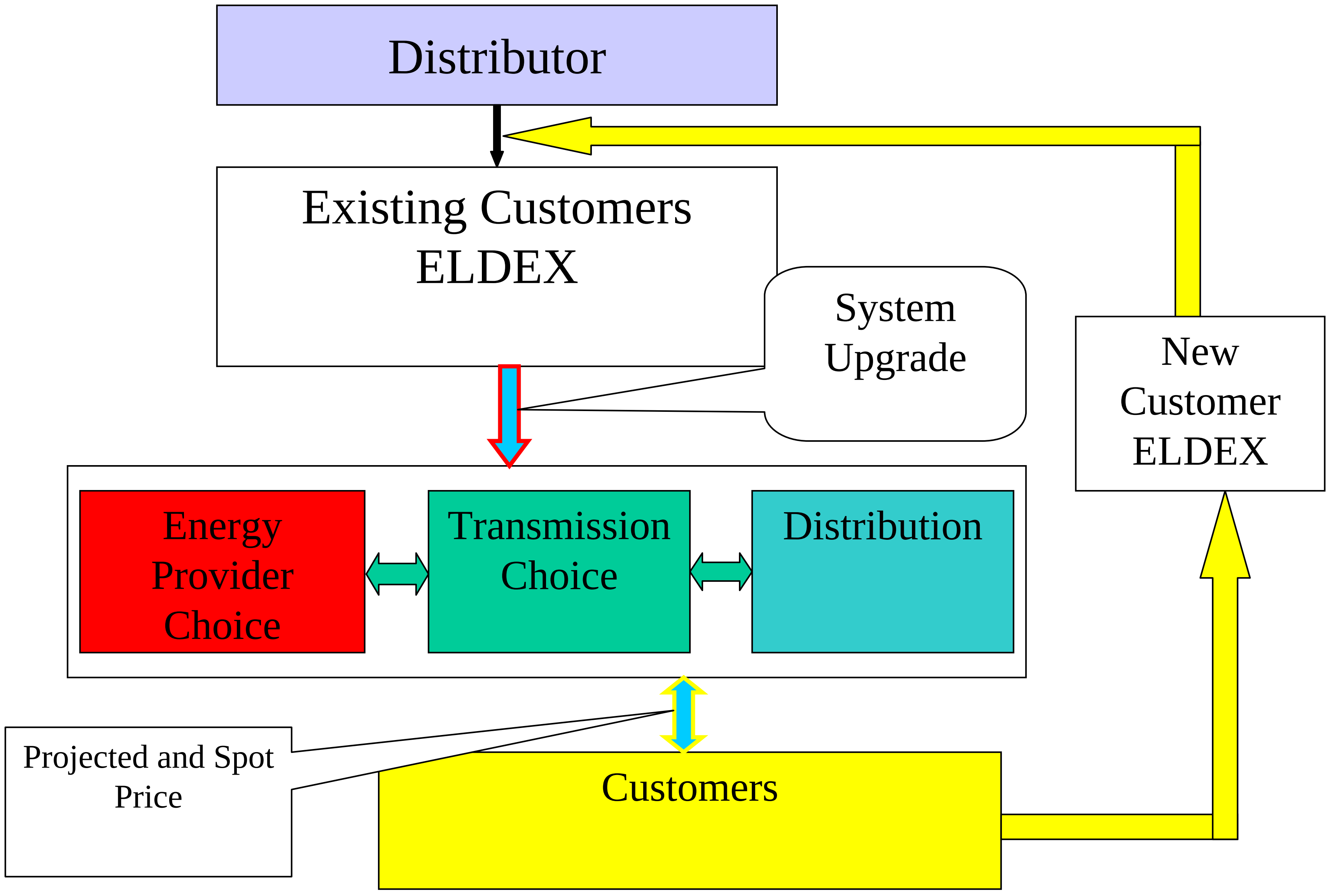
Proposed enhancements-Toward Dynamic Energy Control Protocols (DECPs)

- 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]

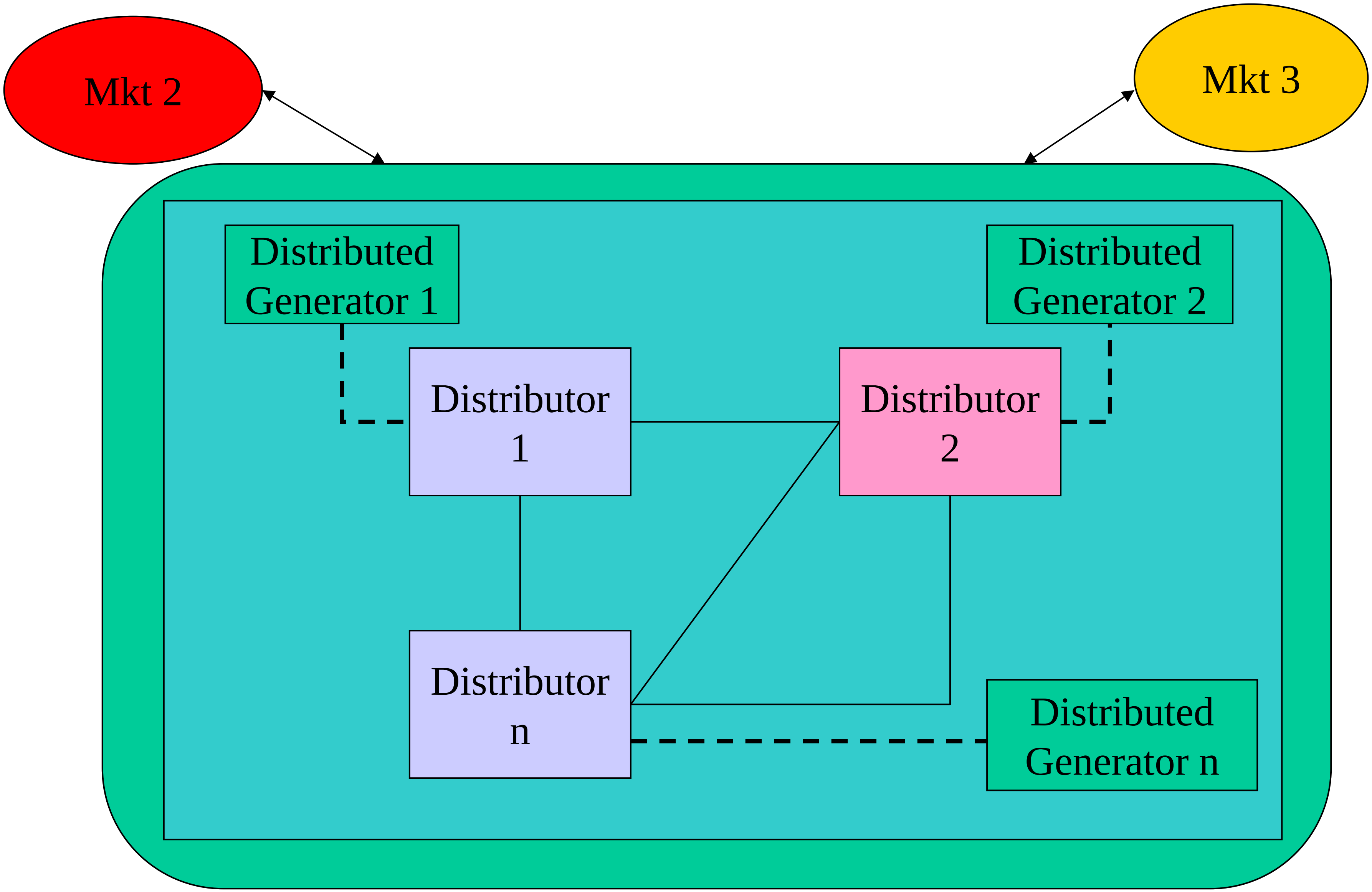

Energy Mkt 2
Energy Mkt 3
Energy Mkt 1
Utility 1
Utility 2
Distributor 1
Distributor 2
Customer 1
Customer 2
Customer n

Dynamic Protocol --- Distributor Level

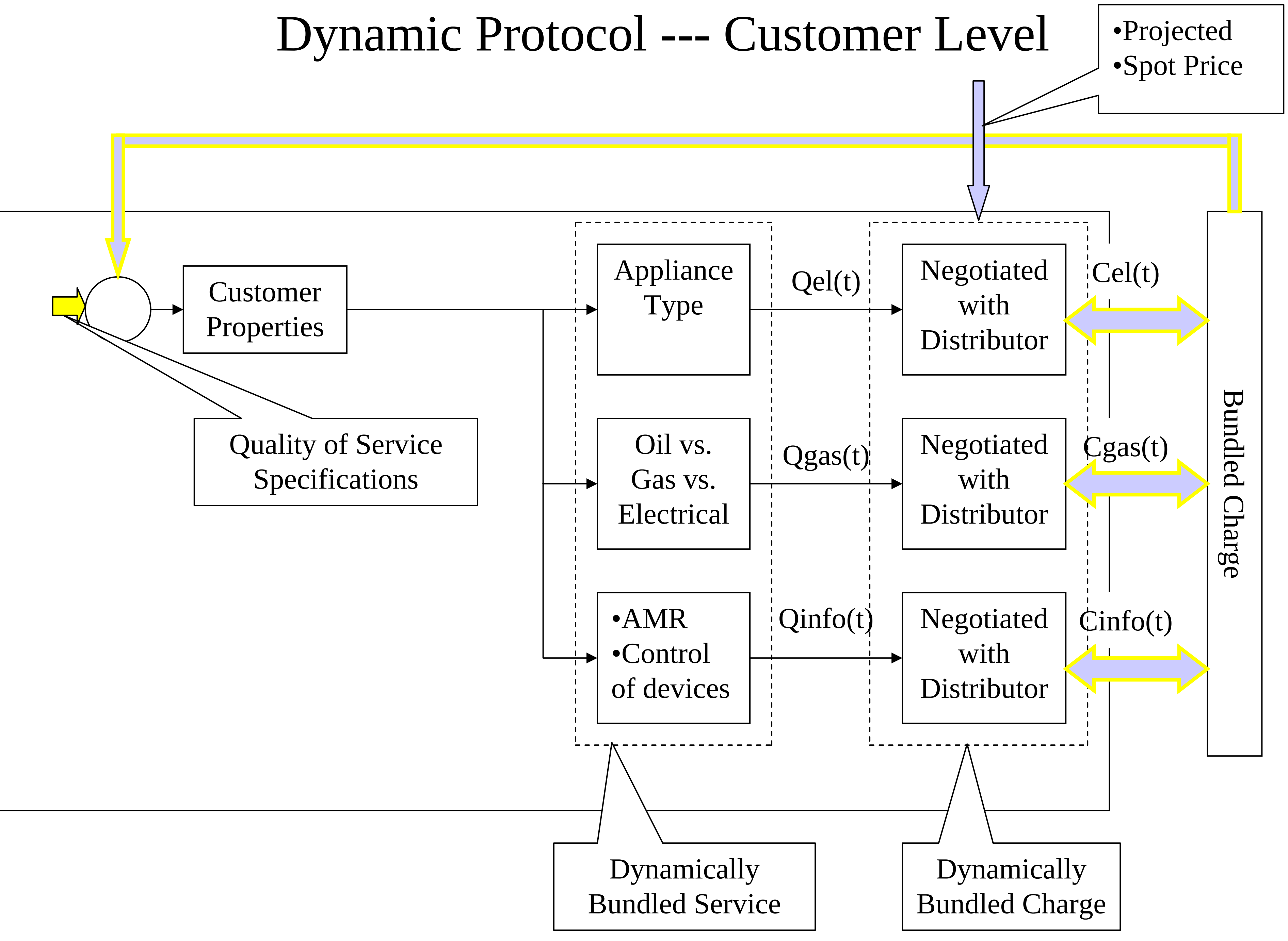
KEY ROLE



Dynamic Protocol --- Utility Level



Dynamic Protocol --- Customer Level



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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- [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.